Novel Measurement Systems based on Electromagnetic Sensors on board Unmanned Aerial Vehicles for Subsurface Imaging and Antenna Measurement Applications

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Programa de Doctorado en Tecnologías de la Información y Comunicaciones en Redes Móviles

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Justificación

El trabajo realizado por la autora de la tesis tiene gran calidad técnica y es altamente innovador, lo que está refrendado por diferentes publicaciones científicas tanto en revistas como en congresos de ámbito internacional y nacional, así como patentes y proyectos/contratos de relevancia, estancias y premios:

Publicaciones


**Congressos internacionales**


Libros y Congresos nacionales


Patentes

Estancias internacionales
1. Radar Department, The Netherlands Organisation for applied scientific research (TNO), The Netherlands.
   • Research stay under supervision of Dr. Caspar Lageweg and Mr. Maarten Otten.
   • Duration: from 1st June 2019 to 15th August 2019.
   • Fundings: ayudas a la movilidad para estancias breves y traslados temporales del Ministerio de Educación 2018 (ref. EST18/0771).
2. Center for Subsurface Sensing & Imaging Systems (CenSSIS), Northeastern University, USA.
   • Research stay under supervision of Prof. Carey Rappaport.
   • Duration: from 1st May 2018 to 31st July 2018.
   • Fundings: ayudas a la movilidad para estancias breves y traslados temporales del Ministerio de Educación 2017 (ref. EST17/0777).
3. Microwaves and Radar Institute, German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt), Germany.
   • Research stay under supervision of Dr. Markus Peichl.
   • Duration: from 22nd August 2016 to 30th September 2016.
   • Fundings: German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt).

Proyectos y financiación
1. FUO-305-19, Inspección de parques termosolares mediante RPAs equipados con cámaras RGB, térmica y posicionamiento RTK (Inspection of thermosolar plants using RPAs equipped with RGB and thermal cameras, and RTK positioning). TSK, 2019.

Premios y reconocimientos
2. Finalist of the Young Engineer Prize. 15th European Radar Conference (EuRAD), September 2018.
8. UBICA Award to the best academic career. XXXVII edición de los Premios Ingenieros de Telecomunicación del Colegio Oficial de Ingenieros de Telecomunicación, June 2017.
9. IN-NOVA Award to the best Master Degree project in communication, navigation and control systems on board unmanned platforms. XXXVII edición de los Premios
RESUMEN DEL CONTENIDO DE TESIS DOCTORAL

1.- Título de la Tesis

| Español/Otro Idioma: Nuevos sistemas de medida basados en sensores electromagnéticos embarcados en vehículos aéreos no tripulados para aplicaciones de “subsurface imaging” y medida de antenas | Inglés: Novel measurement systems based on electromagnetic sensors on board unmanned aerial vehicles for subsurface imaging and antenna measurement applications |

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| Órgano responsable: Comisión Académica del Programa de Doctorado en “Tecnologías de la Información y Comunicaciones en Redes Móviles” |

**RESUMEN (en español)**

En esta Tesis Doctoral se presentan dos nuevos sistemas de medida basados en embarcar sensores electromagnéticos que trabajan en la banda de microondas a bordo de vehículos aéreos no tripulados (Unmanned Aerial Vehicles, UAVs). La capacidad de inspeccionar zonas de difícil acceso sin interactuar con el medio es una de las razones que han contribuido a incrementar ampliamente el empleo de UAVs en el campo de la evaluación no destructiva. En concreto, los sistemas desarrollados y patentados a lo largo de esta Tesis se centran en dos campos de aplicación: subsurface radar imaging (i.e. obtención de imágenes radar bajo la superficie) y medida de antenas en condiciones de operación. Estas aplicaciones se han denominado aplicaciones más allá de lo visible, ya que la capacidad de penetración en medios opacos de los sensores embarcados permite la detección de fenómenos difícilmente detectables con sistemas ópticos.

En el campo de subsurface imaging, se ha integrado un georradar (comúnmente conocido como Ground Penetrating Radar, GPR) en un UAV. La aplicación principal de los prototipos desarrollados en este ámbito es la detección de objetos explosivos enterrados bajo el suelo, como por ejemplo artefactos explosivos improvisados (Improvised Explosive Devices, IEDs). Por lo tanto, el objetivo del sistema es proporcionar imágenes del suelo inspeccionado y de los objetos enterrados en el mismo. Estas imágenes se obtienen combinando coherente las medidas del radar, empleando un método basado en apertura sintética (Synthetic Aperture Radar, SAR). Además, este método se complementa con otras técnicas para poder estimar la composición del suelo y mitigar el clutter.

En cuanto a la medida de antenas, se ha embarcado un detector de potencia en un UAV para medir niveles de amplitud en campo cercano de la antena bajo medida. Estas medidas se procesan utilizando un método llamado Phaseless Sources Reconstruction Method (PSRM), que es una técnica de recuperación de fase capaz de estimar una distribución de corrientes equivalente en una superficie que encierra a la antena bajo medida. Esta distribución proporciona información de diagnóstico de la antena y puede utilizarse para calcular su diagrama de radiación en campo lejano.

Las técnicas aplicadas para procesar las medidas realizadas con cada sistema deben ser capaces de trabajar con medidas adquiridas en posiciones arbitrarias. Asimismo, las técnicas empleadas imponen un requisito de exactitud en la geo-referenciación de las medidas en el orden de centímetros. Por ello, ha sido necesario integrar sistemas de posicionamiento de alta precisión en los UAVs.

Ambos sistemas de medida se han diseñado tratando de mejorar las capacidades de sistemas existentes para aplicaciones similares a un coste notablemente inferior. En primer lugar, se han
This thesis presents two novel measurement systems based on mounting electromagnetic sensors working at microwave frequencies on board Unmanned Aerial Vehicles (UAVs). The ability of inspecting difficult-to-access areas without interacting with the environment is one of the reasons that have contributed to widely increase the usage of UAVs in the field of Non-Destructive Testing (NDT). In particular, the systems developed and patented in the framework of this thesis are devoted to two main fields of application: subsurface imaging and antenna measurement at operational conditions. These kinds of applications have been given the name of *beyond-the-visible* applications, since the capability of penetration in opaque media of the on-board sensors allows the detection of phenomena that could not be detected with optical systems.

Concerning subsurface imaging, a Ground Penetrating Radar (GPR) has been integrated into the UAV. The primary application of this prototype is the detection of explosive hazards buried below the soil, such as Improvised Explosive Devices (IEDs). Therefore, the goal of this system is to provide radar images of the inspected soil and the objects buried below its surface. These images are obtained by coherently combining the radar measurements with a Synthetic Aperture Radar (SAR) method. Furthermore, this method is complemented with other techniques in order to estimate the soil composition and to mitigate the clutter.

Regarding antenna measurement, a power detector has been mounted on board the UAV to gather amplitude-only data in the Near-Field (NF) region of the Antenna Under Test (AUT). These measurements are post-processed using the Phaseless Sources Reconstruction Method (PSRM), which is a phase retrieval technique able to estimate an equivalent currents distribution at a surface enclosing the AUT. This distribution provides antenna diagnostics information and it can be used to calculate the Far-Field (FF) radiation pattern.

The techniques applied to post-process the measurements collected with each system must be able to deal with measurements gathered at arbitrary positions. On the other hand, the adopted techniques impose a centimeter-level geo-referring accuracy. Therefore, highly accurate positioning systems have been integrated into the UAVs.

Both measurement systems have been designed aiming to cost-effectively improve the performance of existing systems for similar purposes. First, initial prototypes and the measurement processing chains have been developed for each application. Based on the experimental validation performed, several improvements have been proposed and analyzed, yielding enhanced prototypes. The performance of all prototypes has been extensively assessed with several flight validation campaigns. In subsurface imaging, the initial prototype is presented in I and II, where along-track radar images of the subsurface have been retrieved, allowing the detection of both metallic and non-metallic targets. Several improvements are analyzed in III and IV, and some of them are integrated in the enhanced prototype. The enhanced prototype, presented in V, exhibits better penetration capabilities and provides three-dimensional (3D) radar images with higher resolution. In antenna measurement, the proof-of-
The concept is investigated in VI and the first prototype is introduced in VII. Further experimental validation is performed in VIII and IX, showing the capability of the system to detect antenna failures and to calculate the FF radiation pattern. Finally, an enhanced prototype devoted to reduce the acquisition time and to improve the accuracy is tested in X.
# FORMULARIO RESUMEN DE TESIS POR COMPENDIO

## 1.- Datos personales solicitante

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| Curso de inicio de los estudios de doctorado | 2016 |

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Acompaña acreditación por el Director de la Tesis de la aportación significativa del doctorando

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| Copia completa de los trabajos * | X |
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## Artículos, Capítulos, Trabajos

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| Coautor7 | X Doctor □ No doctor . Indique nombre y apellidos |

| Yolanda Rodríguez Vaqueiro |
| Borja González Valdés |
| Fernando Las Heras Andrés |
| Yuri Álvarez López |
| Ana Arboleya Arboleya |
| Antonio Pino García |
**Trabajo, Artículo 2**

**Titulo**

*Synthetic Aperture Radar Imaging System for Landmine Detection Using a Ground Penetrating Radar on board an Unmanned Aerial Vehicle*

**Fecha de publicación**

6 de agosto de 2018

**Fecha de aceptación**

30 de julio de 2018

**Inclusión en Science Citation Index o bases relacionadas por la CNEAI**

SCI

**Factor de impacto**

4.098

**Coautores**

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- Borja González Valdés
- Yolanda Rodríguez Vaqueiro
- Fernando Las Heras Andrés
- Antonio Pino García

**Trabajo, Artículo 3**

**Titulo**

*Improvement of GPR SAR-based techniques for accurate detection and imaging of buried objects*

**Fecha de publicación**

22 de julio de 2019

**Fecha de aceptación**

4 de julio de 2019

**Inclusión en Science Citation Index o bases relacionadas por la CNEAI**

SCI

**Factor de impacto**

3.067 (en 2018, 2019 no disponible)

**Coautores**

- Marcos González Díaz
- Yuri Álvarez López
- Fernando Las Heras

**Trabajo, Artículo 4**

**Titulo**

*Bistatic Landmine and IED Detection Combining Vehicle and Drone Mounted GPR Sensors*

**Fecha de publicación**

02 de octubre de 2019

**Fecha de aceptación**

29 de septiembre de 2019

**Inclusión en Science Citation Index o bases relacionadas por la CNEAI**

SCI

**Factor de impacto**

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**Coautores**

- Ann Morgenthaler
- Yuri Álvarez López
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- Fernando Las Heras

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- Guillermo Álvarez Narciandi
- Ana Arboleya Arboleya
- Fernando Las Heras Andrés
- Silverio García Cortés
- Manés Fernández Cabanas

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Resumen

Las técnicas aplicadas para procesar las medidas realizadas con cada sistema deben ser capaces de trabajar con medidas adquiridas en posiciones arbitrarias. Asimismo, las técnicas empleadas imponen un requisito de exactitud en la geo-referenciación de las medidas en el orden de centímetros. Por ello, ha sido necesario integrar sistemas de posicionamiento de alta precisión en los UAVs.

Ambos sistemas de medida se han diseñado tratando de mejorar las capacidades de sistemas existentes para aplicaciones similares a un coste notablemente inferior. En primer lugar, se han desarrollado los prototipos iniciales y los flujos de procesado de las medidas para cada una de las aplicaciones. A partir de los resultados de la validación experimental, se han propuesto y analizado diversas mejoras, que han dado lugar a prototipos mejorados. El desempeño de todos los prototipos ha sido exhaustivamente evaluado realizando varios vuelos de validación. En el caso de subsurface imaging, el prototipo inicial se ha presentado en [I] y [II], donde ha sido posible obtener imágenes radar del subsuelo a lo largo de la trayectoria de vuelo, en las que se pueden detectar objetos tanto metálicos como no metálicos. En [III] y [IV] se analizan diversas mejoras, algunas de las cuales se han integrado en el prototipo mejorado. Este prototipo mejorado, que se presenta en [V], posee una mejor capacidad de penetración y proporciona imágenes radar tridimensionales con mejor resolución. En el campo de medida de antenas, en [VI] se muestra una prueba de concepto del sistema y en [VII] se introduce el primer prototipo. En [VIII] y [IX] se realiza una validación experimental más extensa, mostrándose la capacidad del sistema para detectar fallos en la antena bajo medida y para calcular su diagrama de radiación en campo lejano. Finalmente, el prototipo mejorado, que se centra en reducir el tiempo de adquisición y mejorar la precisión, se pone a prueba en [X].
Conclusiones

Esta tesis se centra en el diseño, implementación y validación experimental de nuevos sistemas de medida a bordo de UAVs para aplicaciones más allá de lo visible. En particular, se han considerado dos ámbitos de aplicación: subsurface radar imaging, y medida y diagnóstico de antenas. A lo largo de la presente tesis doctoral, se han patentado ambos sistemas, y se han construido y realizado experimentos con los correspondientes prototipos. En base a la experiencia adquirida con los primeros prototipos desarrollados para cada aplicación, se han analizado diversas mejoras tanto en el procesado como en el hardware. Algunas de estas mejoras han sido implementadas en los prototipos mejorados, tratando de incrementar la calidad de los resultados y reducir los tiempos de adquisición y despliegue de los sistemas.

Esta tesis, presentada como compendio de publicaciones, está basada fundamentalmente en el trabajo presentado en las publicaciones [I]-[X]. En este documento se ha resumido el trabajo realizado: el estado del arte y los fundamentos teóricos se analizan en los capítulos 1 y 2, respectivamente; y los resultados más importantes se presentan en el capítulo 3 para subsurface imaging y en el capítulo 4 para medida de antenas. En las publicaciones y las citas incluidas en las mismas se pueden encontrar más explicaciones y resultados. Además, en el apéndice A se incluye un resumen de la arquitectura de los prototipos.

El objetivo final de ambas aplicaciones es que el UAV sobrevuelen de forma autónoma el área de interés, tomando medidas geo-referenciadas. Estas medidas deben ser procesadas para proporcionar los resultados deseados: i) una imagen radar de alta resolución en el caso de subsurface imaging, y ii) información de caracterización y diagnóstico en el caso de medida de antenas. Los algoritmos empleados para obtener dichos resultados imponen una precisión en la geo-referenciación del orden de centímetros y, por ello, ha sido necesario integrar sistemas de posicionamiento de alta precisión en los UAVs. Además, con el objetivo de desarrollar sistemas de coste notablemente inferiores a los
existentes en el mercado, en los prototipos mejorados se ha integrado un sistema de posicionamiento customizado basado en un sensor de Real Time Kinematic (RTK) de doble banda y multiconstelación, lo que ha requerido el desarrollo ad-hoc de un driver.

En el ámbito de subsurface radar imaging, el sistema propuesto consiste en un GPR embarcado en el UAV. Las medidas radar geo-referenciadas se procesan usando técnicas basadas en SAR para obtener una imagen del suelo y los objetos enterrados. Dado que estas técnicas requieren una estimación de los parámetros constitutivos del suelo, para ello se ha propuesto y validado un método basado en las medidas de GPR [I]. La arquitectura del primer prototipo (GEODRON 1.0), el flujo de procesado radar y la validación experimental se presentan en [II]. Dicha validación se ha llevado a cabo en varias etapas: primero, en un entorno controlado (un rango de medida plano); después, con un escáner lineal manual (tanto en interiores como en exteriores) y, finalmente, con vuelos realizados en modo manual. Los resultados obtenidos muestran la capacidad de obtener imágenes bidimensionales del suelo, donde ha sido posible detectar objetos tanto metálicos como no metálicos. También se ha analizado la repetibilidad de los resultados y que las imágenes radar tienen las resoluciones esperadas. Teniendo en cuenta estos primeros resultados, se han identificado y analizado diversas líneas de mejora. Para poder usar un radar de menor frecuencia (lo que permite incrementar la profundidad de penetración) y, a la vez, mantener un gran ancho de banda (para obtener imágenes radar de alta resolución), en [III] se ha empleado otro GPR. Con el objetivo de compensar la variación de la respuesta de las antenas y de los parámetros constitutivos del suelo a lo largo de la banda de frecuencias, se han propuesto tres mejoras en el flujo de procesado radar, que han sido validadas con simulaciones y medidas en [III]. Los resultados muestran que dichas mejoras son esenciales para detectar objetos enterrados en escenarios complejos. Otra posibilidad para facilitar la detección de objetos en dichos escenarios se analiza en [IV]. En este caso, se propone y valida (a través de simulaciones) una nueva arquitectura de GPR distribuida que aúna las ventajas en cuanto a buena capacidad de penetración y buena resolución de Forward Looking GPR (FLGPR) y Downward Looking GPR (DLGPR), respectivamente. En los resultados se observa una mejor discriminación de los objetos en comparación con arquitecturas convencionales. Finalmente, en [V] se ha desarrollado un prototipo mejorado (GEODRON 2.0), que integra el radar de menor frecuencia utilizado en [III] y un sistema de posicionamiento de mayor precisión. Este prototipo permi-
te obtener imágenes radar tridimensionales del área inspeccionada a partir de medidas adquiridas en vuelos autónomos. Debe tenerse en cuenta que es necesario procesar adecuadamente los datos de posicionamiento, para compensar problemas relacionados con el muestreo no uniforme y la desviación del UAV de la ruta de vuelo ideal. También se proponen mejoras adicionales en el flujo de procesado radar, que permiten obtener imágenes radar con mejor resolución y relación señal a clutter, tal y como se muestra en los resultados.

En cuanto a la medida de antenas en condiciones de operación, se ha propuesto una solución de coste reducido y práctica consistente en embarcar un detector de potencia a bordo del UAV para tomar medidas en campo cercano (Near-Field, NF). Las medidas de amplitud geo-referenciadas tomadas en campo cercano se procesan utilizando una técnica de recuperación de fase basada en corrientes equivalentes (PSRM) para obtener información de diagnóstico (lo que permite detectar fallos) y el diagrama de radiación en campo lejano (Far-Field, FF). La idea ha sido puesta a prueba para medir antenas de RFID (Radio Frequency IDentification) con etiquetas RFID [VI]. Tras el éxito de esta prueba inicial, se ha implementado el primer prototipo (UASAM 1.0), que se ha empleado para medir autónomamente arrays en las bandas S y C [VII] empleando rutas de vuelo cilíndricas. Estos resultados han probado la viabilidad de usar UASAM 1.0 para el diagnóstico y la caracterización de arrays de antenas con polarización lineal. Después, para evaluar de forma más extensa la capacidad de diagnóstico de antenas, se ha medido una antena de una red móvil tanto en condiciones normales de operación como con un bloqueo parcial (simulando un fallo) [VIII]. En las medidas es posible detectar dicho defecto, dado que las corrientes equivalentes estimadas desaparecen en el área donde se encuentra el bloqueo. En [VIII] también se investiga de la capacidad del sistema para estimar la cobertura radioeléctrica y para medir antenas de mayor frecuencia. Con el objetivo de reducir el tiempo de adquisición, en [IX] se han analizado otros tipos de rejillas de medida (porciones de cilindros y planos), que son útiles para medir antenas directivas. Asimismo, también se ha comprobado la viabilidad de emplear el sistema propuesto para medir arrays de antenas con polarización circular [IX]. Finalmente, se ha presentado en [X] un prototipo mejorado (UASAM 2.0), que integra un detector de potencia dual y un sistema de posicionamiento de mayor precisión. Ello permite evitar la necesidad de realizar varios vuelos para adquirir las medidas de amplitud en campo cercano en dos superficies diferentes y, además, proporciona una mejor precisión en la geo-referenciación. Las mejoras obtenidas en términos de tiem-
Conclusiones

po de adquisición y precisión se han analizado midiendo una antena de tipo reflector.
Abstract

This thesis presents two novel measurement systems based on mounting electromagnetic sensors working at microwave frequencies on board Unmanned Aerial Vehicles (UAVs). The ability of inspecting difficult-to-access areas without interacting with the environment is one of the reasons that have contributed to widely increase the usage of UAVs in the field of Non-Destructive Testing (NDT). In particular, the systems developed and patented in the framework of this thesis are devoted to two main fields of application: subsurface radar imaging and antenna measurement at operational conditions. These kinds of applications have been given the name of beyond-the-visible applications, since the capability of penetration in opaque media of the on-board sensors allows the detection of phenomena that could not be detected with optical systems.

Concerning subsurface imaging, a Ground Penetrating Radar (GPR) has been integrated into the UAV. The primary application of this prototype is the detection of explosive hazards buried below the soil, such as Improvised Explosive Devices (IEDs). Therefore, the goal of this system is to provide radar images of the inspected soil and the objects buried below its surface. These images are obtained by coherently combining the radar measurements with a Synthetic Aperture Radar (SAR) method. Furthermore, this method is complemented with other techniques in order to estimate the soil composition and to mitigate the clutter.

Regarding antenna measurement, a power detector has been mounted on board the UAV to gather amplitude-only data in the Near-Field (NF) region of the Antenna Under Test (AUT). These measurements are post-processed using the Phaseless Sources Reconstruction Method (PSRM), which is a phase retrieval technique able to estimate an equivalent currents distribution at a surface enclosing the AUT. This distribution provides antenna diagnostics information and it can be used to calculate the Far-Field (FF) radiation pattern.

The techniques applied to post-process the measurements collected with each system must be able to deal with measurements gathered at arbitrary
Abstract

positions. On the other hand, the adopted techniques impose a centimeter-level geo-referring accuracy. Therefore, highly accurate positioning systems have been integrated into the UAVs.

Both measurement systems have been designed aiming to cost-effectively improve the performance of existing systems for similar purposes. First, initial prototypes and the measurement processing chains have been developed for each application. Based on the experimental validation performed, several improvements have been proposed and analyzed, yielding enhanced prototypes. The performance of all prototypes has been extensively assessed with several flight validation campaigns. In subsurface imaging, the initial prototype is presented in [I] and [II], where along-track radar images of the subsurface have been retrieved, allowing the detection of both metallic and non-metallic targets. Several improvements are analyzed in [III] and [IV], and some of them are integrated in the enhanced prototype. The enhanced prototype, presented in [V], exhibits better penetration capabilities and provides Three-Dimensional (3D) radar images with higher resolution. In antenna measurement, the proof-of-concept is investigated in [VI] and the first prototype is introduced in [VII]. Further experimental validation is performed in [VIII] and [IX], showing the capability of the system to detect antenna failures and to calculate the FF radiation pattern. Finally, an enhanced prototype devoted to reduce the acquisition time and to improve the accuracy is tested in [X].
Dissertation

This thesis, presented by compendium of publications, consists of the following publications, which are referred to in the text by their Roman numerals. A complete copy of all the publications is included in the final part of the dissertation. The publications do not appear in chronological order, but grouped by topic:


Other publications and works related to the topics of the thesis but not included as part of the dissertation

In addition to the above-mentioned references, the following publications also related to the topics of the thesis have been authored or coauthored by María García Fernández during her time as doctoral candidate at Universidad de Oviedo:

**International journals**


**International conferences and workshops**


National journals and books


National conferences


Patents


International research stays

During the development of this doctoral thesis, the author carried out several research stays abroad: at the German Aerospace Centre, the Center for Subsurface Sensing & Imaging Systems (CenSSIS) at Northeastern University and The Netherlands Organisation for applied scientific research (TNO).

1. Radar Department, The Netherlands Organisation for applied scientific research (TNO), The Netherlands.
   - Research stay under supervision of Dr. Caspar Lageweg and Mr. Matern Otten.
   - Fundings: ayudas a la movilidad para estancias breves y traslados temporales del Ministerio de Educación 2018 (ref. EST18/0771).

2. Center for Subsurface Sensing & Imaging Systems (CenSSIS), Northeastern University, USA.
   - Research stay under supervision of Prof. Carey Rappaport.
   - Duration: from 1st May 2018 to 31st July 2018.
   - Fundings: ayudas a la movilidad para estancias breves y traslados temporales del Ministerio de Educación 2017 (ref. EST17/0777).
3. Microwaves and Radar Institute, German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt), Germany.

- Research stay under supervision of Dr. Markus Peichl.
- Duration: from 22nd August 2016 to 30th September 2016.
- Fundings: German Aerospace Centre (Deutsches Zentrum für Luft- und Raumfahrt).

**Research projects and funding**

The doctoral candidate has been awarded an FPU grant (Formación de Profesorado Universitario, ref. FPU15/06341), funded by Ministerio de Educación, for the realization of the PhD degree.

The doctoral thesis has also been developed in the framework of several national and regional research projects in which the candidate has been actively involved:


In particular, the work carried out in this thesis has notably contributed to obtain the following funding:

Furthermore, the doctoral candidate has also been involved in several contracts with companies:

1. FUO-305-19, Inspección de parques termosolares mediante RPAs equipados con cámaras RGB, térmica y posicionamiento RTK (Inspection of thermosolar plants using RPAs equipped with RGB and thermal cameras, and RTK positioning). TSK, 2019.


**Awards and recognition**

During her time as doctoral candidate at Universidad de Oviedo, the candidate has received the following awards:


2. Finalist of the Young Engineer Prize. 15th European Radar Conference (EuRAD), September 2018.


6. TICRA grant to attend the *12th European Conference on Antennas and Propagation (EuCAP)*. TICRA, March 2018.


8. UBICA Award to the best academic career. XXXVII edición de los Premios Ingenieros de Telecomunicación del Colegio Oficial de Ingenieros de Telecomunicación, June 2017.

9. IN-NOVA Award to the best Master Degree project in communication, navigation and control systems on board unmanned platforms. XXXVII edición de los Premios Ingenieros de Telecomunicación del Colegio Oficial de Ingenieros de Telecomunicación, June 2017.

Author’s contribution

This section states the contribution of the doctoral candidate and the coauthors for each of the publications that compose this dissertation.

• Publication [I] “SAR-based technique for soil permittivity estimation”
  Dr. Yuri Álvarez, who was the main author, developed the processing code for estimating the soil constitutive parameters and performed the measurements. The candidate developed the underground-SAR code and built the outdoor measurement system. She also assisted in writing the manuscript and processing the data. The rest of the coauthors supervised the work.

• Publication [II] “Synthetic Aperture Radar imaging system for landmine detection using a Ground Penetrating Radar on board an Unmanned Aerial Vehicle”
  This publication was mainly done by the doctoral candidate. She developed the processing methods, and designed and built the prototype. She also carried out the measurements and the data post-processing. Dr. Yuri Álvarez was mainly in charge of writing the publication and he piloted the UAV. Dr. Ana Arboleya assisted in performing the on-ground testing. Prof. Fernando Las Heras assisted in the in-flight tests and supervised the work. The rest of the coauthors co-supervised the work.

• Publication [III] “Improvement of GPR-SAR-based techniques for accurate detection and imaging of buried objects”
  The doctoral candidate formulated the proposed improvements and assisted in developing the algorithms and the numerical simulations. She also performed some of the measurements in the controlled scenario and helped in writing the manuscript. Mr. Marcos González developed some of the codes and performed several simulations. Mr. Marcos González and Dr. Yuri Álvarez carried out the outdoor measurements and wrote the manuscript. Prof. Fernando Las Heras supervised the work.
Author’s contribution

• Publication [IV] “Bistatic Landmine and IED Detection Combining Vehicle and Drone Mounted GPR sensors”
This work is the result of a collaborative work during the research stay of the doctoral candidate at Northeastern University. She developed the ray-tracing code, performed the numerical simulations and analysis, post-processed the data and wrote the manuscript. Dr. Ann Morgenthaler developed the FDFD code. Prof. Carey Rappaport formulated the methodology and supervised the research. The rest of the authors co-supervised the work.

• Publication [V] “Autonomous airborne 3D SAR imaging system for subsurface sensing: UWB-GPR on board a UAV for landmine and IED detection”
The author design and built the prototype, developed the driver of the high accuracy positioning system and the post-processing code. She was supervising the measurements and the UAV telemetry during the flights. Dr. Yuri Álvarez assisted in the development of the post-processing algorithms and in the measurement campaign, where he was in charge of controlling the UAV. The contribution was written by the doctoral candidate and supervised by the rest of the coauthors.

• Publication [VI] “In situ antenna diagnostics and characterization system based on RFID and Remotely Piloted Aircrafts”
This is the result of a collaborative work. Dr. Yuri Álvarez designed the experiment, developed the post-processing code and wrote the manuscript. The doctoral candidate was mainly in charge of the accurate positioning system to post-process the measurements and assisted in the preparation of the manuscript. She also assisted in the measurement campaign together with Mr. Guillermo Álvarez Narciandi. The rest of the authors supervised the work.

• Publication [VII] “Antenna Diagnostics and Characterization using Unmanned Aerial Vehicles”
The doctoral candidate was in charge of building the prototype (including the integration of the power detector) and developed the code for defining the autonomous flight paths. She assisted in the post-processing and the measurement campaigns. Dr. Yuri Álvarez developed the post-processing code and wrote the manuscript. The rest of the authors supervised the work.

• Publication [VIII] “On the use of Unmanned Aerial Vehicles for Antenna and Coverage Diagnostics in Mobile Networks”
The author was responsible of the prototype (both hardware and software) and assisted in the post-processing and the measurement campaigns.
Dr. Yuri Álvarez developed the post-processing code and wrote the manuscript. Prof. Fernando Las Heras assisted in the measurement campaigns and supervised the work.

- **Publication [IX]** “Unmanned aerial system for antenna measurement and diagnosis: evaluation and testing”
  This is an extended version of the contribution presented at EuCAP 2018 [xiii], including the results shown in the contribution presented at APS 2018 [xi]. These contributions were written by the author, who was also in charge of the prototype and designed the measurement campaigns. Dr. Yuri Álvarez worked in the post-processing. Prof. Fernando Las Heras assisted in the measurements and supervised the work.

- **Publication [X]** “Dual-probe near-field phaseless antenna measurement system on board a UAV”
  The author came up with the idea and designed and implemented the enhanced prototype. Dr. Yuri Álvarez was responsible for the post-processing and wrote the manuscript. Prof. Fernando Las Heras supervised the work.
## List of acronyms

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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>1D</td>
<td>One-Dimensional.</td>
</tr>
<tr>
<td>2D</td>
<td>Bi-Dimensional.</td>
</tr>
<tr>
<td>3D</td>
<td>Three-Dimensional.</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter.</td>
</tr>
<tr>
<td>AR</td>
<td>Antenna Range.</td>
</tr>
<tr>
<td>AUT</td>
<td>Antenna Under Test.</td>
</tr>
<tr>
<td>DAS</td>
<td>Delay-And-Sum.</td>
</tr>
<tr>
<td>DLGPR</td>
<td>Downward Looking Ground Penetrating Radar.</td>
</tr>
<tr>
<td>FD</td>
<td>Frequency-Domain.</td>
</tr>
<tr>
<td>FDFD</td>
<td>Finite-Difference Frequency-Domain.</td>
</tr>
<tr>
<td>FDTD</td>
<td>Finite-Difference Time-Domain.</td>
</tr>
<tr>
<td>FF</td>
<td>Far-Field.</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform.</td>
</tr>
<tr>
<td>FLGPR</td>
<td>Forward Looking Ground Penetrating Radar.</td>
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<tr>
<td>FT</td>
<td>Fourier Transform.</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System.</td>
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<tr>
<td>GPR</td>
<td>Ground Penetrating Radar.</td>
</tr>
<tr>
<td>GPU</td>
<td>Graphics Processing Unit.</td>
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<tr>
<td>IED</td>
<td>Improvised Explosive Device.</td>
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<tr>
<td>IMU</td>
<td>Inertial Measurement Unit.</td>
</tr>
<tr>
<td>IoT</td>
<td>Internet of Things.</td>
</tr>
<tr>
<td>IRF</td>
<td>Impulse Response Function.</td>
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<tr>
<td>JCR</td>
<td>Journal Citation Reports.</td>
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<tr>
<td>LM</td>
<td>Landmine.</td>
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<tr>
<td>MLBS</td>
<td>Minimum Length Binary Sequence.</td>
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**List of acronyms**

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<tbody>
<tr>
<td>NDT</td>
<td>Non-Destructive Testing.</td>
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<tr>
<td>NF</td>
<td>Near-Field.</td>
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<tr>
<td>PSM</td>
<td>Phase Shift Migration.</td>
</tr>
<tr>
<td>PSRM</td>
<td>Phaseless Sources Reconstruction Method.</td>
</tr>
<tr>
<td>RC</td>
<td>Radio Control.</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency.</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency IDentification.</td>
</tr>
<tr>
<td>RTK</td>
<td>Real Time Kinematic.</td>
</tr>
<tr>
<td>RX</td>
<td>Receiver.</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar.</td>
</tr>
<tr>
<td>SBC</td>
<td>Single Board Computer.</td>
</tr>
<tr>
<td>SCI</td>
<td>Science Citation Index.</td>
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<tr>
<td>SRM</td>
<td>Sources Reconstruction Method.</td>
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<tr>
<td>TD</td>
<td>Time-Domain.</td>
</tr>
<tr>
<td>TRL</td>
<td>Technology Readiness Level.</td>
</tr>
<tr>
<td>TX</td>
<td>Transmitter.</td>
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<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle.</td>
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<tr>
<td>UHF</td>
<td>Ultra-High-Frequency.</td>
</tr>
<tr>
<td>UWB</td>
<td>Ultra Wide Band.</td>
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<tr>
<td>VHF</td>
<td>Very-High-Frequency.</td>
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<tr>
<td>VNA</td>
<td>Vector Network Analyzer.</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network.</td>
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1.1 Introduction

In the last decade, there has been an increasing interest in developing novel applications using UAVs. The improvement in their technical features, flight autonomy, autonomous navigation capabilities and ease of sensor integration, together with a great cost reduction, have fostered their introduction in a wide range of
1. Introduction

applications. They have been successfully used in fields such as precision agriculture [1], environmental monitoring [2], archaeology [3], civil engineering [4] or assistance in natural disasters [5], among others. The ability of flying over difficult-to-access areas without interacting with the surroundings is one of the key advantages that contributed to widely increase their usage in the fields of NDT and Remote Sensing [6].

Current UAV-based systems are mainly based on mounting well-known sensors, such as photographic [7] or thermal cameras [8]. However, the Internet of Things (IoT) revolution is driving new cost-effective and reduced-size sensors, thus boosting the integration of more advanced and complex payloads and, as a result, widening the scope of applications. Recently, novel systems based on mounting electromagnetic sensors working at microwaves frequencies (from 300 MHz to 300 GHz [9]) on board UAVs have been proposed. Among them, two innovative UAV-systems have been patented and developed in the framework of this thesis: one for subsurface imaging, presented in Patent (a), and the other for antenna measurement and diagnostics, presented in Patent (b).

The main aim of subsurface imaging is to provide images of the inspected medium (such as a soil) and the objects hidden below its surface [10]. The imaging sensor detects changes that the concealed objects cause in a signal, which are processed to create the images. The most commonly used signals are: electrostatic and magnetic fields, electromagnetic and acoustic waves, and beams of accelerated particles. Depending on the configuration, imaging systems can be classified as passive (when the objects create their own signals) or active (when an external sensor generates a signal, which is transmitted through or reflected from the objects). In this thesis, the main application within the field of subsurface imaging is the detection of explosive hazards buried below the soil, such as Landmines (LMs) and IEDs. For this application, GPR, which is an active electromagnetic imaging system working mainly at microwave frequencies, has been widely employed [11]. It is based on transmitting an electromagnetic wave and receiving its reflection, which is backscattered by the soil surface, the soil inhomogeneities, and the buried targets. Consequently, the system developed for subsurface imaging consists of a GPR mounted on board the UAV.

Concerning antenna measurement, its goal is to properly characterize the behavior of the antennas, mainly in terms of its radiation pattern [12]. Once the AUT is properly characterized, antenna diagnostics can be employed to detect defects in its behavior [13], e.g. by analyzing an equivalent currents distribution on a surface enclosing the AUT. Antenna measurement facilities, also called Antenna Ranges (ARs), can be classified taking into account several criteria [14]. According to the distance between the AUT and the probe antenna, they can be classified as NF or FF systems. In the former, the probe antenna is placed in the
1.1 Introduction

Radiating near field region of the AUT, which ranges from a distance of $\lambda_0$ from the AUT aperture to the limit of the NF-FF region (given by $r_{\text{FF}} = 2D_{\text{AUT}}^2/\lambda_0$ and $r_{\text{FF}} >> \lambda_0$, $D_{\text{AUT}}$, where $D_{\text{AUT}}$ is the diameter of the smallest sphere enclosing the AUT and $\lambda_0$ the wavelength in free-space). Then, a NF-FF transformation can be applied to retrieve the FF radiation pattern [15]. Another criterion distinguishes between indoor measurement systems (such as anechoic chambers) and outdoor ranges. The AUT is not usually measured at operational conditions, but moved to one AR to be measured, resulting in a temporary interruption of the communication system. To overcome this issue, the development of UAV-based antenna measurement systems have enabled the cost-effective evaluation of the AUT at operational conditions (in-situ). In general, antenna measurement techniques require to know the amplitude and phase of its radiated field. Nevertheless, phase acquisition needs complex and expensive equipment, and it is difficult to perform with UAV-based systems due to the lack of phase reference between the AUT and the on-board probe. Consequently, this fact strongly favors the usage of phaseless techniques [16], which are able to estimate the phase of the fields from amplitude-only measurements. In this case, a power detector is integrated into the UAV.

Measurements gathered with the UAV-based systems must be adequately combined to provide: i) a well-focused image in the subsurface imaging application, and ii) the FF radiation pattern and antenna diagnostics information in the antenna measurement application. In both cases, one key aspect is that the measurements must be accurately geo-referred. In fact, this accuracy limits the upper working frequencies of the measurement systems. In order to obtain the required accuracy, an enhanced Global Navigation Satellite System (GNSS) receiver has been integrated into the UAV to complement common positioning sensors on-board. In particular, a Real Time Kinematic (RTK) system has been selected for this purpose [17]. It is a differential GNSS that makes use of the signals carrier phase to provide accurate coordinates in real-time.

Regarding the post-processing techniques, it is worth noting that they must be able to deal with measurements gathered at arbitrary positions, since it is not possible to perform ideal uniform acquisitions with a UAV.

For subsurface imaging [18], SAR-based algorithms have been implemented to focus the radar measurements. They are based on coherently combining the measurements gathered at different positions to provide high-resolution radar images. Furthermore, they can be modified to take into account some electromagnetic characteristics of the medium, which helps to obtain a better focused image. These focusing techniques are complemented with other techniques (e.g. clutter reduction or equalization techniques) to further enhance the resulting SAR image.
1. Introduction

For antenna measurement, iterative phaseless techniques have been adopted [19], mainly because they help to reduce the hardware complexity (as compared with other phaseless techniques, such as those based on interferometry). The adopted approach, based on the PSRM, is based on minimizing a cost function that relates the amplitude measured at NF with an equivalent currents distribution at the AUT aperture.

1.2 Motivation and scope

As previously explained, a wide range of applications using UAVs are being developed, mainly due to their capability to fly and gather valuable information in difficult-to-access areas. This thesis is devoted to design, implement and validate two electromagnetic measurement systems on board UAVs where, instead of well-known conventional sensors (such as photographic or thermal cameras), electromagnetic sensors working at microwave frequencies are mounted (a radar and a power detector, respectively). Consequently, these kinds of applications have been given the name of beyond-the-visible applications [xix].

The three main goals of this thesis are:

- Design and integration of the payload architecture to be mounted on the UAV, including highly accurate positioning systems.
- Development and validation of radar processing techniques to obtain high-resolution radar images of the subsurface from the radar measurements gathered with a prototype for subsurface imaging (called GEODRON).
- Development and validation of antenna measurement techniques to retrieve the FF radiation pattern and antenna diagnostics information from the NF amplitude-only measurements collected with a prototype for antenna measurement (called UASAM).

Furthermore, the subsystems that compose the prototypes and the methods developed for the post-processing have been selected aiming to improve and optimize existing systems. The cost-effectiveness of the systems is mainly measured in terms of not only cost itself, but also hardware complexity, measurement time, robustness and ease of deployment.

An scheme of the proposed systems is shown in Figure 1.1 for GEODRON and in Figure 1.2 for UASAM, where the expected outcomes have also been represented (i.e. a radar image in GEODRON, and antenna diagnostics information and the FF pattern in UASAM).
1.3 State of the art

This section is devoted to provide a review of the state of the art in the fields of subsurface imaging (subsection 1.3.1) and antenna measurement and diagnostics (subsection 1.3.2). In particular, special attention is given to analyze UAV-based systems in these fields, which will be used as benchmark to show the advances and innovations proposed in this thesis.

1.3.1 Subsurface imaging

Electromagnetic radar imaging employs electromagnetic waves (at radio waves, microwaves and higher frequencies) to provide an image of a scenario and, depending on the materials and working frequencies, even of the objects embedded in the scenario. A radar is an active electromagnetic imaging system, which is based on transmitting an electromagnetic wave and collect the reflected wave coming from the inspected scenario. In particular, radar imaging at microwave frequencies has been successfully used in several fields [20], such as security screening, bio-medical imaging, civil engineering, through-wall imaging, and the aforementioned GPR, among others.

When a radar system is used to image the soil and the objects buried inside, it is usually known as GPR [18]. Its working frequencies usually range from Very-High-Frequency (VHF) (30 to 300 MHz) up to S-band (2 to 4 GHz), depending on whether the goal is to detect deeply or shallowly buried targets, respectively.
1. Introduction

Geo-referred amplitude-only NF measurements

Phaseless Sources Reconstruction Method

Antenna diagnostics

Normalized Amplitude [dB]

Figure 1.2: Scheme of the system for antenna measurement (UASAM).

has been widely employed in NDT applications, such as archaeological surveys, road and pavement inspection, geophysics, tunnel and underground facilities detection, and LM and IED detection. Since this last application is the main one targeted in this part of the thesis, the state of the art presented below is focused on radar imaging and, namely, on GPR.

1.3.1.1 Radar systems and architectures

Radar systems can be classified according to different criteria, such as the number and arrangement of the Transmitters (TXs)- Receivers (RXs) antennas, the nature of the excitation source, the waveform and the working frequencies [21].
According to the first criterion, it can be distinguished between: multistatic, which is the most general setup, and where the TXs and RXs are placed at and moved between arbitrary positions; bistatic, when there is only one TX and one RX, which is placed at a significant distance (in terms of the wavelengths) from the TX; monostatic, when there is one single antenna acting as TX and RX; and quasi-monostatic, when two independent TX and RX antennas are placed closely (in terms of wavelengths). Furthermore, when monostatic (or quasi-monostatic) and bistatic setups are synchronously moved around several positions, they are called multimonostatic and multibistatic, respectively.

The nature of the excitation classifies the systems into Time-Domain (TD) and Frequency-Domain (FD), depending on the domain in which measurements are acquired. The main advantages of the former are the higher measurement speed and the possible lower cost, at the expense of an inefficient use of the transmitted power and lower dynamic range.

The nature of the excitation also determines which waveforms are employed [22]. Thus, in TD systems the transmitted signal is usually a short pulse (also called impulse), which yields a high bandwidth. More recently, M-sequence Ultra Wide Band (UWB) radars, which transmit a pseudo-random binary signal periodically, have been employed to achieve even higher bandwidths. On the other hand, in FD systems, the excitation is a continuous wave, which can be modulated (e.g. in frequency or in stepped frequency). In portable and handheld systems, TD radars are usually preferred, mainly due to their lower acquisition time, cost, size and weight.

Working frequencies are usually selected according to the application at hand. Lower frequencies allow a better penetration of the waves. Alternatively, at higher frequencies, it is easier to build antennas and circuits with higher bandwidths and their size and weight are usually smaller.

One of the most important parameters in radar systems is the resolution, which determines the minimal separation between two objects to be distinguished. According to this definition, the size of the resolution cell, which is the smallest volume in which a radar cannot distinguish between multiple targets, can be calculated in the different directions of the space. It is worth noting that, although it might seem confusing, if the resolution cell size is small, then it is said that the radar has a high resolution. The size of the resolution cell in the direction of the incident wave, called range resolution cell, is inversely proportional to the bandwidth. The size of the cross-range resolution cell is directly proportional to the wavelength and the distance to the target, and inversely proportional to the antenna size. However, in order to obtain a good cross-range resolution (without using extremely large size antennas) several radar measurements can be taken
1. Introduction

around the region of interest, generating a so-called synthetic aperture. Consequently, UWB-SAR systems are used to provide the best resolution [23].

Once the main features of radar systems have been presented, closer attention is paid to GPR systems. The main differences and challenges of GPR systems compared to common radar systems are [24]: i) they deal with more complex scenarios, penetrating in media with losses and frequency-dependent properties; ii) they usually work in the NF; and iii) better resolutions are usually required. Furthermore, GPR capabilities are noticeably affected by the medium heterogeneity, the roughness of the air-subsurface interface, and the possible low contrast between the medium and the embedded targets.

In addition to the classification of radar systems previously shown, there are several criteria to further classify GPR systems. Depending on whether the antennas are directly placed in contact with the surface or above it, it can be distinguished between ground-coupled and air-launched systems [25]. The former architecture usually yields better signal to clutter ratio, thanks to the better penetration into the ground and the weaker reflections from the air-subsurface interface. However, its main drawback is exactly due to the physical contact between the antennas and the subsurface, which prevents its usage in applications where a stand-off distance must be kept (e.g. in LM and IED detection to avoid accidental detonation). The latter architecture is able to keep this safety distance, but suffers from stronger clutter (due to the reflections at the air-subsurface interface). Thus, it makes the target detection more difficult. Another classification criterion takes into account the orientation of the antennas with respect to the inspected subsurface, distinguishing between Forward Looking Ground Penetrating Radar (FLGPR) [26] and Downward Looking Ground Penetrating Radar (DLGPR) [27]. In FLGPR, the antennas are placed looking ahead of the structure or vehicle where the radar is placed. This helps to minimize the reflection coming from the air-subsurface interface, at the expense of lower sensitivity and vertical resolution (compromising the distinction of whether the concealed targets are below or above the surface). Alternatively, in DLGPR the antennas look downwards, thus obtaining better resolution but suffering from stronger clutter.

As explained before, in LM and IED detection, the scanning system must keep a safety distance from the inspected area. Consequently, this favors the usage of FLGPR architectures, due to the challenge of keeping this stand-off distance with a DLGPR system. Nevertheless, the approach proposed in this thesis, based on a UAV-mounted radar, allows the use of a DLGPR configuration in safe conditions.
1.3 State of the art

1.3.1.2 UAV-based radar systems

Airborne radar imaging has been extensively studied and discussed [28, 29]. However, the use of radar imaging systems on board small UAVs of reduced size and weight, typically multicopters up to 10 kg, has just become a trending research topic in the last few years. At the beginning of this thesis research, most of the research effort in this emerging topic was devoted to observation and surveillance applications [30–32], thus avoiding the additional challenges that GPR imposes. In the field of subsurface imaging, just only feasibility studies had been published [33], mainly without including the development of prototypes or another kind of experimental validation.

Recently, novel UAV-based radar imaging prototypes have been presented [34–36]. Regarding GPR itself, UAV-mounted GPR prototypes in current literature have been used to: i) detect buried targets (but without providing images of the subsurface) [37]; ii) obtain images of IEDs placed above the surface [38]; and iii) estimate the snow depth [39].

Consequently, the prototypes developed in this thesis [II],[V], which have been used to obtain high resolution SAR images of the subsurface (allowing the detection of buried targets), present significant advances compared to existing state of the art systems.

It is worth noting that in order to obtain these high-resolution subsurface images, a real-time highly accurate positioning system on board the UAV is required because: i) the UAV needs to follow the predefined flight-path with sufficient accuracy; and ii) the application of SAR algorithms imposes a geo-referring accuracy several times better than the smallest wavelength. This requirement cannot be achieved with common GNSS receivers, thus preventing from obtaining radar images (e.g. in [37]).

1.3.1.3 GPR processing techniques

GPR processing requires the development of not only radar imaging algorithms, but also techniques to deal with the difficulties that arise in subsurface sensing. Besides radar imaging algorithms, techniques to estimate the medium constitutive parameters and to mitigate the clutter are needed to obtain a well-focused image [18, 22].

Concerning subsurface imaging, from a mathematical point of view, it is a particular case of an inverse scattering problem, where the concealed targets (scatterers) are embedded in a medium and the goal is to retrieve their geometry and/or their constitutive parameters [24]. To cope with the ill-posedness and
the non-linearity of the inverse problem, optimization algorithms are usually applied to solve it. However, these algorithms might get trapped in local minima of the cost function and they are usually computationally expensive [40],[ii],[iii]. In some fields, where the detection of the targets is the main concern, the scattering equations are linearized to build a simplified scattering model [41]. Thus, most subsurface imaging algorithms are based on this assumption, which allows the development of faster algorithms at the expense of limited accuracy. These algorithms can be categorized by two main groups: i) focusing or SAR-based algorithms, relying on ray-tracing, such as Delay-And-Sum (DAS) [42], or on migration approaches [43], such as Phase Shift Migration (PSM) [44] and Stolt or f-k (frequency-wavenumber) migration [45]; and ii) inverse filtering algorithms, which try to solve the linearized inverse problem (derived from the Born approximation) using a regularization technique such as Truncated Singular Value Decomposition (TSVD) [46] or Tikhonov method [47]. In practical GPR systems, SAR-based algorithms are usually preferred since they are less computationally demanding. More specifically, migration algorithms based on Fourier techniques are more frequently employed due to their efficiency (at the expense of requiring uniformly sampled acquisitions).

In general, subsurface imaging algorithms require the knowledge or the estimation of the electromagnetic properties (namely, dielectric permittivity and conductivity) of the medium in which the targets are buried. The estimation of the medium constitutive parameters can be mainly performed in three different ways: i) using parametric models [48, 49]; ii) analyzing the GPR measurements [I]; or iii) employing specific equipment to characterize the medium, such as reflectometers [50]. In GPR applications, the first two approaches are usually preferred, thus avoiding the need of additional hardware. Within the second approach (based on GPR measurements), a considerable number of techniques has been proposed, for instance based on extracting the main parameters of the radargrams hyperbolas [51], on analyzing changes in the radar crosstalk [52], or on performing a full-wave inversion [53], among others.

One of the major challenges in GPR processing is the removal or mitigation of the clutter, which is mainly produced by the strong reflections at the air-surface interface. These reflections might hinder the detection of buried targets, especially when they are shallowly buried [54]. Clutter removal processing techniques can be categorized by two groups: those that are based on parametric or statistical models of the clutter [55], and those that rely on filtering techniques, mainly average subtraction [56] or subspace projection methods [57],[xv].
1.3 State of the art

1.3.2 Antenna measurement and diagnostics

Antennas are primarily characterized by their radiation pattern in the FF region, where the relative angular field distribution is independent of the distance [14] to the antenna. For electrically or physically large antennas, the FF region can be located at a physical distance of more than several meters. This distance between the AUT and the probe might be difficult to achieve at dedicated antenna measurement facilities. Thus, to overcome this issue, there are two main approaches: Compact Antenna Test Ranges (CATR), which create artificial conditions that allow to measure the FF radiation pattern at NF distances, and ARs directly measuring the NF, which are widely employed [58, 59]. In the latter, the FF radiation pattern is determined applying a NF-FF transformation [15].

Furthermore, once the radiation pattern is measured or retrieved, the field in a region extremely close to the AUT aperture can be obtained (with a NF/FF-NF transformation) and/or an equivalent currents distribution at the aperture can be estimated. These are the basis of an antenna diagnostics technique, which is a non-invasive technique that allows the detection of defects (e.g. malfunctioning elements in an antenna array) without physically interacting with the antenna. It is worth noting that these defects might be difficult to detect in the radiation pattern.

The prototypes developed in this thesis have been designed to work in the NF region [VII],[X], in order to overcome some issues present in FF UAV-based measurements as it will be explained later. Therefore, the state of the art introduced in this section is focused on NF antenna measurement and diagnostics.

1.3.2.1 Antenna measurement systems

An AR usually requires a probe antenna, Radio Frequency (RF) instrumentation for transmitting, receiving and acquiring the measurements, a positioning system and a data processing technique.

Concerning the RF instrumentation, most systems use a Vector Network Analyzer (VNA) for transmitting and receiving, acquiring both amplitude and phase data. In particular, due to the reciprocity exhibited by passive antennas, the probe can be connected to the VNA input (acting as source) and the AUT to the output (working as receiver), or vice versa. In some cases, for instance at high frequencies, phase acquisition can be difficult. Thus, phaseless measurement techniques have been developed, avoiding the use of complex RF equipment that requires the TX and the RX to be phase-locked.

Focusing on NF systems, the probe antenna and the AUT are moved relatively to each other so that the probe describes a scanning surface around the AUT,
which is usually a canonical surface (planar, cylindrical or spherical). In a planar range [60], the NF radiated by the AUT is measured on a planar surface in front of it and the probe heading is always kept perpendicular to the plane. Planar ranges are useful to measure high directive antennas, with reduced back radiation. In cylindrical setups [61], the probe describes a cylindrical surface and the heading is directed towards the cylinder axis and perpendicular to this axis. In this case, back radiation can be measured. Spherical ranges are more complex [62], but they provide the most accurate patterns because the AUT is completely enclosed by the scanning surface. In this case, the probe is always facing the AUT. In both planar and cylindrical acquisitions, the AUT is not completely enclosed by the scanning surface and, consequently, there are truncation errors and the FF radiation pattern is only valid within the so-called reliable region [63].

Besides these truncation errors (primarily due to the limited size of scanning surfaces), other sources of errors [64] common in AR are: RF reflections (such as mutual coupling between the AUT and the probe, or multipath), mechanical errors (e.g. positioning errors), and system errors (e.g. phase variation of the measurement cables). It is also worth noting that the pattern of the probe antenna should be known or measured in order to apply probe correction techniques [65].

As aforementioned, in case of NF measurements, a NF-FF transformation is needed to retrieve the FF radiation pattern. There are two different approaches to perform this transformation, based on modal expansion [66] or on an equivalent currents computation [67]. The former, which is the conventional approach, relies on the fact that the field over a given canonical surface can be recast as a linear combination of a set of orthogonal functions (modes). Thus, the main limitation is that they are restricted to uniformly sampled canonical surfaces, unable to deal with arbitrary acquisition grids. The latter consists of characterizing the AUT using an equivalent currents model, so that the field radiated by the AUT and by the model is the same. This approach can be employed to process measurements collected at arbitrary positions, at the expense of a higher computational cost (associated to the need of solving the corresponding set of integral equations). Therefore, this last approach is more adequate to deal with measurements gathered with UAVs where it is not practically possible to perform uniform acquisitions.

Regarding antenna diagnostics techniques, first approaches consisted of retrieving the field in a region extremely close to the AUT [68, 69]. Nevertheless, techniques based on an equivalent currents model have also been employed, since they can be used to estimate the currents actually flowing in the AUT, providing diagnostics information [70].
1.3.2.2 UAV-based antenna measurement systems

In the last years, several UAV-based systems for antenna measurement applications have been proposed [71]. Although they are less accurate than measurements taken at conventional ARs, such as anechoic chambers or outdoor ranges, they enable the measurement of the radiation pattern in-situ. Consequently, they can take into account the influence of the environment (e.g. reflections due to the multipath) on the antenna performance. Furthermore, they are less expensive than other systems for in-situ antenna measurement, such as those employing manned aircrafts [72].

Different approaches have been adopted for antenna measurement systems on board UAVs, usually working in the FF region. Existing approaches at the beginning of this thesis research were mainly based on: i) acquiring the FF radiation pattern with a power detector [73]; and ii) using an RF transmitter on-board (with the AUT acting as RX) [74]. As aforementioned, the FF region of the AUT might be considerably far from the AUT for electrically or physically large antennas. On the one hand, measurements in the FF region have two main advantages: i) positioning errors are less critical; and ii) NF-FF transformations are not needed since the measurements are directly collected in the FF region. On the other hand, there are also significant drawbacks associated to this approach: i) longer flight paths are required for full radiation pattern measurements; and ii) flight restrictions might limit the scanning area (such as beyond the visual line of sight flying).

Consequently, since these constraints might limit the practical usage of existing FF approaches, NF UAV-based measurement systems have been proposed [75], [VII]. In [75], a UAV wired to the ground was employed to perform NF measurements, making use of a laser tracker for accurate positioning. To reduce the hardware complexity (avoiding the need of the wire connection and the laser tracker), a novel system, based on acquiring amplitude-only data in the NF region, has been proposed during the development of this thesis [VII], [X]. Furthermore, it is also worth noting that antenna diagnostics cannot be conducted from amplitude-only acquisitions performed in the FF region. This limitation is also overcome with the techniques implemented in the developed prototypes.

UAV-based antenna measurement systems have been successfully tested for measuring the antennas of the Square Kilometer Array (SKA) [76], analyzing radionavigation signals [77], and for characterizing antenna arrays [VII], among others. Furthermore, they have also been used for antenna diagnostics and coverage estimation [VIII].
1. Introduction

1.3.2.3 Phaseless processing techniques

One of the main research efforts in both antenna measurement and electromagnetic imaging is devoted to phaseless techniques [78],[i]. They enable the estimation of the phase from amplitude-only information, thus avoiding the need of complex and expensive measurement systems.

Phaseless techniques can be mainly categorized by two main groups, depending on whether they are based on interferometric or on iterative approaches [79]. Interferometric techniques [80, 81] rely on creating an interference pattern through the combination of a reference field and the unknown field from the AUT. From the amplitude of this interference pattern (hologram) and the knowledge of the reference field, an iteration-free filtering technique is applied to estimate the phase of the AUT radiation pattern. The main drawback of these techniques is that they require additional hardware to create the reference field. On the other hand, iterative techniques consist of minimizing a non-linear cost function [82, 83] and, as a result, they may have convergence problems. These techniques are particularly useful to keep the hardware complexity as low as possible.

Furthermore, if the iterative phaseless technique is based on the Sources Reconstruction Method (SRM), the acquisition can be performed at arbitrary positions [19], thus strongly favoring its usage in UAV-based measurement systems. In particular, the adopted technique in this thesis [VII], PSRM, is based on minimizing a cost function that relates the amplitude measured at two or more acquisitions surfaces in the NF region with an equivalent currents model of the AUT. To efficiently address the requirement of taking measurements at two different surfaces, a dual-probe setup on board the UAV has been proposed in the enhanced prototype [X].

1.4 Research objectives and contributions

This thesis is focused on developing novel measurement systems on board UAVs for beyond-the-visible applications and, in particular, for subsurface imaging and antenna characterization. An scheme showing the main goals and relationships between the publications that compose this dissertation is shown in Figure 1.3.

The main milestones defined and achieved in this thesis and the related contributions are the following:

- Design and development of a modular payload architecture to be mounted on the UAV. The subsystems composing the UAV architecture are the same
1.4 Research objectives and contributions

Beyond-the-visible applications with UAVs

- Subsurface imaging
  - Soil composition estimation
  - Analysis of distributed configurations
  - Lower frequency GPR

- Power detector onboard
  - First prototype
  - Enhanced prototype

GEODRON 1.0

- First prototype
- Enhanced prototype

GEODRON 2.0

- Single-band RTK
- Enhanced prototype

Antenna measurement

- First prototype
- Dual-channel power detector
- Enhanced prototype

UASAM 1.0

- First prototype
- Dual-band RTK
- Enhanced prototype

UASAM 2.0

- Dual-band RTK
- Enhanced prototype

Figure 1.3: Scheme of the publications that compose this dissertation and the relationships between them.

for both applications, except the RF measurement subsystem (a radar for subsurface imaging and a power detector for antenna measurement). Furthermore, the positioning systems must provide the required high accuracy. This is achieved by means of a single-band RTK system and a laser rangefinder. One prototype for each application has been built integrating the designed payload [II], [VII].

- Proof of concept of the subsurface imaging system. A GPR system that can be easily mounted on a UAV [xvi] and post-processing techniques to obtain a well-focused image [xvi],[xv],[I] have been developed. The system has been initially designed at C-band, to keep a low size and weight, facilitating the integration into the UAV.

- Proof of concept of the antenna measurement and diagnostics system. The idea has been initially validated measuring an antenna working as Radio Frequency IDentification (RFID) reader by integrating RFID tags on board a UAV [VI].

- Development and testing of a prototype for UAV-based subsurface imaging. This prototype, called GEODRON 1.0, has been validated with in-flight measurements along a One-Dimensional (1D) acquisition grid, providing a Bi-Dimensional (2D) radar image [II].

- Development and testing of a prototype for UAV-based antenna measurement. The prototype, called UASAM 1.0, has been validated with measurements of antenna arrays at different frequencies [VII] and a mobile
1. Introduction

communications base station antenna [VIII]. In [IX] the analysis of different acquisition grids and the measurement of circularly-polarized antenna arrays have been performed.

• Analysis and design of improvements for the subsurface imaging application. The integration of a low-frequency radar (to allow better penetration) and improvements in the processing are presented in [III]. A novel setup combining two different GPR configurations is analyzed in [IV].

• Analysis and design of improvements for the antenna measurement application. A dual probe setup, composed by two antennas connected to a dual-channel power detector, has been tested to avoid the need of acquiring the data at two surfaces [vi].

• Development and testing of enhanced prototypes. A dual-band RTK system has been integrated into the UAVs to increase the accuracy and the performance of the positioning system. Furthermore, some of the improvements previously proposed (in [IV] for subsurface imaging and in [vi] for antenna measurement) yield to the enhanced prototypes GEODRON 2.0 [V] and UASAM 2.0 [X], respectively. The former allows to autonomously acquire 2D radar measurements and, as a result, it provides 3D radar images. The latter enables to measure the AUT by acquiring NF amplitude data at two different surfaces simultaneously.

1.5 Innovation and applicability

The systems developed in this thesis exhibit several novelties and advances compared to existing state of the art systems. They take advantage of some advantages of electromagnetic sensors at microwave frequencies, such as their capability to penetrate in opaque surfaces and/or objects. This enables the detection of phenomena that could not be detected with optical systems, so they were given the name of beyond-the-visible applications. Furthermore, they have been experimentally validated, showing their feasibility to detect buried targets (in the case of GEODRON prototypes) and to characterize antennas (in the case of UASAM prototypes).

The proposed system for subsurface imaging (GEODRON) is based on a GPR mounted on board a UAV, capable of providing 3D high-resolution radar images of the soil and the buried targets, without mechanically interacting with them. Therefore, it is of great interest in security and defense (to detect explosive hazards such as IEDs and LMs), civil engineering (to detect underground facilities or...
structural damages), search and rescue operations (to detect people trapped after natural disasters) and archaeology, among others.

Concerning antenna measurement, the developed system (UASAM) is based on NF amplitude-only measurements, which are post-processed to provide the FF radiation pattern and antenna diagnostics information. Consequently, it can be used to analyze antennas at operational conditions: i) to retrieve the radiation pattern of radio and television broadcasting systems, mobile networks, radionavigation systems; ii) to detect defects, such as malfunctioning elements in antenna arrays; iii) tilt testing; and iv) coverage estimation.

In both cases, the fact that the measurement systems are mounted on board UAVs enables the inspection of difficult-to-access areas in a fast and safe way, which constitutes a significant advantage in several fields, such as in security and defense.

1.6 Outline of the thesis

The following chapters of this thesis are organized as explained below.

Chapter 2 presents an overview of the methods applied to process the measurements gathered with the prototypes. Special attention is given to the SAR techniques used for subsurface imaging and the PSRM applied for antenna measurement.

The main analysis and results obtained with the implemented prototypes are summarized in Chapter 3 for subsurface imaging and in Chapter 4 for antenna measurement.

In Chapter 5, the main conclusions, the impact and technology transfer and the future lines are thoroughly explained.

Finally, the architecture of the payload on board the UAVs is detailed in Appendix A.
2 Theoretical Fundamentals

2.1 Subsurface imaging methods

This section presents an overview of the radar processing chain used to obtain well-focused radar images of the soil and the buried targets from the GPR measurements.
2. Theoretical Fundamentals

As explained in 1.3.1, radar resolution depends mainly on the frequency bandwidth (which is inversely proportional to the range resolution cell) and on the antenna beamwidth (which is related to the cross-range resolution). Good range resolution is achieved using UWB radars, whereas improving cross-range resolution relies on taking several measurements along the inspected area, generating a synthetic aperture. If the measurements gathered all over the synthetic aperture are represented in the time or range domain, it can be observed that a point scatterer is detected with a hyperbolic or elliptic shape (in 1D and 2D acquisition domains, respectively) [84]. Thus, the main goal of focusing (or SAR-based) algorithms is indeed to coherently combine these measurements, providing a well-focused radar image.

Furthermore, it is worth noting that GPR is quite sensitive to the soil composition and heterogeneity, to the soil surface roughness, and to the possible low contrast between the soil and the targets. Therefore, it is particularly important to take into account the soil composition when applying the focusing algorithms and to mitigate the clutter (mainly due to the strong reflections coming from the soil surface). In order to cope with these issues, additional processing techniques must be considered [18].

Concerning soil composition, the common strategy consists of assuming that the soil is homogeneous (with constant relative permittivity $\varepsilon_r$ and conductivity $\sigma$) or is composed by layers of homogeneous materials. The constitutive parameters, namely relative permittivity and conductivity, are used to compute the soil wave velocity, which is taken into account in the focusing algorithm to obtain a better focused image. Therefore, the soil constitutive parameters must be estimated, for instance using statistical models [48] or the actual GPR measurements [I]. If, instead of estimating the soil constitutive parameters, free-space propagation is assumed, the objects will be detected deeper than in reality (due to the slower wave velocity in the soil) and the image will not be properly focused (as refraction effects are not taken into account). This might even end up preventing the detection of targets in some scenarios [85].

Regarding clutter removal [54], the main goal is to mitigate the strong reflections from the air-soil interface and, in the case of multilayer media, from the interfaces between the layers. These undesired reflections might mask the detection of buried targets and thus, clutter removal techniques have significant importance in GPR processing.

2.1.1 Processing chain

The raw radar data is processed following the general radar processing chain shown in Figure 2.1. It mainly consists of four steps: early preprocessing (applied
to each measurement independently); preprocessing (usually applying a clutter removal technique after several or all measurements are gathered); processing (i.e. focusing the measurements); and post-processing. Since an estimation of the soil composition is required in the processing, it may include an additional step where this estimation is performed using the radar measurements.

![Flowchart of the radar processing chain.](image)

It must be noticed that this processing chain has been used to process not only the data gathered with the prototypes, but also the data collected in controlled environments (e.g. in a planar measurement range), where the initial experiments have been carried out.

The early preprocessing aims to prepare the raw radar data for the processing, by calibrating the data and removing those parts that are worthless. This step depends on the radar equipment. If measurements are performed with a radar working in the TD, this step usually consists of estimating the time-zero and selecting the time-window [18]. The time-zero, which is the instant of time in which the signal leaves the transmitting antenna, must be estimated to properly shift the data, removing the effect of the wires and the radar internal delays. Then, a time window is selected to reduce the data size, since measurements at larger distances are worthless due to the limited penetration of waves into the soil. It must be remarked that the time-zero estimation and the time window se-
lection are only performed at the beginning of the experiment and, according to these values, the samples that fall within the resulting time window are selected. In addition, if the radar transmits a pseudorandom binary sequence, the impulse response function must be obtained first (by cross-correlating the raw radar data with the ideal transmitted sequence). However, if measurements are carried out with a VNA (as in some experiments in controlled environments), the early preprocessing step is not needed as long as the device is calibrated before measuring and the frequency bandwidth and step are properly configured.

The preprocessing step tries to remove undesired signals from the radar data, thus mitigating the clutter and improving the signal to clutter ratio. Generally, an average subtraction approach (in the time or range domain) has been adopted in this thesis [56]. It consists of computing the average of all measurements and then removing it from each measurement. In addition, in the radar measurements gathered with the enhanced prototype [V], a height correction method is proposed to further improve the signal to clutter ratio. It is based on shifting each radar measurement according to the height given by the positioning system (as if measurements were taken at a constant height) and then applying average subtraction again. The improvements in the signal to clutter ratio and in the resolution resulting from this preprocessing step are shown in [V].

The goal of the processing stage is to obtain a well-focused radar image from the radar measurements. Two focusing algorithms have been mainly compared to process the radar measurements: DAS [42, 86], based on ray-tracing, and PSM [43, 87], derived from the wave equation. The main advantage of the former is that it can be used to handle radar measurements taken at arbitrary positions, which is particularly useful for focusing data collected by UAVs. On the other hand, PSM is based on applying Fourier Transform (FT) operations, so it is more computationally efficient but it requires the data to be acquired on a uniformly sampled canonical grid. The processing stage is explained in detail in the next subsection (Subsection 2.1.2).

As explained before, the previous step must take into account the composition of the soil in order to obtain a well-focused radar image. The most straightforward approach consists of estimating $\varepsilon_r$ and $\sigma$ from datasheets or from previous measurements, based on the material composing the soil and the moisture level [48]. In addition, in this thesis, a simple technique has been proposed to estimate these values using a reference target which is buried at a known distance ($d_{obj}$) [I]. The estimation of $\varepsilon_r$ relies on the fact that, assuming free-space propagation, the object will be detected at a depth of $\sqrt{\varepsilon_r d_{obj}}$ in the SAR image.

Finally, some postprocessing techniques can be applied to improve the target discrimination in the resulting SAR image. For instance, in [xv] a clutter removal
2.1 Subsurface imaging methods

2.1.2 Focusing algorithms

Focusing algorithms are devoted to combine the radar measurements (i.e. the scattered field) in order to provide a well-focused radar image (also called reflectivity or SAR image). The multilayer formulations of DAS and PSM are presented below. In both cases, the algorithms assume that the scattered field is measured in the FD. Thus, in case of measurements performed with a TD radar, an FT must be applied before the focusing algorithm.

2.1.2.1 Delay-And-Sum (DAS)

DAS consists of coherently combining the radar measurements weighted by phase correction terms. These phase shifts take into account the wave velocity at each layer of the soil, and the distance between the TX-RX antennas and the points where the reflectivity is computed. A general multistatic configuration (with the TX and RX placed at arbitrary positions) and a multilayer scenario (as shown in Figure 2.2) have been considered. Furthermore, it is also assumed that each layer is homogeneous (being $\varepsilon_{rp}$ the relative permittivity for the $p$-th layer) and that the interfaces between layers are flat.

![Figure 2.2: General scheme of a multistatic GPR in a multilayer scenario.](image-url)
2. Theoretical Fundamentals

Assuming the scattered field is collected on $M$ acquisition points of the observation domain at $N$ frequencies, $E_{\text{scatt}}(r_{0,m}, r'_{0,m}, f_n)$, the reflectivity $\rho(r'_u)$ at a single point $r'_u$ in the $P$-layer of the investigation domain is calculated as follows:

$$\rho(r'_u) = \sum_{n=1}^{N} \sum_{m=1}^{M} E_{\text{scatt}}(r_{0,m}, r'_{0,m}, f_n) \prod_{p=1}^{P} \exp(j\phi^t_{p,m,n}) \exp(j\phi^r_{p,m,n}), \quad (2.1)$$

where $r'_{0,m}$ and $r_{0,m}$ are the positions of the TX and the RX at the $m$-th acquisition point, $f_n$ is the $n$-th frequency, and $\phi^t_{p,m,n}$ and $\phi^r_{p,m,n}$ are the phase-shifts due to the wave propagation in the $p$-th layer (for the incident and reflected waves, respectively).

These phase-shifts for the $m$-th acquisition point at the $n$-th frequency are given by (2.2), where $k_{p,n} = k_{0,n} \sqrt{\varepsilon_{r_p}}$ is the wavenumber in the $p$-th layer for the $n$-th frequency, $r^t_{p,m}$ and $r^r_{p,m}$ ($p = 1, ..., P - 1$) are the refraction points at the $p$-th layer (for the incident and reflected wave, respectively), and $r'_{u} = r^t_{p,m} = r^r_{p,m}$ is one point of the investigation domain (where the reflectivity is computed).

$$\begin{cases} \phi^t_{p,m,n} = k_{p,n} ||r^t_{p,m} - r^t_{p-1,m}||_2 \\ \phi^r_{p,m,n} = k_{p,n} ||r^r_{p,m} - r^r_{p-1,m}||_2 \end{cases} \quad (2.2)$$

Therefore, this method requires the knowledge of the point where the wave is refracted at each interface between layers. Refraction points can be derived from Snell’s law solving a fourth order equation. However, in order to reduce complexity and computational time, it is usually estimated using an approximation method.

A 2D or 3D SAR image is then obtained by computing the reflectivity, that is by applying (2.1), at all points composing the investigation domain $r'$ (a rectangular or a cubic grid, respectively).

**Refraction point estimation**

One of the simplest methods to estimate the refraction point in a two-layer media is given by (2.3), where $r_1$ is the refraction point, and $r_{1,1}$ and $r_{2,1}$ are the possible extreme paths of a wave traveling from $r_0$ to $r_2$ [86]. These paths correspond to consider $\varepsilon_{r_1} = \varepsilon_{r_2}$ (free-space propagation) and $\varepsilon_{r_1} >> \varepsilon_{r_2}$, respectively, where $\varepsilon_{r_1}$ and $\varepsilon_{r_2}$ are the relative permittivities of each layer. An scheme of this method for computing the refraction point of a wave between $r_0$ (in the first layer) and $r_2$ (in the second layer) is shown in Figure 2.3a.

$$r_1 = r_{2,1} + \sqrt{\frac{\varepsilon_{r_1}}{\varepsilon_{r_2}}}(r_{1,1} - r_{2,1}) \quad (2.3)$$
2.1 Subsurface imaging methods

(a) Two-layers scenario

(b) Three-layers scenario

Figure 2.3: Scheme of the method for estimating the refraction points.

This formula provides a good estimation when the distance between the points of the observation and the investigation domains (r₀ and r₂) is not significantly large. Therefore, it is adequate for processing measurements collected with DL-GPR systems (such as the developed prototypes).

Based on this model, an extension to deal with a three-layer scenario has been proposed in [III]. This extension consists of solving a system of equations derived from the two-layer model. According to the scheme shown in Figure 2.3b, the refraction points can be obtained from (2.4), where \( \tilde{r}_p = r_p - r_0 = (\tilde{x}_p, \tilde{y}_p, d_p) = (x_p - x_0, y_p - y_0, d_p) \), \( d_p \) are the distances in the z-axis referred to the antenna position (e.g. \( d_1 \) is the distance from the interface between the first two layers and the antenna), and \( \Delta_{1,2}, \Delta_{2,3} \) are given by (2.5).

\[
\begin{align*}
\tilde{r}_1 &= (\Delta_{1,2}\tilde{x}_2, \Delta_{1,2}\tilde{y}_2, \ d_1) \\
\tilde{r}_2 &= (\Delta_{2,3}\tilde{x}_3, \Delta_{2,3}\tilde{y}_3, \ d_2)
\end{align*}
\]  (2.4)

\[
\begin{align*}
\Delta_{1,2} &= 1 + \sqrt{\frac{\varepsilon_{\tau 1}}{\varepsilon_{\tau 2}} \left( \frac{d_1 - d_2}{d_2} \right)} \\
\Delta_{2,3} &= \frac{1 + \sqrt{\frac{\varepsilon_{\tau 2}}{\varepsilon_{\tau 3}} \left( \frac{d_2 - d_3}{d_3 - d_1} \right)}}{1 - \sqrt{\frac{\varepsilon_{\tau 2}}{\varepsilon_{\tau 3}} \left( \frac{d_3 - d_2}{d_3 - d_1} \right)}}
\end{align*}
\]  (2.5)

It must be noticed that, for each measurement, this estimation must be performed once in case of a monomostatic configuration and twice in a multistatic
or multibistatic configuration (one for the wave leaving the TX and one for the wave impinging in the RX).

**Path length approximation**

Another approach consists of calculating the wave path lengths, thus avoiding the need of estimating the refraction points [88]. As a result, the reflectivity at the point $r_u$, $\rho(r_u)$, is recast as follows:

$$
\rho(r_u) = \sum_{n=1}^{N} \sum_{m=1}^{M} E_{\text{scatt}}(r_{0,m}^t, r_{0,m}^r, f_n) \exp(+jk_{0,n} R_m),
$$  \hspace{1cm} (2.6)

where $R_m$ is the path length (at the $m$-th acquisition point) between the TX (located at $r_{0,m}^t$), the point where the reflectivity is computed $r_u$ and the RX (located at $r_{0,m}^r$).

If free-space propagation is assumed, then $R_m = \|r_{0,m}^t - r_u\|_2 + \|r_{0,m}^r - r_u\|_2$. For a two-layer medium (composed by a layer of air and a layer with relative permittivity $\varepsilon_r$), the path length can be estimated according to (2.7), where $n_s = \sqrt{\varepsilon_r - 1} - \sqrt{\varepsilon_r}$ and the rest of parameters involved are defined according to Figure 2.4 for each $m$-th acquisition point.

$$
R_m = 2d \sqrt{\varepsilon_r - 1} + \frac{d_t(d_t - d_n \cos(2\phi_t))}{d_t + d_n \sin(2\phi_t)^2} + \frac{d_r(d_r - d_n \cos(2\phi_r))}{d_r + d_n \sin(2\phi_r)^2}
$$  \hspace{1cm} (2.7)

**Figure 2.4:** Main parameters involved in the estimation of the path length (dash-dotted line represents the true path).
2.1 Subsurface imaging methods

2.1.2.2 Phase-Shift-Migration (PSM)

PSM is based on the Exploding Reflector Model (ERM), originally developed for seismic applications. The algorithm, which is derived from the scalar wave equation, assumes that each point in the investigation domain explodes at time-zero and thus, only one-way propagation (up-going) is considered. As a result, the propagation velocity is considered to be half its true value.

This algorithm requires the acquisition points to be uniformly distributed (describing a canonical grid). Assuming a multimonostatic scenario, with the TX-RX antennas describing a rectangular grid at $z_0$ height, the reflectivity at a plane $z'_u$ in the $P$-layer is calculated as follows:

$$\rho(z'_u) = \sum_{n=1}^{N} \mathcal{F}^{-1}_{xy} \left\{ E_{\text{scatt}}(k_x, k_y, f_n) \exp \left(-j\varphi_n(z_0, z'_u)\right) \right\}, \quad (2.8)$$

where $\mathcal{F}_{xy}$ denotes the FT in the $x$-$y$ space domain, $\mathcal{F}^{-1}_{xy}$ is thus the inverse FT in the $x$-$y$ space domain, $E_{\text{scatt}}(k_x, k_y, f_n) = \mathcal{F}_{xy}(E_{\text{scatt}}(x, y, f_n))$ and $\varphi_n(z_0, z'_u)$ is the phase-shift between $z_0$ and $z'_u$ for the $n$-th frequency.

This phase-shift is calculated according to (2.9), where $k_{zp,n}$ is the $z$ component of the wavenumber at the $p$-th layer and the $n$-th frequency, $z = z_p$ ($p = 1, \ldots, P - 1$) are the planes corresponding to the interfaces between layers $p$ and $p + 1$ and $z = z'_u$ is the plane where the reflectivity is computed. $k_{zp,n}$ is defined in (2.10), taking into account that only one-way propagation is considered.

$$\varphi_n(z_m, z'_u) = k_{z1,n}(z_1 - z_0) + \sum_{p=2}^{P-1} k_{zp,n}(z_p - z_{p-1}) + k_{zp,n}(z'_u - z_{p-1}) \quad (2.9)$$

$$k_{zp,n} = \sqrt{4k_p^2 - k_x^2 - k_y^2} \quad (2.10)$$

Applying (2.8) to all $z$ planes in the investigation domain, i.e. $\forall z = z'_u, z''_u \in z'$, a 3D SAR image is obtained.

It it worth noting that PSM is mainly based on FT operations, which can be performed using the Fast Fourier Transform (FFT) algorithm. Consequently, PSM has a significantly lower computational complexity than DAS, providing close to real-time operation. However, it requires the measurements to be collected on a uniform grid, which is not practically possible in UAV-based measurements. Thus, in this case, an interpolation is needed before applying the PSM.
2. Theoretical Fundamentals

2.1.2.3 Improvements

Some supplementary methods have been proposed to improve the resulting SAR images [III], mainly to enhance the signal to clutter ratio and the resolution. The effective use of the entire frequency bandwidth (when applying the previously explained focusing techniques) becomes challenging in UWB radars because the propagation losses and the directivity of the transmitting and receiving antennas vary significantly with frequency. Thus, several methods have been proposed in order to overcome these limitations: equalization, sub-band processing and investigation domain partitioning.

If the SAR images are computed for each frequency independently, it can be concluded that the amplitude levels exhibit a significant variation across the whole frequency band (mainly due to changes in the antenna response). In particular, it has been observed that the data at lower frequencies usually masks the data at higher frequencies. In some cases, the SAR image obtained for a low frequency sub-band is almost the same as the one obtained for the whole band (due to the lower amplitude of higher frequency data). This means that the resulting SAR image presents worse resolution than expected. Therefore, in order to effectively use the entire bandwidth, the equalization of the frequency response has been proposed. It consists of normalizing the SAR image obtained for each $n$-th frequency by the maximum of its absolute value, and then adding the $N$ SAR images to retrieve the final SAR image.

As aforementioned, besides the antenna response, the propagation losses and the constitutive parameters of the soil also vary with frequency. Consequently, it might be useful to process the data in several sub-bands (instead of in the whole bandwidth). Lower frequency sub-bands present better penetration capabilities, whereas higher frequency sub-bands usually exhibit better cross-range resolution (due to the greater directivity of the employed antennas at higher frequencies). Thus, obtaining and comparing the SAR images for the whole frequency band and for several sub-bands can provide complementary information.

Finally, in the case of DAS, thanks to its flexibility to deal with arbitrary observation and investigation domains, an investigation domain partitioning technique has been proposed to take into account the beamwidth of the TX and RX antennas along the frequency band. It helps to improve the signal to clutter ratio and to reduce the computational time. The idea, which is depicted in Figure 2.5, is based in the fact that each measurement is used to calculate the reflectivity not in the entire investigation domain, but only in some cells of the investigation domain. The number of cells whose reflectivity is updated (i.e. voxels in a 3D SAR image or pixels in 2D) is calculated according to the beamwidths of the antennas for each frequency as explained in [III].
2.2 Antenna measurement and diagnostics methods

In this section, an overview of the antenna measurement methods employed to retrieve antenna diagnostics information and the FF radiation pattern from amplitude-only NF measurements is presented.

As explained in Section 1.3.2, among the different phaseless processing techniques, in this thesis iterative techniques have been chosen over interferometric approaches to minimize hardware complexity, which is critical concerning UAV-based systems. Furthermore, since the UAV-based acquisitions are performed at arbitrary positions, a phaseless technique based on equivalent currents (the so-called PSRM) has been adopted to estimate the phase [19], since it is capable to handle non-uniformly sampled acquisitions. Then, an equivalent currents distribution on a surface fitting the AUT geometry or the field in the vicinity of the AUT (e.g. aperture fields retrieved with a NF-NF transformation) can be used to obtain antenna diagnostics information. Finally, a NF-FF transformation can be applied to retrieve the FF radiation pattern.

2.2.1 Processing chain

The NF amplitude is processed according to the antenna measurement processing chain shown in Figure 2.6. As aforementioned, this processing relies on
applying PSRM, which is an iterative phase retrieval technique based on recovering an equivalent electric and/or magnetic currents distribution on a surface enclosing the AUT. Due to the lack of phase information, it is required to measure the NF amplitude on two or more acquisition surfaces, in which the spatial variation of the field distribution with distance provides enough information to estimate the phase.

\[
\hat{I}_{eq} = |E_p| \exp(j\langle E_p\rangle), \quad p = 1, 2
\]

**Figure 2.6:** Flowchart of the antenna measurement and diagnostics processing chain.

First, PSRM is applied to find an estimation of an equivalent currents distribution \( \hat{I}_{eq} \) on a surface considered to be enclosing the AUT (called reconstruction surface), assuming that the NF has been measured at two different surfaces \(|E_1|, |E_2|\). It must be noted that an initial estimation of an equivalent currents distribution \( I_{eq,0} \) is needed. Once \( \hat{I}_{eq} \) is retrieved, the phase at the positions where the NF was measured is estimated.

Then, the measured NF amplitude \(|E_1|, |E_2|\) and the estimated phase obtained with PSRM \((\langle \hat{E}_1 \rangle, \langle \hat{E}_2 \rangle)\) are employed to obtain a better estimation of an equivalent currents distribution on the reconstruction surface \( I_{eq} \) applying SRM \([89]\). \( I_{eq} \) directly provides antenna diagnostics information.

Finally, from the improved estimation of \( I_{eq} \), the FF pattern of the antenna, \( E_{FF} \), can be calculated by applying a NF-FF transformation based on a discrete form of free-space electric field integral equations, derived from Maxwell equations.
2.2 Antenna measurement and diagnostics methods

2.2.2 Sources Reconstruction Method (SRM)

Relying on the electromagnetic equivalence principle [90] and assuming that the AUT is enclosed by a surface \( S' \) (called reconstruction surface), SRM provides an equivalent electric and/or magnetic currents distribution defined on such surface \( S' \) that accurately models the AUT. This means that this distribution radiates the same field as the AUT at any point outside the reconstruction surface.

An equivalent currents distribution can be calculated from the field acquired on a surface \( S \) (called observation surface). The integral equations, derived from the Maxwell equations, which relate the electric fields \( E_{I_{eq}} \) and \( E_{M_{eq}} \) at a position \( r = (x, y, z) \in S \) radiated by the electric and magnetic currents distributions \( (J_{eq}, M_{eq}) \) defined on a surface \( S' \) are given by 2.11 and 2.12, respectively, where \( k_0 \) is the free-space wavenumber, \( \eta \) is the intrinsic impedance and \( R(r; r') = \|r - r'| \_2 \).

Applying superposition, the electric field is then \( E = E_{I_{eq}} + E_{M_{eq}} \).

\[
E_{I_{eq}}(r) = -j \frac{\eta}{4\pi k_0} \int_{S'} k_0^2 J_{eq}(r') \frac{\exp(-j k_0 R(r; r'))}{R(r; r')} \, dS' \nonumber + \nabla \cdot \left( J_{eq}(r) \frac{\exp(-j k_0 R(r; r'))}{R(r; r')} \right) \, dS' \tag{2.11}
\]

\[
E_{M_{eq}}(r) = -\frac{1}{4\pi} \int_{S'} \nabla \times \left( M_{eq}(r') \frac{\exp(-j k_0 R(r; r'))}{R(r; r')} \right) \, dS' \tag{2.12}
\]

In order to numerically evaluate the integral equations, the Method of Moments (MoM) can be applied to recast these equations into a matrix form (2.13), where \( Z_{E,I_{eq}} \) is the impedance matrix relating the electric field \( E \) with the equivalent currents \( I_{eq} \) (magnetic and/or electric).

\[
E = Z_{E,I_{eq}} I_{eq} \tag{2.13}
\]

Therefore, to model the AUT with an equivalent currents distribution \( I_{eq} \) on a surface enclosing it (\( S' \)) from the knowledge of the electric field on an observation surface \( S \), the impedance matrix \( Z_{E,I_{eq}} \) must be computed and then the matrix system (2.13) must be solved. This inverse problem can be recast as an optimization problem, where the objective is to minimize the cost function \( F_{SRM} = \|E - Z_{E,I_{eq}} I_{eq}\|_2^2 \). Among the different strategies that can be adopted to solve it, the Conjugate Gradient (CG) has been applied in this thesis.

Alternatively, if the AUT is modeled through an equivalent currents distribution \( I_{eq} \), the FF radiation pattern can be directly retrieved as \( E_{FF} = Z_{E_{FF},I_{eq}} I_{eq} \).
It is worth noting that depending on the geometry of the acquisition and reconstruction surfaces, the inverse problem to be solved can be simplified. For instance, an infinite plane can be considered as a enclosing surface of the AUT (that is, as reconstruction domain) and, consequently, the Second Equivalence Principle can be applied to retrieve an equivalent magnetic currents distribution ($I_{eq} = M_{eq}$) radiating the same field as the AUT outside this reconstruction domain (in front of the infinite plane). In practice, such infinite plane is truncated to a finite planar surface where the AUT aperture fields are confined, which can be a good approximation for the case of directive or sectorial antennas.

### 2.2.3 Phaseless Sources Reconstruction Method (PSRM)

As explained in the previous subsection, an equivalent currents distribution can be estimated from the electric field acquired on one observation surface applying SRM. However, when dealing with amplitude-only acquisitions, a phase retrieval method must be applied first due to the lack of phase information. The adopted phase retrieval method, PSRM, which also relies on the sources reconstruction approach, is based on estimating an equivalent currents distribution from the knowledge of the NF amplitude on at least two observation surfaces.

Two different strategies can be applied to solve the resulting electromagnetic inverse problem: i) a forward-backward scheme, where the fields are propagated from one acquisition surface to another until reaching a stationary solution, and ii) a minimization scheme, where a non-linear cost function that relates the measured NF amplitude with an equivalent currents distribution is minimized. The second approach has been adopted for processing the measurements gathered with the UAV since it provides slightly better results [viii]. Different numerical techniques can be applied for minimizing the cost function, which is given in (2.14). Due to non-linearity of the cost function, non-linear optimization techniques, such as inexact Newton–Raphson or Levenberg–Marquardt, must be used. The latter has been adopted as it has shown a better convergence.

\[
F_{PSRM} = \left\| \begin{bmatrix} E_1 \\ E_2 \end{bmatrix} - \begin{bmatrix} Z_{E_1;I_{eq}} \\ Z_{E_2;I_{eq}} \end{bmatrix} I_{eq} \right\|_2^2
\]  

(2.14)

An initial guess for the equivalent currents is needed for the optimization method. This initial guess can be set based on a-priori knowledge of the AUT physical geometry (e.g. a uniform distribution on the area covering the antenna aperture, $I_{eq,0} = 1$, and $I_{eq,0} = 0$ elsewhere).

It is worth noting that if linear field components are considered (for instance $E_x$ and $E_y$) and a planar reconstruction surface in an XY plane is selected, the
integral equations that relate the NF and the aperture fields can be decoupled, thus yielding two non-linear cost functions, relating $|E_x|$ with $M_y$ and $|E_y|$ with $M_x$. This decoupling of the integral equations reduces the complexity and non-linearity of the problem.

The retrieved equivalent currents distribution ($\hat{I}_{\text{eq}}$) is used to estimate the phase of the NF at the acquisition surfaces ($\langle \hat{E}_1 \rangle$, $\langle \hat{E}_2 \rangle$) considering the following relationship:

$$
\begin{pmatrix}
\hat{E}_1 \\
\hat{E}_2
\end{pmatrix} = 
\begin{pmatrix}
|E_1| \exp(j\langle \hat{E}_1 \rangle) \\
|E_2| \exp(j\langle \hat{E}_2 \rangle)
\end{pmatrix} = 
\begin{pmatrix}
Z_{E_1;\hat{I}_{\text{eq}}} \\
Z_{E_2;\hat{I}_{\text{eq}}}
\end{pmatrix} \hat{I}_{\text{eq}}
$$

(2.15)

Then, taking into account the measured NF amplitude and the estimated phase, $\hat{E}_1 = |E_1| \exp(j\langle \hat{E}_1 \rangle)$ and $\hat{E}_2 = |E_2| \exp(j\langle \hat{E}_2 \rangle)$ are used to apply SRM in order to obtain a better estimation of the equivalent currents distribution $I_{\text{eq}}$. This distribution directly provides antenna diagnostics information and, applying the NF-FF transformation, the FF radiation pattern is retrieved.
This chapter is devoted to summarize the results presented in the publications composing this dissertation in the field of subsurface imaging. A discussion about the results achieved with the first prototype (GEODRON 1.0) is given in Section 3.1, including 2D radar images obtained from UAV flights performed in manual mode. Taking into account these results, several improvements are proposed and
studied in Section 3.2. Some of them are also adopted in the enhanced prototype (GEODRON 2.0), whose results are presented in Section 3.3, including 3D radar images from autonomous UAV flights. In Section 3.4, novel GPR distributed configurations are studied and compared with conventional GPR configurations, in order to conceive a novel configuration with better performance. Finally, a summary with the main results in the field of subsurface imaging achieved during the thesis is presented in Section 3.5.

3.1 First prototype

The first prototype (called GEODRON 1.0) has been designed to operate at C band. It comprises an impulse radar working from 3.1 to 5.3 GHz and two helix antennas with circular polarization and reverse handedness. Besides, the accurate positioning system relies on a single-band multiconstellation RTK system and a laser rangefinder (to improve the accuracy in the vertical direction). Further details about the prototype and its subsystems can be found in Appendix A.

The proposed prototype is shown in Figure 3.1a and the processing chain is summarized in Figure 3.1b (which is a particularization of the general processing chain, shown in Figure 2.1).

![Prototype and Processing Chain](image)

**Figure 3.1:** GEODRON 1.0: prototype (a) and processing chain (b).

The working frequencies of the radar mounted in this first prototype are higher than those usually employed in GPR systems. However, they were chosen as a trade-off between ease of integration of the radar into the UAV (due to smaller size and weight) and penetration depth. Regarding the TX-RX antennas,
3.1 First prototype

the fact that they have orthogonal polarization (with a good cross polar discrimination) helps to reduce the coupling between them, improving the quality of the results.

Background subtraction is applied as a prior clutter removal technique. It consists of subtracting the average of the radar measurements from each measurement. Unless otherwise stated, the focusing algorithm is based on DAS (using the refraction point approach), due to its ability to deal with measurements gathered at arbitrary positions. Furthermore, in [xvi] a posterior clutter removal technique (based on subspace projection) has also been developed and analyzed and in [vi] a comparison between the results obtained with DAS and PSM is presented.

In order to properly assess the performance of the proposed system, the experimental validation has been divided into several stages: validation of the radar and the processing chain in a controlled environment (subsection 3.1.1) [I],[xvi] and in an outdoor scenario [I]; validation of the payload (subsection 3.1.2) [II]; and flight tests (subsection 3.1.3) [III]. In addition, a comparison between the results obtained with DAS and PSM is shown in subsection 3.1.4 [vi].

3.1.1 Experiments in a controlled environment

The first stage of the system validation consists of performing measurements with the radar module in a controlled environment (in particular, in a planar measurement range [91]). The main objectives of this stage are: i) to compare the performance of the radar module and a VNA; ii) to analyze the performance of the focusing method (based on DAS); and iii) to evaluate the capability of estimating the constitutive parameters of the soil from the GPR measurements.

The setup is shown in Figure 3.2. Several materials have been used to fill plastic boxes, simulating different types of soils (e.g. sandy, loamy and stratified soils). In this case, average subtraction has not been applied due to the limited and small size of the boxes.

The YZ slices of the radar images obtained when a metallic disk (of 5 cm radius and 2 cm thickness) has been buried at $d_{obj} = 8$ cm depth in a box filled with dry sand (up to 21 cm height) are shown in Figure 3.3. Measurements have been performed with the radar module and with a VNA (configured to work at the same frequencies). When free-space propagation is assumed to process the VNA measurements with DAS, the buried target and the metallic floor of the measurement facility are detected deeper than in reality (Figure 3.3a). The former is detected at $d_{tg} = 0.13$ m, so the estimated relative permittivity is $\varepsilon_r \approx (d_{tg}/d_{obj})^2 = 2.6$ (which agrees with typical values for dry sand). When this value is used in the DAS processing, both the target and the metallic floor are detected
at their true depths (Figure 3.3b). The same scenario has been measured with the radar module. The resulting radar image (Figure 3.3c) exhibits less sharpness, although it is still possible to distinguish the buried target and the interfaces. Therefore, the main conclusions are that the focusing technique is useful to obtain images from the subsurface and that the radar module can be used instead of a VNA with only a slightly worse performance.

Furthermore, additional experiments with different types of soils to estimate both the relative permittivity and the conductivity are given in [I]. The estimated values agree with with reference values given in the literature for similar soils and moisture levels.

3.1.2 Payload validation

Once the radar module and the focusing method have been tested, the validation of the payload designed to be mounted on the UAV has been performed. The primary objective is to analyze the capability of the payload to provide radar images of the subsurface from the geo-referred radar measurements.

The setup deployed in a sandy beach to validate the payload is shown in Figure 3.4. It consists of a portable linear scanner, where the payload is placed to be manually displaced along 1 m length over two plastic tubes located 0.5 m above the soil. The payload comprises: the radar module and the radar antennas, the UAV flight controller, the common positioning sensors on board UAVs, the RTK beacon and a wireless link to send the geo-referred radar measurements to
3.1 First prototype

$dt_g = 0.08 \text{ m}$

$dt_g = 0.09 \text{ m}$

Figure 3.3: Results of the experiments in a controlled environment. DAS processing: from VNA measurements assuming free-space propagation (a) and $\varepsilon_r = 2.6$ (b), and from radar measurements assuming $\varepsilon_r = 2.6$ (c).

In order to analyze the capability of providing images of the subsurface, several objects have been buried in the scanned area. In the example shown in Figure 3.5 [II], a metallic disc (of 9 cm radius and 1 cm thickness) has been buried at a depth of $d_{obj} = 0.15 \text{ m}$ (Figure 3.5a). First, the envelope of the measurements (also known as B-scan or C-scan in case of 1D and 2D acquisitions, respectively) is depicted in Figure 3.5b. In particular, the envelope corresponds to the magnitude of the analytic signal (obtained applying a Hilbert transform). This procedure is also called point-to-point backpropagation because the measurements are not combined to improve the resolution. Then, the average trace has been subtracted from the measurements (to mitigate the clutter) and DAS algorithm has been applied to process them. If free-space propagation is assumed (i.e. $\varepsilon_r = 1$), as shown in Figure 3.5c, the target is detected deeper than in reality, at a depth of $dt_g = 0.28 \text{ m}$. The air-sand interface can be also clearly distinguished in spite of its non-uniformity (mainly due to its roughness, which results...
in non-uniform backscattering). Applying the soil constitutive estimation method presented in [I], the relative permittivity of the sand is $\varepsilon_r \approx \left( \frac{d_{tg}}{d_{obj}} \right)^2 = 3.5$, which agrees with typical values for slightly wet sand. If this estimation is taken into account when applying the DAS algorithm, the target is detected at the real depth $d_{tg} = d_{obj} = 0.15$ m, as shown in Figure 3.5d.

Therefore, it can be concluded that the prototype can be used to obtain 2D radar images of the subsurface using the radar measurements and the geo-referring information provided by the RTK system.

### 3.1.3 Flight tests

The next step in the validation campaign consists of mounting the payload on board the UAV and performing in-flight tests. The first tests have been devoted to detect some targets placed over the soil of the airfield [II], [x]. Then, the prototype has been used to detect buried objects. In particular, a plastic box (of 78 cm x 56 cm x 43 cm) has been filled with dry sand (with $\varepsilon_r \approx 2.5$) and placed over the grass
3.1 First prototype

Figure 3.5: Results of the payload validation: buried target (a), envelope of the radar measurements (b), radar image after average subtraction and DAS processing, assuming free-space propagation (c) and considering $\varepsilon_r = 3.5$ (d).

of the airfield. As explained in [II], the sandbox is covered with a plastic canvas to avoid overoscillation of the UAV when flying over it (since the UAV tries to maintain a steady height according to the distance to the ground measured by the laser rangefinder). The measurement setup is shown in Figure 3.6. The UAV has been operated manually, performing several straight-line flight paths along the $x$-axis at heights between 0.5 and 1 m, passing through the center of the box. For each straight line, a 2D SAR image is retrieved.

The results achieved when different objects (metallic and plastic) are buried in the sandbox have been presented in [III],[ix],[vi]. In this subsection, the results obtained when the metallic disk used in the previous subsection (of 9 cm radius
and 1 cm thickness) is buried at $d_{\text{obj}} = 0.12 \text{ m}$ are summarized. The envelope of the measurements gathered along a straight line is shown in Figure 3.7. These measurements are processed according to the procedure outlined in Figure 3.1b, first assuming free-space propagation (Figure 3.8). The improvement thanks to the coherent combination of the measurements can be clearly noticed. The interfaces between the different media can be better distinguished and the target shape is more similar to the real one (instead of hyperbolic). Furthermore, even the tubes from the canvas frame are detected.

As expected, the buried target and the sand-ground interface appear downshifted as the sand permittivity is not taken into account. In order to pay closer
3.1 First prototype

Figure 3.7: Envelope of the radar measurements when a metallic disk is buried at 12 cm depth in the sandbox.

Figure 3.8: Radar image (considering $\varepsilon_r = 1$) when a metallic disk is buried at 12 cm depth in the sandbox.

attention to the detection of targets buried in the sandbox, only the measurements along a synthetic aperture of $L_{ap} = 0.6$ m around the sandbox (instead of the whole aperture) are considered. The radar image obtained assuming free-space propagation is depicted in Figure 3.9a, where the target is imaged at $d_{tg} \approx 0.20$ m. However, if a permittivity of $\varepsilon_r = 2.5$ (which is a common value for dry sand) is assumed for the processing, the disk is detected at approximately its true depth at $d_{tg} \approx 0.12$ m, as shown in figure 3.9b.
3. Subsurface imaging system on board a UAV

Figure 3.9: Radar image when a metallic disk is buried at 12 cm depth in the sandbox considering $L_{ap} = 0.6$ m and $\varepsilon_r = 1$ (a), $\varepsilon_r = 2.5$ (b).

It can also be noticed that, although the theoretical cross-range resolution improves when considering a larger synthetic aperture, in practice, cumulative georeferencing errors cause distortion in the SAR image, limiting the effective size of the synthetic aperture.

The most important conclusion drawn is that GEODRON 1.0 system is able to provide highly accurate 2D radar images along the vertical plane containing the flight path. Furthermore, it has been shown that when the permittivity of the soil is taken into account, the buried objects are detected at their true depth in the radar image.

3.1.4 DAS and PSM comparison

The measurements obtained with the prototype have also been processed using PSM as focusing algorithm. In order to apply PSM, the radar measurements must be first interpolated into a uniform grid. This subsection is devoted to compare the results obtained with the two focusing algorithms (DAS and PSM) in terms of image quality and computational effort [vi]. It is worth noting that, in practical applications, real-time operation of the system is desirable and, in general, the focusing algorithm is the most time-consuming step within the whole radar processing chain.

The radar images obtained with DAS and PSM for the whole synthetic aperture (of 2.5 m length) are shown in Figure 3.10 and 3.11, respectively, when a
3.1 First prototype

plastic cylinder (of 9 cm radius and 9.5 cm thickness) is buried at 10 cm depth in the sandbox. The different interfaces, the buried target and the canvas frame tubes are clearly distinguishable in both images. However, DAS algorithm seems to be more affected by positioning errors, resulting in a noisier radar image. Since the target is not metallic, the reflection from the sand-ground interface (i.e. below the sandbox) is higher than in the results presented in Subsection 3.1.3 (where the buried target is metallic).

![Figure 3.10](image1.png)

**Figure 3.10:** Radar image obtained with DAS (considering $\varepsilon_r = 1$) when a plastic cylinder is buried at 10 cm depth in the sandbox.

![Figure 3.11](image2.png)

**Figure 3.11:** Radar image obtained with PSM (considering $\varepsilon_r = 1$) when a plastic cylinder is buried at 10 cm depth in the sandbox.

Then, the considered aperture has been restricted to $L_{ap} = 60$ cm around the sandbox and the sand permittivity has been taken into account in the focusing
3. Subsurface imaging system on board a UAV

algorithms. As a result, the buried target and the sand-ground interface are detected at their true depths. In this case, the results obtained with both algorithms are almost the same, since the reduction in the aperture length implies a reduction in the cumulative positioning error.

![Radar image obtained with DAS (a) and PSM (b) when a plastic cylinder is buried at 10 cm depth in the sandbox, considering $L_{ap} = 0.6 \, \text{m}$ and $\varepsilon_r = 2.5$.](image)

Figure 3.12: Radar image obtained with DAS (a) and PSM (b) when a plastic cylinder is buried at 10 cm depth in the sandbox, considering $L_{ap} = 0.6 \, \text{m}$ and $\varepsilon_r = 2.5$.

Concerning the computational effort, PSM is significantly faster than DAS, as shown in [vi], since it is mainly based on FFTs. This difference is particularly noticeable when considering the soil permittivity. For instance, if $L_{ap} = 2 \, \text{m}$, the computational time is reduced by a factor of more than 20.

Therefore, PSM is considerably faster and it seems to be less affected by positioning errors. Nevertheless, it requires the measurements to be interpolated into a uniform grid and, in turn, this means that a steady flight is needed to enable an accurate interpolation.

3.2 Analysis of improvements

One of the most straightforward upgrades of the system consists of decreasing the working frequencies in order to increase the penetration depth and to facilitate the detection of targets in soils with higher moisture levels. Furthermore, it is also desirable to increase the frequency bandwidth so as to improve the range resolution. However, the behavior of the antennas (such as the directivity and
3.2 Analysis of improvements

the return losses) and the soil constitutive parameters may vary significantly with frequency. These variations must be taken into account in the processing chain in order to effectively enhance the penetration and the resolution.

Concerning the hardware, the smallest working frequencies are reduced down to Ultra-High-Frequency (UHF) band. In particular, the selected UWB radar is an M-sequence radar working from 100 MHz to 6 GHz, covering from VHF to C-band. Two Vivaldi antennas have been used for transmitting and receiving, due to their ability to work along a large frequency bandwidth. In particular, their return losses are better than 10 dB from 600 MHz to 6 GHz, which is considered the effective frequency band of the system (thus covering from UHF to C band). However, their directivity fluctuates more than 7 dB in this band.

In order to cope with the varying behavior of the antennas and the soil constitutive parameters, to improve the resolution, to mitigate the clutter and to speed up the processing time, several improvements have been proposed. These improvements, which are explained in [III] and summarized in section 2.1.2.3, are: equalization of the frequency response, sub-band processing and investigation domain partitioning.

The validation of the improvements has been conducted in several stages: simulations, measurements in a controlled scenario and outdoor experiments.

3.2.1 Simulations

A preliminary assessment of the focusing methods to deal with multilayer scenarios and of the improvements in the processing chain has been carried out with simulations performed with gprMax [92]. gprMax is an open source software designed to simulate GPR scenarios based on the Finite-Difference Time-Domain (FDTD) method.

First, DAS and PSM have been compared for scenarios composed by two and three different media. It has been observed that in these simulations there are no remarkable differences between the images obtained with both methods, although, as expected, PSM is noticeably faster.

Then, the effect of equalization and sub-band processing has been assessed. In order to analyze the former, a pair of real bow-tie antennas has been employed in the simulations. Since higher frequencies are masked by lower ones, the effective range resolution is worse than expected unless equalization is applied. To illustrate that some targets can be better detected when processing only a sub-band (instead of the whole frequency band), a realistic soil (Puerto Rico clay loam) has been modeled for different moisture levels. In particular, a two-term Debye model has been adopted to take into account the frequency-dependent behavior of the
soil. It has been concluded that, especially for higher moisture levels, it might be easier to detect some targets using only the lower frequencies.

It is worth noting that the effect of the improvements is more evident when dealing with real measurements, due to the stronger frequency-dependent behavior of the RF equipment and the soil and due to the soil heterogeneity.

### 3.2.2 Experiments in a controlled environment

Several measurements have been conducted in a planar measurement range using the Vivaldi antennas connected to a VNA (working at the same frequencies as the radar) with the setup shown in Figure 3.13. These measurements have been processed to validate the multilayer focusing methods as well as the proposed improvements.

![Figure 3.13: Setup of the experiments in a controlled environment to analyze the proposed improvements.](image)

In particular, the effects of sub-band processing and equalization are summarized below for a scenario where two disks (of 9 cm radius) are buried inside the plastic box (filled with dry sand). One of the disks is made of plastic and is buried at 8 cm depth, and the other is metallic and is placed at 12 cm depth. Slices of the radar images obtained with DAS (assuming $\varepsilon_r = 2.5$) are shown in Figure 3.14 when sub-band processing is applied and when the whole bandwidth is considered (both without and with equalization). In all the slices, the
3.2 Analysis of improvements

...air-sand interface (at \( z = 0 \) m), the plastic disk (at \( z = -0.08 \) m), the metallic disk (at \( z = -0.12 \) m) and the sand-metallic floor interface (at \( z = -0.32 \) cm) can be clearly detected. In addition, a high reflectivity area also appears at \( z = -0.46 \) m due to multiple reflections. Comparing the different slices, first it can be observed that the lower frequency sub-band slice (Figure 3.14a) shows better penetration capabilities, whereas the higher frequency sub-band (Figure 3.14b) exhibits better cross-range resolution and less clutter. Then, it can be noticed that the lower frequency sub-band slice (Figure 3.14a) and the entire band result (Figure 3.14c) are really similar. As explained before, this is due to the fact that the frequency response of the system at lower frequencies is higher, masking the higher frequency data. However, if the radar image is equalized (Figure 3.14d), the resulting image has better range resolution and less clutter.

Figure 3.14: Radar image slice (at \( x = 3 \) cm) obtained with DAS when two disks are buried: sub-band processing from 1 to 3 GHz (a) and from 4 to 6 GHz; whole bandwidth processing (1 to 6 GHz) without (c) and with (d) equalization.
From the analysis performed in [III] and the results summarized above, it can be concluded that equalization allows increasing range resolution (bringing it closer to the expected value), at the expense of worse penetration (which is improved if only the lower frequency sub-band is processed).

3.2.3 Outdoor experiments

Finally, these improvements have also been validated in an outdoor scenario, conducting several measurements with the M-sequence UWB radar and the previously used Vivaldi antennas. In this setup, shown in Figure 3.15, the radar is manually moved in 2 cm steps along two plastic tubes, placed parallel to the soil surface at 1.40 m height.

![Figure 3.15: Setup of the outdoor experiments performed to analyze the proposed improvements.](image)

The soil of these experiments was considerably wet and heterogeneous, due to the influence of the sea, so it is a more challenging scenario. To illustrate the effect of the improvements, the results obtained with DAS when two targets were buried are shown in Figure 3.16. One target is a plastic cylinder (of 11.5 cm radius and 8 cm thickness) buried at 14 cm depth and the other is a metallic disk (of 9 cm radius and 1 cm thickness) at 22 cm depth. Although stronger reflections can be observed in the areas where the targets are buried, they cannot be clearly...
distinguished in the radar image obtained without improvements (Figure 3.16a). If equalization is applied (Figure 3.16b), then the metallic disk can be detected, but not the plastic cylinder (since its reflectivity is similar to the clutter levels). However, when both equalization and investigation domain partitioning are applied (Figure 3.16c), the clutter level is mitigated and, as a result, both targets can be discerned from the clutter.

![Radar images](image)

**Figure 3.16:** Radar images obtained with DAS (considering $\varepsilon_r = 3$) for the outdoor experiments performed to analyze the proposed improvements: without improvements (a), with equalization (b) and with equalization and investigation domain partitioning (c).

As shown in these measurement results, in challenging scenarios the proposed improvements in the processing are needed to be able to distinguish the targets due to the higher levels of clutter and noise.

### 3.3 Enhanced prototype

An enhanced prototype (called **GEODRON 2.0**) has been developed taking into account the results obtained with the first prototype and the improvements
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studied in the previous section. This new prototype, which is designed to operate from UHF to C band \([V]\), comprises the M-sequence radar and the two UWB Vivaldi antennas employed in section 3.2. Besides, the accurate positioning system has been upgraded as well, relying now on a dual-band multiconstellation RTK system. Further details about the prototype and its subsystems can be found in Appendix A.

The proposed prototype is shown in Figure 3.17a and the radar processing chain is summarized in Figure 3.17b (which is a particularization of the general processing chain, shown in Figure 2.1). The steps written in gray in the processing chain compose the basic processing, whereas the orange ones highlight the steps corresponding to improvements in the processing.

![Prototype](image)

![Radar processing chain](image)

**Figure 3.17:** GEODRON 2.0: prototype (a) and radar processing chain (b).

The most remarkable feature of this prototype is its capability to provide high-resolution 3D radar images of the subsurface from the radar measurements gathered during autonomous flights. In addition to the high accuracy real-time positioning system requirement, the positioning information must be carefully processed to discard data that could cause unfocusing or degradation in the radar image (for instance due to oversampling in some areas, arising from the difficulty to perform a uniform acquisition with the UAV). Concerning the radar processing, two improvements are proposed to enhance the resolution and the target discrimination: the equalization presented in the previous section and a height correction method. Due to the notable decrease in the lowest working frequencies of the radar, targets buried in higher losses soils can be detected.
3.3 Enhanced prototype

The improvements in the processing chain, for both the radar and positioning data, are presented in subsection 3.3.1. The results of the experimental validation performed with flight tests are shown in subsection 3.3.2. Due to the attenuation produced by the soil at higher frequencies, only the frequency band between 600 MHz and 3 GHz has been selected for processing.

3.3.1 Improvements in the processing chain

The raw radar data is processed according to the scheme shown in 3.17b. Since the selected radar transmits a pseudorandom binary sequence, the first step consists of cross-correlating the raw radar measurements with the ideal transmitted binary sequence to obtain the impulse response function. Then, the next step comprises adjusting to a common time-zero and selecting the desired time-window. After the background subtraction (based on removing the average of the measurements), a height correction method can be applied to mitigate the reflection from the air-soil interface and to improve the signal to clutter ratio. This method consists of first shifting the radar measurements by \( z - \overline{z} \) (where \( z \) is the height of the UAV at each measurement and \( \overline{z} \) its mean value all over the flight path) and applying a second background subtraction afterwards. Then, DAS is selected as focusing algorithm, due to its ability to deal with non-uniformly sampled measurements. In particular, due to the larger distances between the observation and investigation domain coordinates, the DAS approach based on path length calculation has been adopted. Finally, in order to improve the effective range resolution, equalization of the radar image can also be applied.

Concerning the positioning data processing, in the first prototype (where only 2D radar images from 1D flight paths are obtained) just a geodetic to cartesian coordinates transformation is required. However, in the current prototype, further processing steps are needed in order to select which measurements will be processed and to define the 3D investigation domain according to the 2D flight path. The positioning data processing flowchart is shown in Figure 3.18.

First, a transformation from the geodetic system of coordinates (latitude, longitude and height) to a local ENU (East-North-Up) system is performed. Then, the main ground track is estimated (according to the procedure explained in [V]) and the flight path is rotated according to this value. After the rotation, the observation domain is almost aligned with the \( x \)- and \( y \)-axis, which facilitates the visualization of the results and the definition of the investigation domain. The goal of the next step (data selection) is discarding the data that does not add valuable information or that could degrade the radar image (e.g. due to sudden changes in height or due to oversampling). Only the data that fulfills the required conditions is kept for further processing. These conditions aim to ensure that: i)
3. Subsurface imaging system on board a UAV

the UAV is actually moving (extremely close positions are not selected); ii) there is not a noticeable change in attitude (i.e. in the roll, pitch or yaw angles); iii) the ground track does not deviate significantly from the main ground track; and iv) there is not a remarkable height variation. This step also helps to decrease the computational time, since fewer measurements are processed. Finally, the investigation domain \( r' = (x', y', z') \) is set as follows: the investigation plane \((x', y')\) coordinates is defined according to the observation plane \((x, y)\) coordinates and the \(z'\) coordinates are adjusted to the desired depths. Regarding the former, this definition is based on computing the maximum axis-aligned rectangle inside the bounding box that encloses the observation plane (which, in turn, is obtained from the convex hull). These steps are further clarified, including an example of the processing with real flight data, in [V].

3.3.2 Flight tests

The proposed system has been experimentally validated with measurements gathered in autonomous flights in the scenario shown in Figure 3.19.

In order to illustrate the performance of the prototype, the following targets have been placed in the scenario: a metallic disk (of 9 cm radius) is laid on top of a plastic briefcase (of 14 cm height) and an open cylindrical metallic box (of 9.5 cm radius) is buried at 8 cm depth. The predefined flight path is a rectangular grid of 1 m x 4 m size (in the cross-track and along-track directions, respectively) at 2.3 m height. It is worth noting that radar measurements are continuously gathered during all the flight.

The top view of the rotated flight path and of the investigation domain boundaries is shown in Figure 3.20. Concerning the flight path, all measurement positions are depicted in blue, whereas the selected ones are depicted in red. Most of
3.3 Enhanced prototype

Figure 3.19: Measurement setup for GEODRON 2.0.

the discarded data corresponds to oversampled areas (especially when the UAV changes sense of movement). According to the definition of the local coordinate system, the soil surface is approximately at $z = 0 \text{ m}$ and thus, the $z'$ coordinate of the investigation domain has been defined between $-0.6 \text{ m}$ and $0.4 \text{ m}$.

Figure 3.20: Top view of the rotated flight path (all measurements in blue and selected ones in red) and the investigation domain boundaries (in black).

Different slices of the 3D radar images are compared: a $YZ$ plane is an along-track view, a $YX$ plane is a top view and an $XZ$ plane is an across-track view.
In particular, the slices where the buried target is detected are shown below to illustrate the performance of the system and the improvements.

First, the measurements have been processed according to the basic radar processing chain (i.e. without improvements and without considering the soil composition). In this case, the slices of the radar image where the buried box is detected are shown in Figure 3.21. It is detected deeper (at \( z = -0.14 \, \text{m} \)) since the soil composition has not been considered. Furthermore, it cannot be clearly distinguished from the soil interface, since the effective range resolution is not good enough.

![Figure 3.21](image)

**Figure 3.21:** Slices of the 3D radar image obtained with the basic processing at the position where the cylindrical box is detected: along-track view at \( x = -0.05 \, \text{m} \) (a), top view at \( z = -0.14 \, \text{m} \) (b) and across-track view at \( y = 4.55 \, \text{m} \) (c).

As aforementioned, several improvements have been proposed to obtain better resolution and higher signal to clutter ratio. The along-track view at \( x = -0.05 \, \text{m} \) is shown in Figure 3.22, when height correction (Figure 3.22a) and when equaliza-
tion (Figure 3.22b) are applied. In the former, the reflection of the air-soil interface has been mitigated, thus allowing a clear distinction of the buried target. In the latter, the effective range resolution is improved. This can be observed in the narrower width of the high reflectivity areas where the targets and the interface are detected (as compared to the results retrieved with the basic processing). As a result, the buried target can be also distinguished from the interface.

![Figure 3.22: Along-track view of the 3D radar image at \(x = -0.05\) m when height correction (a) and when equalization (b) is applied.](image)

Finally, both height correction and equalization are applied and the soil permittivity (estimated as \(\varepsilon_r \approx 3\)) is taken into account. The combination of these improvements results in better range resolution and signal to clutter ratio. The main slices are shown in Figure 3.23, where the buried target is now detected at its true depth (i.e. \(z = -0.08\) m). Compared to the basic processing results (Figure 3.21) a considerable enhancement can be noticed, in particular, in the across-track slice where it is not possible to identify the target with the basic processing (Figure 3.21c).

The experimental validation performed has proven the capability of the system to provide high-resolution 3D radar images, even when only a basic processing strategy is adopted. Furthermore, the effectiveness of the enhanced radar processing has also been confirmed, concluding that it is essential to detect shallowly buried targets, allowing their distinction from the air-soil interface.
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Figure 3.23: Slices of the 3D radar image at the position where the cylindrical box is detected when all the improvements are applied: along-track view at \( x = -0.05 \text{ m} \) (a), top view at \( z = -0.08 \text{ m} \) (b) and across-track view at \( y = 4.55 \text{ m} \) (c).

3.4 Analysis of distributed configurations

DLGPR systems have been thoroughly analyzed in the previous sections, where two UAV-based DLGPR prototypes have been presented and experimentally validated. Although they are able to provide high-resolution radar images, the strong clutter at the air-soil interface degrades their detection capabilities. On the other hand, FLGPR systems exhibit lower vertical resolution (being difficult to distinguish if the targets are over or under the surface) and sensitivity, but the penetration capabilities are better. Therefore, it would be desirable to combine the advantages of both configurations, aiming to obtain both a good penetration and a good resolution. A novel distributed configuration based on a FLGPR TX and a DLGPR RX has been proposed and analyzed. As shown in Figure 3.24, the
3.4 Analysis of distributed configurations

TX is placed on a vehicle with the antenna looking ahead and the RX is placed on board a UAV with the antenna looking downwards (pointing to the soil surface).

![Figure 3.24: Scheme of the distributed GPR system combining FLGPR and DLGPR configurations.](image)

First, a fast 2D ray-tracing method has been developed to find proper configurations of the system (i.e. the position of the TX and the RX and the angle of incidence). Then, these configurations have been validated using a full-wave 2D simulator based on the Finite-Difference Frequency-Domain (FDFD) method (which allows taking into account the soil surface roughness). The simulated scattered fields have been post-processed with DAS (adopting the path-length approach) to analyze the resulting radar images. Furthermore, these configurations have also been compared with conventional GPR configurations, concluding that they greatly improve the target detection and the surface clutter reduction.

The proposed combination of FLGPR and DLGPR systems has been analyzed for two configurations: with the TX stationary (multistatic) or with the TX moving synchronously with the RX (multibistatic). These two configurations are shown in Figure 3.25a and 3.25b. In the former, the vehicle-mounted TX is placed at a fixed position \( (x = -20\, \text{m}, \, z = 2.5\, \text{m}) \) with the main beam pointing at \( 83^\circ \). In the latter, the TX is placed at \( z = 2.5\, \text{m} \) height and moved between \( x = -20.8\, \text{m} \) and \( x = -19.2\, \text{m} \). In both cases, the UAV-mounted RX is placed at \( z = 1\, \text{m} \) height and moved between \( x = -0.8\, \text{m} \) and \( x = 0.8\, \text{m} \) pointing downwards. These values have been found using ray tracing simulations, so as to be able to detect dielectric targets placed in the area of interest (shown in yellow). Furthermore, these results have been compared with those of multimonostatic DLGPR (with the TX-RX moving as the RX in the FLGPR-DLGPR configurations, as shown in Figure 3.25c) and multimonostatic FLGPR (with the TX-RX moving as the TX in the multibistatic FLGPR-DLGPR, as shown in Figure 3.25d).
3. Subsurface imaging system on board a UAV

Figure 3.25: Schemes of the GPR configurations analyzed: proposed multistatic and multibistatic FLGPR-DLGPR configurations (a, b) and conventional multimonostatic DLGPR and FLGPR configurations (c,d).

In order to compare these four configurations, a simulation of a scenario with a target similar to a PMN landmine (composed of TNT, with a cross-section of 10 cm x 4 cm) buried in a sandy soil at 25 cm depth under a rough surface has been conducted. The simulation has been performed at C band, at the working frequencies of the radar used in the first prototype. This scenario is significantly challenging, due to the high frequencies employed (resulting in lower penetration capabilities), the low-contrast between the target and the soil, and the clutter due to the soil surface roughness. The radar images obtained from the FDFD simulations are shown in Figure 3.26.

The proposed multistatic and multibistatic FLGPR-DLGPR configurations show similar results (Figure 3.26a and 3.26b, respectively). Two reflections coming from the target (mainly from its left and right sides) can be clearly distinguished, thus
enabling the detection of the target. However, in the multimonostatic configurations (i.e. the conventional configurations), whose results are shown in Figure 3.26c and 3.26d for DLGPR and FLGPR respectively, the target cannot be detected at all. In particular, in the multimonostatic FLGPR there is poor resolution in the vertical direction.

As a conclusion, the proposed FLGPR-DLGPR configurations improve the target discrimination and the surface clutter mitigation. Compared to a multimonostatic FLGPR, they yield higher signal strength and better resolution, since the receiver is closer to the investigation domain. Compared to a multimonostatic DLGPR, they contribute to mitigate the strong clutter from the air-soil interface.
3. Subsurface imaging system on board a UAV

3.5 Summary

Two prototypes for UAV-based subsurface radar imaging have been designed, developed and experimentally validated during this thesis.

First, the basic radar processing chain and the initial payload (at C band) have been designed and validated with measurements gathered in a controlled environment, with a linear scanner placed outdoors and during flights [I],[II]. The results show the capability of this first prototype to provide 2D radar images of the subsurface, with both DAS and PSM algorithms.

Then, several approaches to improve the performance of the prototype have been analyzed (mainly in terms of resolution, target discrimination and clutter reduction). One of these approaches [III] consists of developing a GPR system working at lower frequencies to increase the penetration depth and with a higher bandwidth to increase the range resolution. In addition, several improvements in the processing chain have been proposed and experimentally validated to enhance the detection of buried targets using this radar. The other primary line of improvement [IV] is devoted to analyze novel distributed GPR configurations, which exploit the advantages of both FLGPR and DLGPR configurations. These configurations have been numerically evaluated with FDFD simulations.

Finally, the lower frequency radar and a higher accuracy positioning system have been integrated into the UAV [V]. Some improvements in both the radar and positioning data processing chains have also been adopted. Results show the capability of the system to retrieve 3D radar images from measurements autonomously gathered with this enhanced prototype.
This chapter is devoted to summarize the results presented in the publications composing this dissertation in the field of antenna measurement and diagnostics. A discussion about the results achieved with the first prototype (UASAM 1.0) is given in Section 4.1. The comparison between different acquisition surfaces is performed in Section 4.2. In Section 4.3, closer attention is paid to antenna diagnostics capabilities, where a defect has been caused in the measured antenna. Based on the experience acquired during these measurement campaigns, several improvements are proposed and adopted in the enhanced prototype (UASAM 2.0), whose results are presented in Section 4.4. Finally, a summary with the main results achieved during the thesis is presented in Section 4.5.
4. Antenna measurement system on board a UAV

4.1 First prototype

Before the implementation of the first prototype, the idea of performing in-situ antenna measurement and diagnostics from amplitude-only NF measurements has been tested using RFID signals [VI] at 868 MHz. In this proof of concept, several RFID tags and a single-band RTK beacon have been placed on a commercial UAV, and the AUT has been connected to an RFID reader. The UAV is manually piloted in front of the AUT and the RFID received signal strength is forwarded to a ground station together with a timestamp. In addition, the RTK rover beacon sends the corrected coordinates with a timestamp to the ground station. As a result, the RFID measurements can be accurately geo-referred and then, processed using the PSRM. Results show the feasibility of the system to perform antenna diagnostics and to retrieve the FF radiation pattern of RFID antenna arrays.

After the success of the previous proof of concept, the first prototype (called UASAM 1.0) has been developed. It has been designed to operate in the frequency range from 500 MHz to 6 GHz, depending on the selected probe antenna. As in GEODRON 1.0 prototype, the accurate positioning system relies on a single-band multiconstellation RTK system and a laser rangefinder (which helps the UAV to maintain a steady height). Further details about the prototype implementation are given in Appendix A.

![Figure 4.1: UASAM 1.0 prototype.](image)

During the first measurements performed with this prototype, two probe antennas have been employed: one customized hexagon-shaped printed monopole antenna (for measurements at S band) and a commercial printed monopole antenna (for measurements at C band). Both antennas exhibit almost an omni-
directional pattern in the horizontal plane (H-plane), avoiding the need of probe antenna correction. Flights are performed autonomously, with the UAV following a flight path defined with waypoints. In particular, for these measurements the flight path describes a cylindrical surface and the UAV heading is always pointing towards the AUT mast (as in cylindrical ARs).

Before performing the measurements, an analysis about the impact of the positioning and geo-referring errors in the FF radiation pattern has been conducted [VII]. In order to perform this analysis, the AUT has been measured in a spherical range at an anechoic chamber and an equivalent currents model has been retrieved. This allows to evaluate the field radiated by the AUT at any position. For this analysis, positioning error is defined as the distance between the targeted and the true flight path, whereas geo-referring error is the distance between the true UAV position and the UAV position estimated by the positioning systems onboard. Results show that positioning errors (without geo-referring errors) have only slight impact in the FF radiation pattern. However, even for small geo-referring errors, differences in the sidelobe levels are significant. Therefore, geo-referring accuracy is a critical factor that limits the upper working frequency of the prototype.

In order to analyze the performance of UASAM, the comparison flowchart shown in Figure 4.2 has been followed. Results obtained with the prototype (light green boxes) are compared with measurements in a spherical range at an anechoic chamber. Furthermore, these measurements have been used to model the AUT and simulate the NF at the UAV positions. Results obtained at S band are explained in the following subsections, whereas those at C band are shown in Section 4.2, where different acquisition surfaces are considered and compared. To facilitate the comparison of the different results, the systems of coordinates shown in Figure 4.3 have been adopted, where the AUT aperture is on a YZ plane \((x = 0 \text{ m})\) and the spherical system of coordinates use the azimuth angle, \(az \in [-180^\circ, 180^\circ]\), and the elevation angle, \(el \in [-90^\circ, 90^\circ]\) to define the position of a point on the unit sphere.

The setup deployed for measurements at S band is shown in Figure 4.4. The AUT is an array composed by two horn antennas (separated \(2.6\lambda_0\) at the measurement frequency of \(2.95\text{ GHz}\), placed in a mast at \(3 \text{ m}\) height. The flight path consists of two cylindrical surfaces (of radius \(R_1 = 3 \text{ m}\) and \(R_2 = 4.5 \text{ m}\)).

4.1.1 Amplitude-only Near-Field measurements

The measured NF amplitude at the farthest acquisition surface is shown in Figure 4.5a, where the main lobe and the grating lobes can be clearly distinguished. In Figure 4.5b and 4.5c, the YZ plane projection of the measured NF
amplitude is compared with the simulated NF amplitude at the UAV positions (obtained from the model of the AUT). Differences are mainly caused by orientation misalignment between the AUT and the probe antenna and geo-referring inaccuracies.
4.1 First prototype

Figure 4.4: Measurement setup of UASAM at S band.

Figure 4.5: Measured NF amplitude of the S band AUT at $R_2 = 4.5$ m (a), YZ projection of the measured NF (b) and of the simulated NF (c).

4.1.2 Antenna diagnostics

NF measurements are post-processed with the PSRM to retrieve an equivalent magnetic currents distribution (i.e. the aperture fields), depicted in Figure 4.6.
In particular, the distribution obtained from the measurements gathered with the prototype is shown in Figure 4.6c and it is compared with those obtained from the simulated NF at the UAV positions considering both complex and phaseless data (Figure 4.6a and 4.6b, respectively). The two horn antennas are clearly identified at their true positions. It can be noticed that the use of amplitude-only data affects the results, which are further degraded in the case of UASAM measurements due to uncertainties (mainly, geo-referring errors and misalignments).

4.1.3 Far-Field radiation pattern

From the retrieved equivalent currents distribution, the FF radiation pattern can be obtained. Taking into account the dimensions of the flight path, the valid angular margin in the vertical plane (E-plane) is 25°, whereas in the horizontal
one (H-plane) there are no truncation errors. Figure 4.7 shows the comparison of the FF pattern in the horizontal plane. As it has been already explained when comparing the equivalent currents distribution, geo-referring errors and probe misalignments are the primary cause of discrepancies.

![FF radiation pattern for the S band AUT (H plane).](image)

**Figure 4.7**: FF radiation pattern for the S band AUT (H plane).

Results presented in this section prove the feasibility of performing antenna diagnostics and characterization from geo-referred amplitude-only NF measurements gathered with the prototype up to S band.

## 4.2 Analysis of acquisition surfaces

This section is devoted to analyze the effect of acquisition grid truncation in the results [IX],[xiii]. The AUT is an array of two horn antennas (separated around $\lambda_0$) working at C band. As shown in Figure 4.8, it has been placed in a mast (at 3 m height) and it has been measured at 4.65 GHz.

Three different grids have been compared: a cylindrical grid (composed by two concentric cylinders), an arc-cylindrical grid (composed by two concentric arc cylindrical surfaces) and a planar grid (composed by two parallel planar surfaces). In the first two cases, the UAV heading is always point towards the AUT mast (as in cylindrical ARs), whereas when using a planar grid the heading is perpendicular to the measurement planes. The grids analyzed are shown in Figures 4.9a, 4.9c and 4.9e, where the dashed lines indicate the pre-defined flight paths and the dots are the waypoints. The distance from the AUT to the measurement grids has been increased in the second and third cases for safety reasons. The
NF amplitude measured at the farthest distance from the AUT is shown in Figure 4.9b, 4.9d, 4.9f for the cylindrical, arc-cylindrical and planar grid, respectively. The flight times are: 25 minutes for grid #1, 20 minutes for #2 and 17 minutes for #3. Probe antenna misalignment is slightly more noticeable in the planar acquisition.

The recovered equivalent currents distribution is shown in Figure 4.10, when it is obtained from the NF measurements at the anechoic chamber (Figure 4.10a) and from the NF amplitude gathered with UASAM (Figures 4.10b-4.10d).

Comparing Figure 4.10a and 4.10b, it can be noticed that the use of amplitude-only measurements, geo-referring errors and probe antenna misalignment worsen the quality of the reconstructed currents. Furthermore, comparing the results obtained with the different grids, it can be observed that for the arc-cylindrical case the reconstruction is slightly worse due to the truncation of the measurement grid and to the UAV stopping at each arc end point to change direction. On the other hand, when a planar grid is considered, the best reconstruction quality is obtained, which might be related to the fact that the UAV heading does not change. The main drawback is that planar acquisition requires to accurately determine the direction perpendicular to the AUT and, as explained in chapter 1, it is only suitable for directive antennas.

Following the same procedure as in the previous section (Section 4.1), the retrieved equivalent currents distribution is used to calculate the FF radiation pattern. The FF pattern in the horizontal plane is shown in Figure 4.11, where
4.2 Analysis of acquisition surfaces

Figure 4.9: Grid #1: cylindrical grid (a) and NF amplitude at $R_2 = 4\,\text{m}$ (b). Grid #2: arc-cylindrical grid (c) and NF amplitude at $R_2 = 4.5\,\text{m}$ (d). Grid #3: planar grid (e) and NF amplitude at $R_2 = 4.5\,\text{m}$ (f).

a good agreement with the reference pattern can be observed, especially for the main lobes $\theta \in [-20^\circ, 20^\circ]$. The valid angular margins are given in [IX].

From the analysis of the different acquisition grids, it can be concluded that cylindrical surfaces require the longest flight time. Reducing the acquisition grid to arc-cylindrical or planar surfaces can be employed when measuring directive antennas in order to reduce the flight time. In this case, it has been shown that...
4. Antenna measurement system on board a UAV

Figure 4.10: Equivalent magnetic currents retrieved for the C band AUT: from NF measurements at anechoic chamber (a), and from NF amplitude-only measurements with UASAM for grids #1 (b), #2 (c) and #3 (d).

with a planar grid the quality of the results is not degraded and the flight time is considerably reduced. However, planar acquisitions could suffer from large probe antenna misalignment and the definition of the grid is more complex. Furthermore, in this section, the capability of the prototype to work up to C band has been validated.

4.3 Antenna diagnostics capabilities

After the initial validation measuring horn antenna arrays, several experimental campaigns using different antennas have been conducted. For instance, an array of two helix antennas (with circular polarization and reverse handedness) is analyzed in [x],[IX], and a mobile network antenna in [VIII]. The results obtained for the mobile network antenna (shown in the following subsection) are of special
4.3 Antenna diagnostics capabilities

interest since a defect has been caused in the AUT to effectively assess the antenna diagnostics capabilities of UASAM.

4.3.1 Analysis of a mobile network antenna

In the field of mobile networks, UASAM could be used to provide an estimation of the radioelectric coverage within the cells, as well as detecting failures (e.g. incorrect tilt or malfunctioning elements) measuring the antenna at operational conditions. This could be particularly useful in 5G networks, where an increase in network density and thus, in the number of antennas and cells is expected.

A commercial Base Transceiver Station (BTS) for GSM and UMTS mobile networks has been selected as AUT. It has been mounted at a 3.5 m height mast, and measured at 2.35 GHz. The measurements have been conducted using a monopole antenna as a probe and the setup is shown in Figure 4.12.

An arc-cylindrical grid (of 180°) has been used taking into account that BTS antennas exhibit 120°-sector patterns in the horizontal plane and the fact that arc-cylindrical grids are easier to define than planar ones (where the direction perpendicular to the AUT must be accurately estimated). In order to further assess the antenna diagnostics capabilities, a defect in the AUT has been simulated placing a sheet of aluminum foil around it. The measured NF amplitude of the mobile network antenna under normal operation conditions and with partial blockage is shown in Figure 4.13a and 4.13b, respectively.

The AUT has also been measured in a spherical range at an anechoic chamber to obtain reference results, both under normal operation conditions and with par-
4. Antenna measurement system on board a UAV

Figure 4.12: Measurement setup of UASAM for the mobile network antenna.

![Measurement setup of UASAM for the mobile network antenna.](image)

Figure 4.13: NF amplitude of the mobile network antenna under normal operation (a) and with partial blockage (b).

![NF amplitude of the mobile network antenna under normal operation (a) and with partial blockage (b).](image)

In the former conditions, the retrieved equivalent currents exhibit uniform amplitude along the entire length of the antenna, as obtained from the measurements in a spherical range at anechoic chamber considering amplitude and phase or amplitude-only (Figure 4.14b and 4.14c), as well as from UASAM measurements (Figure 4.14d). However, in the malfunctioning antenna, the reconstructed equivalent currents vanish in the area where the aluminum foil is placed, as shown in Figures 4.14f-4.14h.
4.3 Antenna diagnostics capabilities

Figure 4.14: Equivalent magnetic currents retrieved for the mobile network AUT: from NF measurements at anechoic chamber considering amplitude and phase (b,f) and amplitude-only (c,g), and from amplitude-only NF measurements with UASAM (d,h) under normal operation conditions and with partial blockage.

FF radiation pattern from UASAM measurements has been compared with the one obtained from NF measurements in a spherical range at an anechoic chamber, considering amplitude and phase and amplitude-only acquisitions. This comparison is shown in Figure 4.15a under normal operation conditions and in 4.15b with partial blockage. It is worth noting that spherical acquisition is not affected by truncation errors, whereas in measurements with UASAM, the angular reliable margin is 30°. In this reliable region, there is a good agreement between the FF calculated from measurements with UASAM and those conducted at an anechoic chamber.

The retrieved equivalent currents can also be used to assess the radioelectric coverage. This analysis, shown in [VIII], shows that the malfunctioning antenna exhibits lower field levels than the antenna under normal operation, since it has less directivity.
4.3.2 Further analysis

A preliminary evaluation of the antenna diagnostics capabilities at higher frequencies has also been performed [VIII]. An array of four horn antennas with non-uniform excitation working at 25 GHz has been selected for this evaluation. The array has been modeled with equivalent currents and then, the NF has been simulated at two parallel planar grids (at positions where real UAV flights have been conducted). Besides, different geo-referring errors have been considered. Analyzing the results (equivalent currents distribution and FF pattern), it can be concluded that they are similar to the reference ones even for a geo-referring error modeled as a normal distribution with standard deviation of 1.5 cm.

Results presented in this section and in [VIII] show the viability of using UASAM for assessing the performance of mobile network antennas. This is even possible up to K-band using a higher frequency power detector and improving the accuracy of the positioning system.

4.4 Enhanced prototype

An enhanced prototype (called UASAM 2.0) has been developed in order to improve the measurement accuracy and to reduce the measurement time [X]. Compared to the first prototype, the main changes are: i) use of a dual-channel power detector working up to 10 GHz, with two probe antennas placed at different positions on board the UAV (allowing the collection of NF amplitude at two different surfaces simultaneously); and ii) upgrade of the accurate positioning system, relying on a dual-band multiconstellation RTK system (increasing the accuracy and reducing deployment time). The prototype is shown in Figure 4.16 and further information about it is given in Appendix A. Two 3D-printed plastic
structures have been designed and manufactured to mount the two probe antennas on the UAV frame, allowing a maximum separation of 0.8 m between them.

Figure 4.16: UASAM 2.0 prototype.

Figure 4.17: Measurement setup of UASAM 2.0 for the reflector antenna.

In order to analyze the performance of this new prototype, an offset reflector antenna working at 4.65 GHz and fed with a circularly-polarized helix antenna has been selected as AUT. This antenna has a high directivity (around 30 dB) and
the main beam is tilted $\gamma = 20^\circ$ with respect to the vertical axis. Therefore, the capability of the system to measure high directive antennas is also proved. The measurement setup is shown in Figure 4.17. Due to the presence of the probe antenna mounting frames, a planar acquisition was chosen in order to facilitate a stable flight. Before defining the acquisition grid, a preliminary flight along a vertical line in from of the AUT was conducted so as to find the approximate height of the main beam.

For this experiment only the horizontal component of the field has been measured. Nevertheless, the vertical component could be acquired by just rotating the two probes $90^\circ$. The amplitude-only NF measurements gathered with the prototype are shown in Figure 4.18, where the main beam is clearly distinguished.

![Figure 4.18: NF amplitude of the reflector antenna.](image)

The AUT has also been measured in a spherical range at an anechoic chamber for comparison purposes. These measurements have been used to model the AUT and to simulate the NF amplitude at the UAV positions. The simulated and measured amplitudes have been post-processed with the PSRM to retrieve an equivalent currents distribution, shown in Figure 4.19. In both cases, the amplitude of the retrieved distribution fits the shape and size of the AUT, and in
the phase distribution, the phase-shift of off-centered reflector antennas along the vertical direction can be observed.

Figure 4.19: Equivalent magnetic currents retrieved for the reflector: from simulated phaseless NF, amplitude (a) and phase (b) distribution, and gathered with the prototype, amplitude (c) and phase (d) distribution.

In order to get rid of the noise and artifacts before computing the FF radiation pattern, an spatial filtering is applied to the equivalent currents distribution (discarding the values outside the AUT physical size). The FF in the main vertical beam is depicted in Figure 4.20, showing a good agreement between the results from anechoic chamber measurements and from the prototype.

The proposed improvements of the prototype yield better positioning and geo-referring accuracy and smaller flight and deployment times. As a result, the antenna radiation pattern and the diagnostics information are more accurate. Furthermore, these features could facilitate measurements at higher frequency bands.
4. Antenna measurement system on board a UAV

Figure 4.20: FF radiation pattern for the reflector (vertical cut).

4.5 Summary

Two prototypes for UAV-based antenna measurement and diagnostics have been designed, developed and experimentally validated during this thesis.

First, the idea has been tested using RFID tags and an RTK beacon mounted on board a commercial UAV [VI], which has been operated in manual mode. After the successful results obtained for characterizing an RFID antenna array, the first prototype has been built and tested for measuring antenna arrays with linear polarization at S and C bands [VII].

Then, further experiments have been performed with this prototype. In [VIII], it has been used to measure a mobile network antenna under normal operation conditions and with a simulated defect (a partial blockage). Furthermore, these measurements have been used to estimate the radioelectric coverage under both conditions, showing the effect of the simulated defect. In [IX] a comparison of different acquisitions grids has been carried out, analyzing their impact in both the accuracy of the results and the required flight acquisition time. In [IX] and [X] a circularly polarized antenna array has also been measured.

Finally, a dual-channel power detector has been mounted on board the UAV to overcome the need of performing several flights to acquire the measurements at two different surfaces. The idea has been initially tested in [VII], showing the capability of measuring at two different surfaces simultaneously. Results of this dual-probe measurement system with a higher accuracy positioning system integrated into the UAV are presented in [X].
5.1 Conclusions

This dissertation focuses on the design, implementation and experimental validation of novel measurement systems on board UAVs for the so-called beyond-the-visible applications. In particular, two application fields have been considered: subsurface radar imaging and antenna measurement and diagnostics. It is worth noting that both systems have been patented and the corresponding prototypes have been built and tested in the framework of this thesis. Based on the experience gathered with the first prototypes developed for each application, several improvements in both the post-processing and the hardware have been analyzed. Some of these improvements have been also considered to build enhanced prototypes, aiming to increase the quality of the results and to reduce the acquisition and deployment times.

This thesis by publication is mainly based on the research work presented in the publications [I]-[X]. This work has been summarized in this document: a review of the state of the art and of the theoretical fundamentals are given in Chapters 1 and 2, respectively; and the most important results are presented in
Chapter 3 for subsurface imaging and in Chapter 4 for antenna measurement. Further explanations and results can be found in the corresponding publications and the cited references. In addition, Appendix A includes an overview of the prototypes architecture.

The final goal of both applications is that the UAV autonomously flies over the area of interest, gathering geo-referenced measurements. These measurements must be post-processed to provide the desired outcomes: i) a high resolution radar image in the subsurface imaging application, and ii) antenna diagnostics and characterization information in the case of antenna measurement. The algorithms employed to obtain such results impose a geo-referring accuracy in the order of centimeters and, consequently, high accuracy positioning systems have been integrated into the UAVs. Furthermore, aiming to develop cost-effective systems, a customized dual-band multiconstellation RTK system has been included in the enhanced prototypes, requiring the development of an ad-hoc driver.

Concerning subsurface radar imaging, the proposed system consists of a GPR mounted on board the UAV. The geo-referred radar measurements are processed using SAR-based techniques to obtain an image of the inspected soil and the buried objects. Since these techniques require an estimation of the soil constitutive parameters, a method based on GPR measurements has been proposed and validated in [I]. The architecture of the first prototype (GEODRON 1.0), the radar processing chain and the experimental validation are presented in [II]. This validation has been carried out in several stages: first, in a controlled environment (a planar measurement range); then, with a linear manual scanner (both indoors and outdoors) and finally, with flight tests in manual mode. Results show the capability of obtaining 2D radar images of the soil, where both metallic and non-metallic targets have been detected. It has also been proved the repeatability of the results and that the radar images have the expected resolution. Based on these first results, several lines of improvement have been identified and analyzed. In order to use a lower frequency radar (to increase the penetration depth) while keeping a large bandwidth (to obtain high-resolution radar images), another GPR is used in [III]. Aiming to overcome the variation in the antennas response and in the soil constitutive parameters along the working frequency band, three improvements in the radar processing chain have been proposed and validated with simulations and measurements in [III]. Results show that they are essential to enable the detection of buried objects in harsh environments. Another possibility to facilitate the target detection in difficult scenarios is analyzed in [IV]. In this case, a novel distributed GPR architecture exploiting the advantages of FLGPR (good penetration) and DLGPR (good resolution) is proposed and validated with simulations. Results show a better target discrimination as compared to conventional architectures. Finally, an enhanced prototype (GEODRON 2.0) integrating the lower
frequency radar used in [III] and a higher accuracy positioning system has been developed [V]. This prototype has been used to retrieve 3D radar images of the scanned area from measurements gathered in autonomous flights. It is worth noting that a careful processing of the positioning data is required, mainly due to the non-uniform sampling and the deviation of the UAV from the ideal path. Additional improvements in the radar processing chain are also proposed and results show their effectiveness for providing radar images with better resolution and signal to clutter ratio.

In the field on antenna measurement at operational conditions, a power detector mounted on board the UAV working in the NF of the AUT has been proposed as a cost-effective and practical solution. The geo-referred amplitude-only NF measurements are processed using a phase retrieval technique based on equivalent currents (PSRM) to obtain antenna diagnostics information (enabling the detection of failures) and the FF radiation pattern. The idea has been initially tested for measuring RFID antennas with RFID tags [VI]. After this initial success, the first prototype (UASAM 1.0) has been implemented and employed for autonomously measuring arrays at S and C bands [VII] using a cylindrical flight path. These results have proved the feasibility of using UASAM 1.0 for antenna diagnostics and characterization of linearly polarized antenna arrays. Then, in order to further assess the antenna diagnostics capabilities, a mobile network antenna has been measured both under normal operation conditions and with partial blockage (simulating a failure) [VIII]. The simulated defect is clearly detected in the measurements, since the retrieved equivalent currents vanish in the area where the blockage is placed. The capability of the system to estimate the radioelectric coverage and to measure higher frequency antennas is also investigated in [VIII]. Aiming to reduce the acquisition time, other acquisition grids (arc-cylindrical and planar) have been tested in [IX], showing that they are useful to measure directive antennas. The feasibility of using the proposed system for measuring circularly polarized antenna arrays is also validated in [IX]. Finally, an enhanced prototype (UASAM 2.0), integrating a dual-channel power detector and a higher accuracy positioning system, is presented in [X]. This allows to overcome the need of performing several flights for gathering the NF amplitude at two different surfaces and, besides, it provides a better geo-referring accuracy. The resulting improvements in time and accuracy have been analyzed by measuring a reflector antenna.

5.2 Impact and technology transfer

The research work developed within the framework of this thesis has been published in high-impact international journals (most of them in the first quar-
tile) and in contributions to international and national conferences. In particular, the doctoral candidate has authored or co-authored the following number of publications during the thesis research: 13 publications in international journals, 16 contributions to international conferences and workshops, 2 contributions to national journals and 4 contributions to national conferences. The main research topics and the related publications are summarized below, grouped by topic:

- In the field of GPR, simulations, methods, airborne and portable systems and experimental validation results have been published in international journals [I]-[V]; contributions to international conferences [iv]-[vi], [ix], [x], [xv], [xvi]; national journals and books [xvii], [xviii]; and contributions to national conferences [xix], [xxii].

- In antenna measurement field, simulations, methods, airborne systems and experimental validation results have been published in international journals [VI]-[X]; contributions to international conferences [vii], [viii], [xi], [xiii], [xiv]; and contributions to national conferences [xix], [xx].

- In inverse scattering, methods (both in the areas of model-based techniques and SAR techniques) and new architectures have been published in international journals [i]-[iii]; and a contribution to an international conference [xii].

It must be remarked that the research work has achieved significant recognition in the scientific community. This work has received several awards in different conferences. A grant from the company TICRA to attend to the European Conference on Antennas and Propagation (EuCAP) was obtained in 2018, where the contribution [xiii] was selected as finalist in the Best Paper Award in Antenna Measurement. In this conference, the doctoral candidate was also invited as speaker in a scientific workshop about UAV-based antenna measurement systems sponsored by the Antenna Measurement and Techniques Association (AMTA). Furthermore, [xxii] was finalist in ISDEFE Award Antonio Torres sponsored by the Spanish Minister of Defense. Also in 2018, the doctoral candidate received a honorable mention in the Student Paper Competition at the IEEE AP-S Symposium on Antennas and Propagation, thanks to the work developed in [x], and she was finalist of the Young Engineer Prize at the European Radar Conference (EuRAD) within the European Microwave Week, as a result from the work presented in [ix]. In 2019, she received the Best Student Paper Award at the conference EuCAP, in recognition of the research carried out in [vii]. She was also invited by the North Atlantic Treaty Organization Counter IED Center of Excellence (NATO C-IED CoE) as speaker in the 4th C-IED Technology Workshop.
As explained in Section 1.1, the systems developed in the framework of this thesis for subsurface imaging (GEODRON) and antenna measurement (UASAM) with UAVs have been patented (in (a) and (b), respectively). These patents, granted in Spain in 2016 and 2017, have been protected under the Patent Cooperation Treaty (PCT) and their protection is currently being extended to Europe, China and United States.

Concerning the funding, this thesis has been developed in the framework of eight national and regional research projects, mainly funded by the Spanish Ministry of Economy, the Government of Principado de Asturias and FEDER, and the University of Oviedo. Furthermore, it must be highlighted that this work has contributed to obtain specific funding for developing and improving the systems presented in this thesis. For instance, the project SAFEDRON, selected for funding in the framework of the COINCIDENTE program from the Spanish Ministry of Defense, will provide around four hundred thousand euros to improve GEODRON system and validate the prototypes in realistic scenarios. Regarding the technological transfer itself, in addition to several contracts with companies, the Technology Readiness Level (TRL) of UASAM and GEODRON is being currently increased for some specific application areas thanks to the Radio-UAV project, funded by Xunta de Galicia with four hundred thousand euros in the framework of Ignicia proof of concept program. The goal of this project is indeed creating a high-tech spin-off company from University of Vigo and University of Oviedo to exploit the developed systems in the field of beyond-the-visible applications with UAVs.

5.3 Future lines

The capabilities of the proposed measurement systems to provide high resolution subsurface radar images in the case of GEODRON and antenna diagnostics and characterization in the case of UASAM have been validated through extensive validation campaigns. Nevertheless, further improvements can be investigated in order to enhance their performance and to increase their TRL.

Concerning the system architecture, the accurate positioning system is a key element to enable the post-processing of the measurements. Furthermore, its accuracy greatly affects the quality of the retrieved results. Therefore, a higher accuracy positioning system would help to improve the quality and, in the case of antenna measurement, to increase the upper working frequency limit of the system. Positioning systems based on optical recognition could provide improved accuracy and, additionally, they could help to avoid relying mainly on GNSS coverage. The latter is of special interest for the primary application of the sub-
surface imaging system (i.e. the detection of buried explosives), as the inspected area might be affected by GNSS jamming.

In the field of subsurface imaging, better resolution could be achieved if the whole frequency band of the radar is used. This mainly requires the design of appropriate antennas, capable of working along the whole frequency band while keeping a similar response. In order to gather more information and thus, to increase the scanned area per unit of time, an antenna array could be used instead of a single antenna in the receiving stage. This improvement has been initially validated in [v]. Furthermore, closer attention should be paid to distributed GPR systems. In addition to experimentally analyze the proposed combination of FLGPR and DLGPR, further work could be devoted to investigate novel architectures based on UAVs swarms. The integration of additional sensors (such as those based on electromagnetic induction or harmonic radars) could also help to increase the detection capabilities of the system. Finally, the implementation of the processing techniques on Graphics Processing Unit (GPU) could facilitate the real-time processing of the measurements.

Regarding antenna measurement and diagnostics, the main research efforts would be directed towards increasing the upper working frequency limit and reducing the acquisition time. The former requires the aforementioned improvement in the geo-referring accuracy and the integration of a power detector working at higher frequencies. The latter could be achieved by relying on novel post-processing techniques that might overcome the need of acquiring the NF amplitude at two different surfaces. Another line of improvement is related to the cost-effective acquisition of both amplitude and phase (without requiring a phase reference). In this sense, interferometric approaches or the use of phase-difference detectors are potential candidates to obtain phase information. Finally, regarding the hardware, the integration of a receiver based on Software Defined Radio (SDR) could provide more information than the current power detector onboard.


Bibliography


[67] T. K. Sarkar and A. Taaghol, “Near-field to near/far-field transformation for arbitrary near-field geometry utilizing an equivalent electric current and


Appendices
A.1 Introduction

The payload of the developed prototypes is based on the architecture shown in Figure A.1, where the main components composing the different subsystems and the connections between them are represented.

Figure A.1: Scheme of the main components included in the payload (grouped by subsystems) and the connections between them.
The main subsystems composing the payload are:

- **Flight controller subsystem (shown in purple).** The main component is a Single Board Computer (SBC) acting as flight controller itself and gathering information from the different subsystems. The positioning sensors usually on board conventional commercial UAVs are also included in this subsystem: Inertial Measurement Units (IMUs), barometer and GNSS receiver.

- **Communication subsystem (depicted in yellow).** It comprises a Radio Control (RC) link for receiving the pilot orders and a data link for exchanging information with a ground control station (transmitting the geo-referred measurements) and with the RTK base station (receiving GNSS corrections). The RC is implemented with TXs and RXs working at 433 MHz or 2.4 GHz. The data link is based on a Wireless Local Area Network (WLAN), operating in the 2.4 GHz and 5.8 GHz frequency bands. The frequencies of these links are selected to minimize possible interferences.

- **Ground control station (shown in red).** It is a laptop, where the measurements are commanded, received and post-processed. Telemetry information is also received in the ground control station, allowing the supervision of the flights.

- **Accurate positioning system (represented in grey).** The required centimeter-level accuracy has been achieved by means of an RTK system and a laser rangefinder. RTK is a differential GNSS system that makes use of the carrier phase of the satellite signals and the correction data received from an RTK base station to provide accurate coordinates. The laser rangefinder is included to improve the positioning in height when using a single-band RTK and to know the distance to the ground, which the UAV uses to maintain a steady flight.

- **RF measurement system (shown in orange).** For the subsurface imaging system is the radar and the TX and RX antennas, whereas for the antenna measurement system comprises the power detector and the probe antennas.

These last two subsystems are further explained in the following sections: the accurate positioning subsystem in Section A.2 and the RF measurement system in Section A.3 for subsurface imaging and in Section A.4 for antenna measurement.

### A.2 Accurate positioning subsystem

The first prototypes make use of a single-band mult constellation RTK system and a laser rangefinder. The expected positioning accuracy of this RTK receiver is
\( \sigma_x = \sigma_y = 1.5 \text{ cm} \) in the horizontal plane and \( \sigma_z = 3 \text{ cm} \) in the vertical direction. Although the absolute positioning error is considerably high (in terms of wavelength and taking into account the application requirements), it must be taken into account that the relative error between adjacent positions is usually significantly smaller. In order to improve the accuracy in height, a laser rangefinder has been employed, providing an accuracy of \( \sigma_z = 1.8 \text{ cm} \). In subsurface imaging, the maximum synthetic aperture size will be limited by the cumulative geo-referring errors. In the antenna measurement system, these errors will limit the upper measurement frequency.

The accurate positioning system has been upgraded in the enhanced prototypes. In this case, a dual-band multiconstellation RTK beacon is mounted on board the UAVs. Dual-band RTK receivers are more robust to multipath and they can keep a centimeter accuracy even with limited sky view. In addition, the convergence time required to resolve carrier phase ambiguities to an integer number (i.e. to achieve a fix status, where the accuracy is in the centimeter level) is smaller. Therefore, they provide better accuracy and overall performance compared to the previous single-band RTK receivers. In particular, the accuracy is \( \sigma_x = \sigma_y = 0.5 \text{ cm} \) in the horizontal plane and \( \sigma_z = 1 \text{ cm} \) in height. In order to keep the cost-effectiveness of the system, a customized RTK receiver has been integrated. This has required the development of an ad-hoc driver. In the enhanced prototypes, the laser rangefinder is only used to know the distance to the ground, since now the accuracy of the RTK beacon in height is better than the accuracy of the laser rangefinder.

### A.3 Radar subsystem

In the prototypes developed for subsurface imaging (GEODRON), the RF measurement subsystem is composed by a radar and two antennas (acting as TX and RX). The radar is connected to the SBC, which collects the radar measurements and sends them together with the geo-referring information to the ground control station in real-time.

As explained in Section 3.1, the first prototype (GEODRON 1.0) has been designed to work at C band. Although this band is usually higher than the typical bands used in GPR systems, it has been selected as a trade-off between ease of integration into the UAV and penetration depth for this first implementation of the system. In particular, an impulse radar working from 3.1 to 5.3GHz and two helix antennas with circular polarization and reverse handedness have been employed. These antennas have been selected since they are well-matched at the radar working frequencies and they have a good directivity. Furthermore, since
the antennas have orthogonal polarization and their cross polar discrimination is good, the direct coupling between them is mitigated.

The enhanced prototype (*GEODRON 2.0*), presented in Section 3.3, has been designed to operate from UHF to C band. An M-sequence UWB radar (covering the frequencies between 100 MHz and 6 GHz) has been mounted on the UAV. It transmits a type of pseudo-random binary signal called Minimum Length Binary Sequence (MLBS) periodically. Thus, the received signal must be correlated with the ideal MLBS to estimate the impulse response. Regarding the antennas, two UWB Vivaldi antennas (with linear polarization) working from 600 MHz to 6 GHz have been selected. As shown in [III], the antenna response exhibits a significant variation along the working frequencies, thus requiring additional processing techniques to effectively use the whole frequency band.

Due to the considerable size and weight of the payload (especially in the enhanced prototype), a UAV made of carbon fiber (providing good stability and strength) and with a maximum take-off weight of 11 kg has been selected for *GEODRON* prototypes. This large payload capacity allows the integration of lower frequency radars, such as the one used in *GEODRON 2.0*.

### A.4 Antenna measurement subsystem

In the case of antenna measurement (*UASAM* prototypes), the RF measurement subsystem is composed by a power detector and the probe antenna(s). The power detector provides voltage levels, which are mapped to digital output values using an Analog-to-Digital Converter (ADC). The ADC is connected to the SBC, which collects the power measurements and sends them together with the geo-referring information to the ground control station in real-time.

In the first prototype, employed for obtaining the measurements results shown in Sections 4.1 to 4.3, a single channel logarithmic power detector is employed. The working frequencies range from 1 MHz to 8 GHz, with a dynamic range between 50 and 70 dB depending on the specific measurement frequency. Regarding the probe antenna, low-directive antennas have been considered in order to avoid the requirement of probe correction techniques and since UAV attitude uncertainties have higher impact in the NF measurements when considering directive antennas (due to the AUT-probe misalignments). In particular, monopole antennas have been selected: a commercial printed monopole at C band, a customized hexagon-shaped printed monopole for measurements at S band, and a wire monopole antenna tuned to the desired frequency for measurements at lower frequencies. It is worth noting that the system has only been tested for frequencies
higher than 500 MHz, which is considered to be the lowest working frequency of UASAM 1.0.

Concerning the enhanced prototype, presented in Section 4.4, a dual channel logarithmic power detector is employed. The working frequencies range from 1 MHz to 10 GHz, with a dynamic range between 40 and 60 dB depending of the specific measurement frequency. In this case, two probe antennas are needed. Two commercial monopoles have been used for the measurements. Small differences in the probe antennas radiation patterns and the RF cables could yield to unbalance between the two input channels, requiring a calibration stage to overcome it.

In order to minimize possible reflections and due to the limited size and weight of the payload, a UAV mainly composed of plastic (minimizing scattering and interferences from the UAV itself) and with a maximum take-off weight of 2.4 kg has been selected for UASAM prototypes. It must be remarked that 3D printed structures have been designed and manufactured to place the probe antennas away from the UAV power distribution board.
Impact factor report

This section presents the main information regarding the journals where the publications composing this dissertation have been published. Complete references of these journals, which are indexed in the Science Citation Index (SCI) and in the Journal Citation Reports (JCR), can be found in Table P.1.

**Table P.1:** Complete references of the journals with published works.

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<th>IF</th>
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<td>1.782</td>
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<tr>
<td>[II]</td>
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</table>

2019 metrics are not available yet for publications [III]-[V] and [X].

Therefore, among the articles composing this dissertation, seven have been published in journals from the first quartile, two in the second quartile and one in the third one.
Publication I

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SAR-based Technique for Soil Permittivity Estimation

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Abstract

A conventional Synthetic Aperture Radar (SAR)-based technique for soil permittivity estimation is presented in this contribution. Ground Penetrating Radar (GPR) imaging techniques are mainly based on SAR imaging algorithms that take into account the wave velocity in the soil for accurate imaging of buried objects. Reflectometers, datasheets and indirect observation methods are commonly considered for soil characterization. However, factors such as humidity and temperature may cause some variations in the soil constitutive parameters. This contribution proposes a methodology for in-situ characterization of soil permittivity, using the known position of a reference object and the application of conventional SAR imaging to recover the reflectivity image, from which the required information to calculate the complex permittivity can be extracted. Experimental validation in both controlled and realistic scenarios proves the capability of the proposed technique to recover the permittivity of different types of soil, and to improve the quality of the Underground-SAR image.

Keywords: Ground Penetrating Radar (GPR); Synthetic Aperture Radar (SAR); soil characterization; permittivity; dielectric losses

1. Introduction

Development of improved imaging techniques for buried objects detection has potential applications in a wide range of different fields, such as civil engineering (identification of pipes and cracks), archaeology (detection of buried ruins), and security applications
(landmine detection). In this sense, Ground Penetrating Radar (GPR) is a well mature technique (Chen 2007; Stove 2013) capable to detect both metallic and dielectric targets (Gamba 2003; Daniels 2006).

Down-Looking GPR (DLGPR) Synthetic Aperture Radar (SAR) systems (Rosen 2005) achieve high resolution in depth through transmitting ultra-wide-band signals but suffer from strong specular reflections from the ground surface. Most of these systems use transmit and receive antennas mounted at the front or bottom of a moving vehicle and directed downward. Forward-Looking GPR (FLGPR) SAR systems (Liu 2003) use antennas that look ahead of the vehicle, with a standoff distance up to a few tens of meters. These systems achieve worse resolution since they present a smaller effective Synthetic Aperture but they reduce the reflections from the ground surface and they are safer for the vehicle operator.

Multiple SAR based algorithms as migration techniques (Marpaung 2014) or Delay-And-Sum (DAS) (Johansson 1994), among others, can be used to reconstruct images for buried objects detection. All these methods require the correct soil wave velocity in order to provide a well-focused image and to reduce false alarms. Soil wave velocity is calculated from the knowledge of the soil constitutive parameters, namely conductivity and permittivity.

Soil characterization can be done indirectly from datasheets (Dielectric Constant 2016), observation methods (Martinez 2001; Wang 1980), measurement of samples in laboratory using waveguide (Ganadi 2008), coaxial probe techniques (Sreenivas 1995; Matzler 1998 Komarov 2005; Abdelgwad 2016), and strip-line structures (Vall-Llossera 2005). In-situ soil characterization can be carried out mainly by means of reflectometers, capable of providing estimation of conductivity, permittivity and also moisture (Robinson 2003; Skierucha 2012).

The use of both a reflectometer and a GPR for accurate subsurface imaging increases the cost and complexity of the system, as in some cases, the cost of a reflectometer is within the same order of magnitude as the GPR. Therefore, the possibility of using the information collected by the GPR to estimate the soil constitutive parameters would avoid the need for a reflectometer, thus reducing hardware cost.

This contribution proposes a simple technique to estimate the complex permittivity of the soil using a simple reference target (e.g. a metallic plate) and the SAR image retrieved from the backscattered field. The method works under the assumption

2
that the soil permittivity is approximately constant in the area to be scanned, which is realistic in some scenarios (e.g. sandy soil scanning). The method can be of interest as a low-cost solution for soil characterization in GPR imaging applications avoiding the need of a reflectometer.

The wave velocity can be calculated from the recovered complex permittivity, and it can be employed as input in Underground-SAR imaging algorithm to increase the quality of the reconstructed images. Furthermore, this estimation of the soil losses can be used as well for a-priori estimation of the maximum depth at which a target of a given size can be detected.

2. Methodology

2.1. Underground-SAR imaging

The main purpose of Underground-SAR (Martinez-Lorenzo 2011) is to reconstruct images of underground targets, as opposed to conventional SAR (where the targets are above the ground). Assuming a multiple quasi-monostatic configuration, the transmitting and receiving antennas are in one medium (air), at almost the same location, and the Objects Under Test (OUT) are embedded in another medium (e.g. sandy soil).

Given a set of scattered field measurements $E_{\text{scat}}$ collected on a discrete number of points $N$ and frequencies $N_f$, the reflectivity at a single point $\rho(r')$, where $r'$ is the single point represented as a vector of Cartesian coordinates $(x, y, z)$, can be calculated as in Equation (1):

$$
\rho(r') = \sum_{n=1}^{N_f} \sum_{m=1}^{N} E_{\text{scat}}(f_m, r_m) e^{i2(\phi_1 + \phi_2)}
$$

where $\phi_1$ is the phase shift corresponding to a wave propagating from the transmitting antenna (placed at the point $r_m$) to the refraction point $r$ at the air-soil interface, and $\phi_2$ corresponds to the propagation between $r$ and the underground point $(r')$ where the reflectivity is computed. $f_n$ denotes each discrete $n$-th frequency. Specifically, these phase shifts are given by Equations (2) and (3), where the wave number in free-space for the $n$-th frequency is given by $k_{0,n} = 2 \pi f_n / c_0$ ($c_0$ is the speed of light in the air). $k_{1,n} = k_{0,n} (\varepsilon_{r,c})^{1/2}$ is the wave number in a soil with relative complex permittivity $\varepsilon_{r,c}$ (where subscripts ‘r’ and ‘c’ indicates ‘relative’ and ‘complex’). $\Re(k_{1,n})$ denotes the real part of the wavenumber $k_{1,n}$. 
\[
\phi_1 = k_{0,n} \|r_t - r_m\|_2 \\
\phi_2 = \Re(k_{1,n}) \|r' - r_t\|_2
\]

Therefore, in order to apply this method, the refraction point at the air-soil interface must be estimated. Instead of solving a fourth-order equation (derived from Snell’s law), an extension to 3D of the iterative approximation given in Appendix I of (Alvarez 2015) is used to estimate \( r_t \).

If the reconstruction is performed above the ground (i.e. only one medium is considered), then the exponent in Equation (1) equals \( +j2k_{0,e} \|r' - r_m\|_2 \).

2.2. Material characterization from SAR

If conventional SAR imaging is applied to a background medium with \( \varepsilon_{\infty} \neq 1 \) characterized as free space, it is well known that the echoes of targets in that background medium will appear displaced downwards in the SAR image with respect to their true position due to the slower propagation speed of the waves.

Thus, the composition of the background medium (real part of \( \varepsilon_{\infty} \)) can be estimated provided that the position of a reference target is known. This inverse strategy has been tested in (Gonzalez-Valdes 2013) for the characterization of lossless dielectric bodies, but it can also be applied to recover the real part of the permittivity of any medium, provided the reflection associated to the reference target can be identified in the SAR image.

The relationship between the phase terms of Equations (2) and (3) considering air and soil, and the same phase terms but considering air in both cases, for a single frequency and one observation point yields (please refer to the demonstration presented in [Gonzalez-Valdes 2013]):

\[
2d_{\text{echo}}k_{0,n} = 2d_{\text{obj}}(k_{1,n} - k_{0,n}) = 2d_{\text{obj}}k_{0,n}(\Re(\sqrt{\varepsilon_{\infty}}) - 1)
\]

where \( d_{\text{echo}} \) is the distance between the true position of the reference target and the position where the reflectivity associated to that target appears in the SAR image, and \( d_{\text{obj}} \) is the distance between the air-soil interface and the true position of the reference target. Then, assuming \( \Re(\varepsilon_{\infty}) \gg \Im(\varepsilon_{\infty}) \), the real part of the permittivity of the medium can be estimated as in Equation (5):
\[ \Re(\varepsilon_{r,c}) \approx \left(1 + \frac{d_{\text{echo}}}{d_{\text{obj}}}\right)^2 \]  

(5)

The medium losses (imaginary part of \( \varepsilon_{r,c}, \Im(\varepsilon_{r,c}) \)) can also be estimated by taking one additional measurement with the target placed on top of the medium to be characterized. Assuming local plane wave approximation, the reflectivity amplitude difference when the target is buried \(|\rho_{\text{buried}}(d_{\text{obj}})|\), and when placed on top of the medium \(|\rho_{\text{top}}|\) is given by Equation (6):

\[
\ln\left(\frac{|\rho_{\text{buried}}(d_{\text{obj}})|}{|\rho_{\text{top}}|}\right) = \alpha d_{\text{obj}}
\]  

(6)

where \( \alpha \) is the attenuation constant (in nepers per metre, Np/m), related to the imaginary part of the complex wavenumber (and thus the permittivity) as:

\[
\alpha = k_{0,\nu} \Im\left(\sqrt{\varepsilon_{r,c}}\right), \quad \Im(\varepsilon_{r,c}) \approx \Im\left(\sqrt{\Re(\varepsilon_{r,c}) + j \frac{\sigma c}{2\pi f n}}\right)^2
\]

(7)

where \( \Re(\varepsilon_{r,c}) \) has been estimated previously in Equation (5).

The flowchart of the proposed conventional SAR-based technique for soil characterization is summarized in Figure 1. Note that estimation of \( \Re(\varepsilon_{r,c}) \) just requires one measurement with the reference target buried at known depth, \( d_{\text{obj}} \). In the case of \( \Im(\varepsilon_{r,c}) \), an additional measurement with the reference target on top of the medium to be characterized is required.

3. Application Examples

In the following sections and subsections, \( XY, \ XZ, \ YZ \) denote planes. \( z, y, x \) denote the position of the \( XY, \ XZ, \) and \( YZ \) planes respectively. \( X, \ Y, \ Z \) denote size of length.

3.1. XYZ measurement range description

First, the proposed technique has been experimentally validated on a controlled scenario using the \( XYZ \) measurement range described in (Arboleya 2013). A N5244A PNA-X microwave network analyser has been used to collect the measurements. Two helix antennas with S11 parameter below -20 dB from 3 to 6 GHz, circular polarization and reverse handedness in a quasi-monostatic configuration, as shown in Figure 2, have been used. The acquisition grid is a rectangular synthetic aperture of size \((X,Y) = (90,\)
100) cm sampled every 2.5 cm, that is, 0.5 \( \lambda \) at 6 GHz, and placed 90 cm above the floor of the measurement facility (XY measurement plane at \( z = 135 \) cm in the coordinate system used in this contribution).

![Diagram of measurement setup]

Figure 1. Overview of Underground-SAR imaging and context in which the proposed conventional SAR-based technique for constitutive parameters characterization is introduced.

### 3.2. Sand characterization

A 10 cm-side square metallic target is employed as reference target for medium characterization. First, two metallic targets are placed on top of a plastic box of size \( (X,Y,Z) = (45, 62, 32) \) cm filled with dry sand up to a height of \( 22 \pm 1 \) cm (see Figure 2). The measurement facility floor has a layer of absorbers on top of a metallic plate, which
Figure 2. (a) Measurement setup: XYZ positioner, transmitting and receiving antennas, and sand box. (b) Detail of the metallic target used as reference.

had to be partially removed to avoid damaging, so the sand box is placed right above the metallic plate.

Conventional SAR imaging is applied to the scattered field measurements to compute the reflectivity of the sand box with the two metallic targets on top. Results are depicted in Figure 3 for XZ (Figure 3(a)) and YZ (Figure 3(b,c)) planes. Reflectivity is normalized with respect to the maximum of all the SAR images of this Section 3.2.

Next, the two metallic targets are buried in the sand at a depth of $d_{obj} = 9$ cm. Again the scattered field is measured and conventional SAR imaging is applied to obtain the reflectivity. Results are depicted in Figure 3(d-f) for XZ and XY planes. Placement of the two metallic targets can be clearly noticed (Figure 3(d), XY plane at $z = 50$ cm, and Figure 3(f)). Note the lower reflectivity with respect to the case where the targets were on top of the sand. As expected, these reflections occur deeper than the position where the metallic targets actually are (it should be at the XY plane at $z = 57$ cm). Sand complex permittivity can be recovered from the knowledge of $d_{obj}, d_{echo}$ and the SAR images. From Figure 3(d) and $d_{obj} = 9$ cm, $d_{echo} = 66 \pm 1$ cm $- 9$ cm $- 50$ cm $= 7 \pm 1$ cm. Thus, applying Equation (5), $\Re(\epsilon_{r})$ is estimated within the range $[2.7 \ 3.5]$. 
Figure 3. Reflectivity SAR images. Two metallic targets placed on top of a sand box (a-c) and buried in the sand (d-f). (a,d) XZ cut, plane \( y = 14 \text{ cm} \). (b,e) XY cut, plane \( z = 66 \text{ cm} \) (sand surface). (c,f) XY cut, plane \( z = 50 \text{ cm} \). Air-sand interface: \( z = 66 \pm 1 \text{ cm} \).

For \( Z(\varepsilon_{\infty}) \) the amplitude of the normalized reflectivity associated to the metallic target on top of the sand box, \( |\rho_{\text{top}}| \), and buried in the sand, \( |\rho_{\text{buried}} (d_{\text{obj}})| \), is considered. From Figure 3(a) \( |\rho_{\text{top}}| = -5 \pm 1 \text{ dB} \) (\( z = 66 \text{ cm} \)), and from Figure 3(d) \( |\rho_{\text{buried}} (d_{\text{obj}})| = -12 \pm 1 \text{ dB} \) (\( z = 50 \text{ cm} \)). After applying Equation (6), \( \alpha = [7.7 \ 10.2] \). The imaginary part of
the permittivity is calculated from Equation (7) (centre frequency, \( f = 4.5 \) GHz, is considered), \( \Im(\varepsilon_r) = [0.27 \ 0.41] \).

The echo of the metallic plate (the measurement facility floor) below the sand box can also be noticed (Figure 3(a,d), \( z = 28 \) cm). As the sand thickness is \( d_{\text{sand}} = 22 \pm 1 \) cm, the echo due to the reflection on the metallic plate of the measurement facility floor is \( d_{\text{floor,echo}} = 66 \pm 1 \) cm - 22 cm - 28 cm = 16 ± 1 cm. From \( d_{\text{sand}} \) and \( d_{\text{floor,echo}} \) the real part of the permittivity is estimated yielding \( \Re(\varepsilon_r) = [2.8 \ 3.3] \), which is in agreement with the values recovered using the metallic target.

3.3. Loamy soil characterization

Second test is devoted to analyse a different kind of medium with higher losses than sand. For this purpose, a second box has been filled with 20 \( \pm 1 \) cm of loamy soil, as shown in Figure 4(a). A larger 20 cm × 20 cm metallic plate has been chosen as reference target due to the fact that the higher losses of loam prevent the 10 cm × 10 cm to be detected even if shallowly buried. The sand box is placed next to the loam for reference purposes and also to test the detectability of an arbitrary shaped metallic target (Figure 4(b)).

Conventional SAR imaging has been applied to the following cases: i) the metallic plate is placed on top of the loamy soil and there is no metallic target in the sand (Figure 5(a,d)); ii) the metallic plate is buried \( d_{\text{obj,large}} = 4 \) cm in the loamy soil, and the arbitrary shape metallic target of Figure 4(b) is buried \( d_{\text{obj,arb}} = 5 \) cm in the sand (Figure 5(b,e)); and iii) there are no targets buried neither in the sand nor in the loamy soil (Figure 5(c,f)).

A qualitative analysis of the reflectivity for the three cases depicted in Figure 5 shows that: i) the loam losses are so high that the reflection from the metallic plate below the plastic boxes cannot be detected. Note the high detectability in the case of sand (\( z = 28 \) cm, Figure 5(a-c)); ii) even being the 20 cm × 20 cm metallic plate larger than the arbitrary shape object, their detectability is similar (Figure 5(b,e)), in agreement with the expected sand and loam losses.

Next, the complex permittivity of the loam is recovered from the reflectivity values of Figure 5. Given \( d_{\text{obj,large}} = 4 \) cm, and \( d_{\text{echo,large}} = 6 \pm 1 \) cm, then \( \Re(\varepsilon_r) = [2.5 \ 3.2] \). In the case of the imaginary part, \( \Im(\varepsilon_r) \), \( |\rho_{\text{top,large}}| = 0 \) ± 1 dB from Figure 5(a) \( (z = 64 \) cm), and \( |\rho_{\text{buried,large}}(d_{\text{obj,large}})| = -7 \pm 1 \) dB from Figure 5(b,e) \( (z = 54 \) cm). After applying Equation (6), \( \alpha = [17.3 \ 23.0] \). Finally, from Equation (7), the imaginary part of the
permittivity is estimated within the range $\Im(\varepsilon_r) = [0.58 \ 0.88]$, that is, twice the one for sandy soil.

![Measurement setup](image)

Figure 4. Measurement setup. (a) Two boxes filled with loamy soil and sand. A 20 cm $\times$ 20 cm metallic plate is used as reference object for the loamy soil. (b) Metallic object buried in the sand.

### 3.4. Stratified media

The proposed technique for medium characterization is based on the assumption that the constitutive parameters remain constant within the volume-of-interest. Its extension to stratified media is tested by means of a simple experiment. The upper part of the loamy soil box has been emptied and filled with $11 \pm 1$ cm of sand, as shown in Figure 6. In this case, the goal is to check if it is possible to identify the different layers of the soil in the box with two media. For this experiment, no metallic objects have been buried.

After applying conventional SAR imaging, the recovered reflectivity is depicted in Figure 7. For the sand box, the air-sand interface as well as the echo associated to the reflection on the metallic floor of the measurement facility ($d_{floor,echo}$) is again noticeable (Figure 7(a,c), $z = 32$ cm) as in the previous experiments. The estimation of the permittivity agrees too, since $d_{sand} = 18 \pm 1$ cm, and $d_{floor,echo} = 14 \pm 1$ cm, which yields $\Re(\varepsilon_r) = [2.8 \ 3.5]$. In the case of the two media box, Figure 7(b,c), the air-sand interface is clearly noticeable ($z = 70$ cm), but also the sand-loam interface ($z = 50$ cm). The higher
Figure 5. Reflectivity SAR images. A metallic target placed on top of a loamy soil box (a,d), two metallic targets buried in loam and sand respectively (b,e), and sand and loamy soil boxes with no targets on it (c,f). XZ planes: (a-c), XY planes: (d-f). Air-sand interface: \( z = 66 \pm 1 \) cm. Air-loam interface: \( z = 64 \pm 1 \) cm.

The depth of the sand layer is known, \( d_{\text{sand}} = 11 \pm 1 \) cm, as well as the depth of the echo associated to the reflection on the sand-loam interface, \( d_{\text{sand-loam,echo}} = 70 \pm 1 \) cm – 11 cm – 50 cm = 9 \( \pm 1 \) cm, then it is possible to estimate the complex permittivity yielding \( \Re(\varepsilon_r) = [2.8 \ 4] \).
Figure 6. Measurement setup. Left box filled with loamy soil up to a height of $14 \pm 1$ cm, with a layer of sand on top. Right box filled with sand.

Figure 7. Reflectivity SAR images. YZ cuts: (a) air-sand interface: $z = 64 \pm 1$ cm, (b) air-sand interface: $z = 70 \pm 1$ cm, and sand-loam interface: $z = 50 \pm 1$ cm. (c) XZ cut.
3.5. Mixed soil

To conclude this section, a more complex setup has been considered. The sand box has been replaced by a smaller box containing a 50% mix of sand and loam. Half of the box filled with a layer of sand and a layer of loam has been emptied in order to refill that half with the 50% mix of sand and loam, as shown in Figure 8. Notice the different heights of the different media.

A first measurement with no objects buried has been taken. Next, the 10 cm × 10 cm metallic reference target has been buried at a depth of $d_{obj} = 7$ cm in the box filled with mixed soil. Finally, the reference object has been placed on top of the mixed soil concerning soil losses estimation.

Results for the recovered reflectivity using conventional SAR imaging are shown in Figure 9. First, results for the boxes with no metallic objects on them are depicted (Figure 9(a-d)). The different air-sand ($z = 70$ cm), air-mixed soil ($z = 58$ cm), and sand-loam interfaces ($z = 50$ cm) can be identified. The losses of the mixed soil are still large enough to allow the detection of the echo associated to the metallic floor of the measurement facility, even in the case of the small box, filled just up to $d_{mix} = 14 \pm 1$ cm.

Figure 9(e-f) corresponds to the SAR images when the metallic target is buried $d_{obj} = 7$ cm in the small box. The echo appears at $d_{echo} = 5 \pm 1$ cm, thus from Equation (5), $\Re(\varepsilon_e) = [2.4 \ 3.4]$. To recover the imaginary part of the permittivity, the metallic target is placed on top of the mix soil (Figure 9(g,h)), recording the reflectivity amplitude.

![Figure 8. Measurement setup. (a) Right (small) box filled with 50% mix of sand and loam up to a height of $14 \pm 1$ cm. Left (large) box partially filled with 50% mix of sand and loam up to a height of $18 \pm 1$ cm, with the other half filled with a layer of loam and an upper layer of sand (detailed in (b)).](image-url)
Figure 9. Reflectivity SAR images. XY, XZ, and YZ plane cuts. (a-d) Boxes with no metallic targets. (e-f) Metallic target buried 7 cm in the mixed soil. (g-h) Metallic target placed on top of the mixed soil box.
Table 1. Permittivity reconstruction results.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Figure</th>
<th>$\Re(\varepsilon_r)$</th>
<th>$\Im(\varepsilon_r)$</th>
<th>Reference values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Figure 3</td>
<td>[2.7 3.5]</td>
<td>[0.27 0.41]</td>
<td>$\Re(\varepsilon_r)=2.55$ (Dielectric Constant, 2016)</td>
</tr>
<tr>
<td>Sand</td>
<td>Figure 7 (sand box)</td>
<td>[2.8 3.5]</td>
<td>N/A</td>
<td>$\Re(\varepsilon_r)=2.7 3.7$, $\Im(\varepsilon_r)=0.05 0.5$ (Wang and Schmugge 1980)</td>
</tr>
<tr>
<td>Sand</td>
<td>Figure 7 (sand box)</td>
<td>[2.8 4.0]</td>
<td>N/A</td>
<td>$\Re(\varepsilon_r)=2.6 2.55$, $\Im(\varepsilon_r)=0.02 0.03$ (Abdelgawad and Said 2016)</td>
</tr>
<tr>
<td></td>
<td>Figure 11 (d$_{ag} = 20$ cm)</td>
<td>[2.9 3.2]</td>
<td>[0.32 0.47]</td>
<td>$\Re(\varepsilon_r)=3.6$, $\Im(\varepsilon_r)=0.7 0.8$ (Gadani and Vyas 2008, Figure 8(a))</td>
</tr>
<tr>
<td></td>
<td>Figure 11 (d$_{ag} = 15$ cm)</td>
<td>[2.7 3.2]</td>
<td>[0.32 0.40]</td>
<td>$\Re(\varepsilon_r)=3.4$, $\Im(\varepsilon_r)=0.1 0.4$ (Vall-Llosera et al. 2005)</td>
</tr>
<tr>
<td>Loam</td>
<td>Figure 5</td>
<td>[2.5 3.2]</td>
<td>[0.58 0.88]</td>
<td>$\Re(\varepsilon_r)=3.4$, $\Im(\varepsilon_r)=0.2 0.7$ (Vall-Llosera et al. 2005)</td>
</tr>
<tr>
<td>Mixed soil</td>
<td>Figure 9</td>
<td>[2.4 3.4]</td>
<td>[0.38 0.58]</td>
<td>$\Re(\varepsilon_r)=3.5$, $\Im(\varepsilon_r)=0.1 0.6$ (Gadani and Vyas 2008, Figure 8(b))</td>
</tr>
</tbody>
</table>

(Dielectric Constant, 2016) Loss tangent (tan δ) defined as: $\tan \delta = \frac{\Im(\varepsilon_r)}{\Re(\varepsilon_r)}$

(Vall-Llosera 2005) Soil moisture from 3% to 7%.

From Figure 9(e-f), $|\mu_{\text{air}}(d_{ag})| = -13 \pm 1$ dB ($z = 46$ cm), and from Figure 9(g-h), $|\mu_{\text{ag}}(d_{ag})| = -5 \pm 1$ dB ($z = 58$ cm). Then, $\alpha = [11.5 14.8]$. And finally, after applying Equation (7), $\Re(\varepsilon_r)=0.38 0.58$.

A summary of the soil characterization results is presented in Table 1, together with the references where typical permittivity values for these kinds of soils can be found. It must be remarked that the experiments were conducted in a dry environment, so the moisture content of the soil is expected to be less than 10%. It can be noticed a good agreement between the values given in the literature using reflectometry, measurement of samples in laboratory, or indirect observation techniques, and the ones obtained with the proposed SAR-based technique. Note that the samples used in this contribution and in the literature may vary in the composition, thus resulting in different permittivity ranges as noticed in Table 1. This is especially noticeable in the case of $\Re(\varepsilon_r)$, which is more sensitive to soil moisture (Vall-Llosera 2005).

4. Outdoor scenario

4.1. Soil characterization

The proposed methodology has been validated in a realistic outdoor scenario, a sandy beach (coordinates 43.547,-5.589). For this test, a PulsOn P410 monostatic radar module (PulsOn Radar Module 2016) working from 3.1 GHz to 5.3 GHz has been used.
The radar module has been mounted on a platform that allows manual scanning in cross-range (x axis), as depicted in Figure 10. The radar module is connected to a laptop for data collection and processing. Cross-range scanning is performed 45 cm above the surface of the beach creating a synthetic aperture of 1 m sampled every 2 cm (0.35 λ at 5.3 GHz). The OUT is a circular metallic target of diameter 18 cm and 1 cm thickness.

First, the sand permittivity is characterized. For this purpose, the target is buried at a known depth of $d_{\text{obj}} = 20$ cm (see Figure 10). When conventional SAR imaging is applied, Figure 11(b), it can be observed that the echo of the metallic target appears $35 \pm 1$ cm below the soil surface, so $d_{\text{echo}} = 35 \pm 1$ cm - $d_{\text{obj}} = 15 \pm 1$ cm. By applying Equation (5), the estimated relative permittivity of the sand is $\Re(\varepsilon_r) = [2.9 \ 3.2]$.

In order to estimate the imaginary part of the permittivity, an additional measurement with the metallic target uncovered (as in Figure 10) is performed. The recovered reflectivity is depicted in Figure 11(a). As observed in Figure 11(b), the amplitude of the echo due to the reflection on the buried metallic target is $|\rho_{\text{buried}}(d_{\text{obj}})| = -14 \pm 1$ dB ($z = 82$ cm), and from Fig. 11(a), when the target is on top of the sand, $|\rho_{\text{top}}(d_{\text{obj}})| = 0 \pm 1$ dB. Then, $\alpha = [8.2 \ 9.0]$. Finally, after applying Equation (7), $\Im(\varepsilon_r) = [0.32 \ 0.37]$ (centre frequency, 4.2 GHz).
The same experiment has been repeated with the object buried in another position at a depth of $d_{obj} = 15$ cm. Results are depicted in Figure 11(c). For this case, $\mathcal{R}(\varepsilon_r) = [2.7 \ 3.2]$ and $\mathcal{I}(\varepsilon_r) = [0.32 \ 0.40]$, in agreement with the previous case.

4.2. Application to Underground-SAR

Once the capability of the proposed conventional SAR-based technique to recover the permittivity of the medium has been proved, practical application of the interest on accurate permittivity estimation is shown in this section.

Conventional SAR imaging results depicted in Figure 11(b,c) show that the buried target is detected at a depth of 35 cm and 26 cm, that is, about 75% deeper than expected. For some GPR applications where just detection is required it is not a major drawback. However, in fields such civil engineering or archaeology, accurate estimation of the depth is required in order to avoid damaging the buried object (metallic pipe, buried artwork, etc.).

The estimated permittivity of the sand (centre value of the estimated range, $\mathcal{R}(\varepsilon_r) = 3.0$ and $\mathcal{I}(\varepsilon_r) = 0.35$) has been introduced as an input in an Underground-SAR imaging algorithm (see Figure 1 flowchart). The recovered reflectivity is depicted in Figure 12. Note that the metallic target buried at $d_{obj} = 20$ cm is now imaged at a depth of $21 \pm 1$ cm (Figure 12(a)), and when buried at $d_{obj} = 15$ cm, the metallic object reflection is detected at $14 \pm 1$ cm (Figure 12(b)). In both cases, depth estimation error is less than 10%.

5. Conclusions

From the experimental results presented in this contribution, it can be concluded that the proposed method for in-situ characterization of the soil permittivity provides an accurate estimation of this parameter. Using the estimated permittivity value the Underground-SAR imaging allows a correct recovery of the depth of buried targets, which can be of interest in applications such as civil engineering or archaeology.

One of the advantages of this method is that it avoids the need of additional hardware such as reflectometers, thus reducing the overall cost of the GPR system. Besides, it does not require additional measurements, since the information is extracted from the Underground-SAR images of the domain-under-test. The main drawback is that the method is invasive, as it requires burying a reference object in the soil to be
Figure 11. Reflectivity (amplitude, in dB, normalised with respect to the maximum of Figures 11 and 12) on AZ plane recovered from conventional SAR imaging. (a) Metallic target uncovered. (b) Metallic target buried at $d_{o1} = 20$ cm. (c) Metallic target buried at $d_{o1} = 15$ cm.
characterized. However, once the permittivity is recovered, at the beginning and for a small part of the complete scenario, the same value is used for the whole reconstruction, assuming a homogeneous background medium.

An additional advantage of the proposed method is that, thanks to the fact that the depth and size of the reference target is known, it can be used to calibrate GPR parameters such as transmitting power or sensitivity from the resulting Underground-SAR image.
Geolocation information

Outdoor measurements conducted at coordinates 43.547443, -5.589923.

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Disclosure statement

No conflict of interest is declared by any of the authors.

References


Publication II

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Synthetic Aperture Radar imaging system for landmine detection using a Ground Penetrating Radar on board an Unmanned Aerial Vehicle

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ABSTRACT This work presents a novel system to obtain images from the underground based on Ground Penetrating Radar (GPR). The proposed system is composed by a radar module mounted on board an Unmanned Aerial Vehicle (UAV), which allows the safe inspection of difficult-to-access areas without being in direct contact with the soil. Therefore, it can be used to detect dangerous buried objects, such as landmines. The radar measurements are coherently combined using a Synthetic Aperture Radar (SAR) algorithm, which requires cm-level accuracy positioning system. In addition, a clutter removal technique is applied to mitigate the reflection at the air-soil interface (which is caused by impedance mismatching). Besides the aforementioned advantages, the system can detect both metallic and dielectric targets (due to the use of a radar instead of a metal detector) and it allows to obtain high-resolution underground images (due to the SAR processing). The algorithms and the UAV payload are validated with measurements in both controlled and real scenarios, showing the feasibility of the proposed system.

INDEX TERMS Ground Penetrating Radar (GPR), subsurface sensing and imaging, Synthetic Aperture Radar (SAR), landmine detection, Unmanned Aerial Vehicle (UAV), drones, Real Time Kinematic (RTK).

I. INTRODUCTION THERE has been a massive introduction of UAV-based systems for remote sensing applications in the last decade [1], thanks to the improvements in technical features such as avionics and propulsion systems, capacity of batteries, autonomous navigation capabilities, and ease of sensor integration, together with a significant reduction in their cost. These achievements have fostered the use of UAVs in fields such as precision agriculture and forestry monitoring [2], [3], and in glaciology [4], where factors such as remoteness and severe weather conditions limit the extent of human-assisted measurement campaigns.

Small, lightweight UAVs (less than 3 kg) are being introduced for airborne Synthetic Aperture Radar (SAR)-based terrain observation, avoiding the need of large aircrafts (especially for monitoring small size areas). For example, in [5] a polarimetric radar mounted on a UAV for SAR imaging applications is described. Similar to other UAV-based SAR
imaging systems [6], [7], it has a Global Navigation Satellite System (GNSS) receiver and an Inertial Measurement Unit (IMU) which provide in-flight guidance and positioning information. While range resolution is given by the radar bandwidth, ranging from few cm [6], [7] to 1-2 m [5], cross-range resolution is limited by measurement geo-referencing uncertainty. In the case of conventional GNSS receivers, typical uncertainty ranges from 1 to 3 m.

UAVs have been also proved to be of great help for electromagnetic compatibility and antenna measurements [8], [9]. In this case, the use of positioning and geo-referencing systems capable of providing cm-level accuracy enabled working at higher frequency bands, as long as the wavelength is larger than the positioning and geo-referencing uncertainty [8], [9]. Finally, UAV-assisted applications in the area of communications, mainly devoted to improve connectivity in remote areas, are being developed [10], [11].

A. LANDMINE DETECTION: SYSTEMS AND METHODS

Detection of concealed objects in an opaque medium using Non-Destructive Testing (NDT) techniques has been of great interest in sectors such as mining and geology, civil engineering and civil works, and archaeology [12]. These NDT techniques allow to detect, locate, and, eventually, obtain an image of the concealed object, avoiding the interaction with both the object and the surrounding medium [13]. The main advantages are scanning time and cost savings, as invasive excavations in the area of interest to search for the objects are not required, also preventing accidental damage. Among the aforementioned fields of application, there are some scenarios where the concealed objects are a threat in case of accidental contact, such as weapons or explosives. In these cases, detection and location have to be carried out under safe conditions for both the scanning device and the operators. One of the scenarios of interest is landmine detection. Landmines cause about 4000 deaths and injuries every year, 90 per cent corresponds to civilians, happening in those 60 countries where part of their territory is affected by the deployment of this kind of countermeasure. The number of landmines worldwide is estimated between 60 and 70 million. Only in 2016 the total global clearance of landmines was about 170 km², with at least 232,000 landmines destroyed [14].

Landmine detection methods can be classified in two main groups: invasive and non-invasive techniques. Invasive techniques are based on a contact device capable of detonating the mines [15]. The main disadvantage of these systems is their impact in the scanned area, as they plow the terrain while scanning, as well as their limited lifespan. The advantage is their fast scanning speed, up to 1 square meter per 0.73 seconds. On the other hand, non-invasive techniques allow to detect the presence of concealed objects thanks to an adequate processing of the received signals. These non-invasive techniques can be sorted according to the physical principle in which the detection method is based [16].

i) Electromagnetic induction: based on inducing an electric current in the concealed metallic objects using a transmitting coil. The induced current re-radiates an electric field which is detected by a receiving coil. The main advantage of this system is its low cost and simplicity. However, it suffers from a high false-alarm rate when several metallic objects are also in the scenario under test (shrapnel, bolts, etc.).

ii) Nuclear Quadrupole Resonance (NQR): based on the detection of the radiofrequency signals emitted by certain substances that are likely to be in explosive materials. This technique has high probability of detection, but it involves the use of complex devices.

iii) Thermal imaging: infrared sensors are capable of detecting the different thermal behavior of landmines with respect to the surrounding medium. In particular, thermal image time series acquisition is proposed in [17], using thermal response analysis in the time domain to detect landmines. The main weakness of this methodology is the dependence with weather conditions that affect soil thermal conductivity, and thus the thermal contrast between soil and buried landmines.

iv) Ground Penetrating Radar (GPR): it has been considered as one of the best techniques for underground imaging thanks to the capability of creating images of the soil and the objects buried in it [13]. In consequence, GPR has been widely used for landmine detection [18]–[21]. GPR is based on emitting electromagnetic waves to the soil, whose reflection at the soil and at potential concealed objects allows to recover a radar image where these concealed objects can be identified. It must be remarked that GPR is quite sensitive to the soil composition and the air-soil interface roughness, requiring additional signal processing techniques for image artifacts and clutter removal.

Regardless the operating principle, the application of non-invasive techniques for landmine detection requires the scanning system to be placed at a safety distance with respect to the potential placement of the landmine, typically 3-5 m, to avoid the accidental detonation of the landmine by the scanning device. To achieve this goal there are several possibilities:

i) Forward-looking radar systems, where the transmitting antenna illuminates the soil under an angle of incidence such as the injected power in the soil is maximized [22], [23]. In this case, due to the angle between the radar and the soil, only part of the reflected energy is backscattered towards the radar, thus requiring higher dynamic range in the receiver to detect the buried targets.

ii) Downward-looking systems, where the incident wave direction is perpendicular to the soil surface [22], [24]. In this case, the fact that the transmitted power is not maximized is partially compensated thanks to the shorter distance between the radar and the soil; and also the backscattered power is directed towards the radar (although it also depends on the geometry of the buried target). In this kind of systems, the challenge is to achieve normal incidence while keeping the security distance of 3-5 m. One solution is based on small lightweight unmanned autonomous robots, capable of performing detection with a minimum landmine detonation...
risk [25], [26]. In these systems, transmitting and receiving antennas are placed in the air-soil interface at different positions separated half wavelength, so that the coherent combination of the received signal at each position results in a bi-dimensional radar image (in range or depth, and cross-range or movement direction of the robot). However, the main limitations are the slow scanning speed (around 5 cm per second) and the maximum weight of the entire robot to avoid accidental detonation.

An alternative to the use of terrestrial detection vehicles and their limitations in terms of scanning speed (and risk of detonation as they are in touch with the soil) is given by airborne devices. Among them, Unmanned Aerial Vehicles (UAVs) or commonly drones have been considered of great relevance in multiple fields thanks to their versatility and low cost.

B. UNMANNED AERIAL SYSTEMS FOR LANDMINE DETECTION

Improvements in UAV technology have made possible the development of UAV-assisted landmine detection systems, as they exhibit disruptive advantages such as: i) higher scanning speed compared to existing solutions in the market based on autonomous robots; ii) possibility of inspection of remote areas, unaccessible with other systems; and iii) higher safety throughout the scanning process, especially when looking for explosives, since contact with soil is avoided.

A prototype consisting of a metal detector onboard a UAV that also includes a robotic arm capable of placing a remotely controlled detonator to blow out the landmine is described in [27]. This system provides contactless (and thus safe) and fast scanning capabilities. However, metal detectors cannot distinguish between different kinds of metallic targets. Furthermore, non-metallic buried explosives cannot be detected.

Latest advances for landmine detection are based on placing a GPR onboard a UAV [28]–[32]. The implemented prototypes are mostly based on a compact GPR unit that forwards geo-referred measurements to a ground station for post-processing and results displaying. Again, cross-range (horizontal) resolution is limited by positioning and geo-referring accuracy, mostly relying on GNSS receivers integrated within the UAV controller. In consequence, these state-of-the-art systems have been proved to be effective for detecting buried targets larger than 25-30 cm, and/or exhibiting significant contrast with the medium (e.g. metallic targets buried in clay or sand).

However, existing UAV-based GPR systems do not provide high resolution subsurface images as they do not support SAR imaging capabilities, that is, GPR measurements collected at each position of the flying path cannot be coherently combined. This is because positioning and geo-referring accuracy using GNSS-based techniques is in the order of 50-60 cm in the best case. Thus, enabling SAR imaging techniques (i.e. coherent combination of measurements) requires the use of cm- or mm-level accuracy geo-referring and positioning techniques.

C. AIM AND SCOPE OF THIS CONTRIBUTION

Aiming to overcome the limitations in terms of detection capabilities of current UAV-based GPR imaging system, this contribution introduces a system and method for high accuracy underground SAR imaging, conceptually depicted in Fig. 1. The developed technology allows the UAV to autonomously explore a particular area using GNSS coordinates, while transmitting and receiving radio signals using a radar module. The collected data includes timestamps to enable synchronization and is sent in real time to a computer, where it is processed to generate SAR images of the subsurface with a resolution of centimetres. In addition, algorithms for proper characterization of the soil and clutter removal have been implemented.

The main innovation of this contribution is the capability of using SAR-based techniques for subsurface imaging with range and cross-range resolution of a few cm, overcoming the limitation of current UAV-based GPR systems where coherent combination of measurements taken at different positions (i.e. creating a synthetic aperture) is not possible.

II. METHODOLOGY

As opposed to conventional SAR imaging, where targets are above the ground, the main purpose of Underground-SAR [33], [34] is to reconstruct images of underground targets, taking into account the different wave velocity in the air and in the soil. Microwave imaging of the ground and the objects buried in it can be performed by means of SAR-based algorithms such as migration techniques [35], Delay-And-Sum (DAS) [36], or Wiener filter-based SAR [37], among others. In all these cases, soil wave velocity has to be properly estimated in order to provide a well-focused image and to reduce false alarms. From the knowledge of the soil constitutive parameters, namely conductivity and permittivity, soil wave velocity can be estimated.

Assuming a multiple quasi-monostatic configuration (i.e. the transmitting and receiving antennas are almost at the
same location), the basic principle of underground SAR imaging is as follows: given a set of scattered field measurements collected on $M$ acquisition points and $N$ frequencies, $E_{\text{scatt}}(r_m, f_n)$, the reflectivity at a single point $\rho(r')$ can be calculated as indicated in Eq. 1:

$$\rho(r') = \sum_{m=1}^{M} \sum_{n=1}^{N} E_{\text{scatt}}(r_m, f_n)e^{j2(\phi_0 + \phi_1)}$$  \hspace{1cm} (1)

where $r_m$ is the position of the $m$-th acquisition point, $f_n$ is the $n$-th frequency and $\phi_0, \phi_1$ are the phase-shifts due to the wave propagation in the air and in the soil, as depicted in Fig. 2. These terms are defined in Eq. 2 and Eq. 3:

$$\phi_0 = k_0,n ||r_i - r_m||_2$$  \hspace{1cm} (2)

$$\phi_1 = k_0,n \sqrt{\frac{\rho}{r}} ||r' - r_i||_2$$  \hspace{1cm} (3)

$k_0,n$ is the free-space wavenumber for the $n$-th discrete frequency, $\rho_i$ is the relative permittivity of the soil and $r_i$ is the refraction point at the air-ground interface, as indicated in Fig. 2. The refraction point, whose calculation requires solving a fourth order equation derived from Snell’s law, is estimated using an iterative algorithm. In case of using a time-domain acquisition, a Fourier transform is applied to the collected measurements before the SAR processing.

This simple Delay-And-Sum (DAS) formulation is based on a coherent combination of the measurements taken at different $r_m$ positions. Note that the only restriction is that acquisition points must fulfill Nyquist sampling rate, that is, the separation between two consecutive points must be smaller than $\lambda_{\text{min}}/2$, with $\lambda_{\text{min}} = c/f_N$ ($c$ is the speed of light in free space). In addition to this, acquisition points have to be accurately geo-referenced to minimize uncertainties that will distort the recovered SAR image. For this purpose, geo-referencing uncertainty should be better than $\lambda_{\text{min}}/4$ in cross-range and $\lambda_{\text{min}}/8$ in range.

With respect to conventional point-to-point SAR back-propagation, coherent combination of multiple measurements improves cross-range resolution. Free-space range $\Delta r$ and cross-range $\Delta l$ resolution (under free-space consideration) are given by Eq. 4 and Eq. 5:

$$\Delta r = \frac{c}{2(f_N - f)}$$  \hspace{1cm} (4)

$$\Delta l = \frac{R \lambda_c}{2L_{\text{ap}}}$$  \hspace{1cm} (5)

where $R$ is the distance from the radar to the target, $\lambda_c = 2c/(f_1 + f_N)$ is the wavelength at the center frequency, and $L_{\text{ap}}$ is the synthetic aperture width.

As mentioned before, soil characterization is required to get an estimate of $\epsilon_r$. This characterization can be done indirectly from datasheets generated from previous measurements [38]-[40], or by means of in-situ measurements, which are more suitable for practical operation of the airborne radar proposed in this contribution. Methodologies based on GPR measurements to estimate conductivity and permittivity have been proposed in [34], [41]. Basically, if the depth of a reference target is known, then, the permittivity can be estimated by comparing the distance where the buried target is detected ($d_{\text{echo}}$) with its true depth ($d_{\text{target}}$). Thus, the permittivity is given by Eq. 6:

$$\epsilon_r = \left(\frac{d_{\text{echo}}}{d_{\text{target}}}\right)^2$$  \hspace{1cm} (6)

If the soil permittivity cannot be estimated, it can be assumed $\epsilon_r = 1$, that corresponds to the case in which conventional SAR imaging is applied to the soil medium. Then, the echoes of targets buried in the soil will appear displaced downwards in the SAR image with respect to their true position due to the slower propagation speed of the waves in the soil.

The strong clutter produced by the specular reflection from the ground surface (i.e. air-soil interface) is one of the main issues for accurate detection of buried objects using GPR imaging. Several clutter removal techniques have been proposed, such as time-gating [42], average subtraction, and subspace projection methods [43].

In this contribution, time-gating and average subtraction techniques are used to improve the quality in the reconstructed SAR image. Both techniques are applied to the measurements in the distance domain (which is equivalent to the time domain, taking into account the relationship between the two-way distance and the time $r = c t/2$). With the time-gating technique, only the reflected signal between 20 cm and 4 m (away from the antennas) is selected. This helps to remove the coupling between the transmitter and receiver antennas as well as the effects of radiofrequency cables connecting the antennas and the radar module. Then, the average of all measurements along the whole aperture is computed and subtracted from each measurement, as given by Eq. 7, helping to improve the contrast in the image and mitigating the clutter.
\[
E_{\text{meas}}(r_m, r) = E_{\text{meas}}(r_m, r) - \frac{1}{M} \sum_{n=1}^{M} E_{\text{meas}}(r_m, r)
\]

A flowchart of the methodology is shown in Fig. 3, where it has been assumed that the radar signal is acquired in the time domain (as in the presented prototype). First, time gating is applied to each measurement. Then, once all the measurements have been acquired, their average is computed and subtracted from each measurement. It must be noticed that the average is also a time domain signal. Finally, the Fourier transform is applied before performing the underground SAR (U-SAR) processing.

III. UAV-BASED UNDERGROUND SAR IMAGING SYSTEM IMPLEMENTATION

The proposed airborne-based GPR imaging system for detection of buried objects is composed by the following devices, represented in Fig. 4 scheme (grouped by subsystems):

- Flight control subsystem, which consists of a microcomputer (Raspberry Pi), a UAV flight controller and common positioning sensors (IMU, barometer, GNSS).
- Communication subsystem.
- Accurate positioning subsystem to provide cm-level accuracy. It includes a Real Time Kinematic (RTK) system and a LIDAR (Light Detection And Ranging) altimeter. There are two RTK beacons: one on the UAV and another on the ground at a fixed position.
- Radar subsystem.
- A ground station (e.g. a laptop), which receives radar measurements and positioning and geo-referring information, and processes it to map radar measurements with centimeter-level accuracy. Geo-referenced measurements are processed together with the underground SAR imaging algorithm to create radar images of the soil and objects buried in it.

![Scheme describing the implementation of the airborne-based GPR. Description of the connection between different subsystems and devices of the prototypes.](image)

A UAV model with a payload up to 5 kg has been acquired [44] to have enough capacity for further improvements of the prototype with additional sensors or devices. This UAV provides around 15 min flight with a 2-3 kg payload, which is enough for initial validation flight tests.

A lightweight, compact impulse radar working in the 3.1 to 5.1 GHz frequency band [45] has been selected, aiming to obtain a trade-off between range resolution \(\Delta r = 7.5\) cm according to Eq. 4, ease of integration in the UAV, and penetration depth. Radar transmitting and receiving ports are connected to two customized helix antennas, one having right-handed circular polarization (RHCP), and the other left-handed circular polarization (LHCP). It must be noticed that since the antennas have orthogonal polarizations and their cross polar discrimination (XPD) is good (around 24 dB at central frequency), the direct coupling between the antennas is mitigated, which helps to improve the quality of the results. These antennas are well matched between 3 to 6 GHz, having \(\theta_{\text{3DB}} = 47\) degrees beamwidth, thus resulting in \(D = 12.7\) dB directivity. As in the case of the radar, there is a trade-off between the antenna size and its directivity. Nevertheless, cross-range resolution \(\Delta d\) given by the helix antenna beamwidth is further improved by means of SAR techniques.

Communication between UAV, RTK beacons, and the ground station is managed through a Wireless Local Area Network (WLAN), deploying a wireless router close to the area to be scanned to provide coverage to the ground station, the UAV, and the RTK ground beacon. WLAN operating frequency can be set to 2.4 GHz or 5.8 GHz as those frequencies do not interfere with the radar frequency band. In any case, radar antennas are directive and always pointing towards the ground so, even in the case of sharing the same frequency band, co-channel interference would be negligible.
Also, aiming to minimize interference, UAV transmitter and receiver modules are set to work at 433 MHz.

Concerning UAV positioning and geo-referring system, RTK [46] has been selected as it provides cm-level accuracy and ease of deployment and integration within the UAV controller. RTK ground beacon forwards the corrections that must be applied to the GNSS signal to the RTK beacon placed in the UAV (rover beacon) in real time. The latter uses these corrections to improve the position accuracy down to cm-level.

RTK positioning uncertainty indicated by the manufacturer [46] is $\sigma_x = \sigma_y = 1.5$ cm, $\sigma_z = 3$ cm. Taking into account the maximum working frequency of the radar, $f = 5.1$ GHz, uncertainty in the horizontal (XY) plane (i.e. in cross-range) is $0.26\lambda_{\min}$ for any arbitrary direction in this plane, and in height (z axis, i.e. range) it is $0.51\lambda_{\min}$. Although absolute positioning error in the horizontal plane is worse than $\lambda_{\min}/8$, it must be taken into account that the relative error between adjacent positions is much smaller than $\lambda_{\min}/8$, thus enabling coherent combination of the measurements.

As the positioning uncertainty is twice in the vertical axis, a more accurate height measurement sensor is required. Among different possibilities, a LIDAR altimeter [47] has been chosen, as it is more robust and accurate than an ultrasonic sensor of similar size and cost. The selected LIDAR altimeter has $\sigma_z = 1.8$ cm height measurement uncertainty, that is $0.31\lambda_{\min}$. Again, the relative error between adjacent positions is much smaller than $\lambda_{\min}/8$ and thus, it does not significantly affect the results. Nevertheless, it must be noted that the maximum synthetic aperture length will be limited by cumulative geo-referring errors.

A picture of the UAV with all the devices and modules integrated (ready-for-operation configuration) is shown in Fig. 5. In-flight operation mode of the system can be watched at https://youtu.be/gsKptOPVARI.

### IV. SYSTEM VALIDATION

For a proper validation of the airborne-based GPR system, validation and testing has been divided into several stages:

i) Validation in a controlled environment of the radar module [45]: measurements have been conducted using a planar measurement range [48]. Different kinds of soils (sand, loam, mixed) have been evaluated aiming to determine the capability of recovering constitutive parameters of the medium as well as testing the performance of the radar for detecting buried objects. Methodology and results have been presented in [34].

ii) On-ground validation: once the radar module has been tested in a controlled environment, validation in a realistic scenario has been carried out. In this stage, the main goal is to evaluate the capability of the system to create underground SAR images using geo-referring information provided by the positioning systems onboard the UAV.

iii) In-flight tests: last step is the integration of the payload (namely the radar module and some of the sensors of the positioning subsystem) into the UAV. An extensive validation campaign for different scenarios has been conducted to ensure proper functionality of the implemented system.

For this first prototype of airborne-based GPR the selected frequency band (3.1 - 5.1 GHz) limits its range of application to low loss soils. Thus, the results presented in this contribution will be devoted to sandy soils, with permittivity ($\varepsilon_r$) ranging from 2.5 to 4 (depending on the degree of water moisture) and conductivity ($\sigma$) lower than 0.01 S/m.

### A. ON-GROUND TESTING

For the validation of the radar module in a realistic scenario (sandy beach, coordinates 43.533, -5.383), a homemade portable linear scanner has been used. The radar module [45] and the helix antennas are mounted on a portable platform that can be manually displaced along two parallel plastic bars placed 50 cm above ground and parallel to it. Measurements were taken along 1 m distance, geo-referring them by means of the RTK system. The RTK rover beacon was placed on the portable platform, and the RTK ground beacon around 20 m away. Measurements and RTK coordinates were sent to the ground station using a wireless link. A general overview of the setup is depicted in Fig. 6.

To test the detection capability of the radar, a metallic disc (of 9 cm radius and 1 cm thickness) was buried at $d_{\text{d1}} = 15$ cm in a sandy soil (with estimated permittivity $\varepsilon_r = 3.5$ [34], [40]) as depicted in Fig. 7 (a). In order to illustrate the average subtraction procedure, the average is shown in Fig. 7 (b), and the imaging results with and without average subtraction are compared.

First, imaging results were obtained by just representing the envelope of the collected measurements (obtained using the Hilbert transform). This will be called point-to-point backpropagation, since the measurements are not combined to improve the resolution of the image. Imaging results are shown in Fig. 7 (c) and (d), without performing average subtraction and performing it. In both cases, a buried target
is observed, although its depth and size do not match the true ones. As expected, the average subtraction helps to improve the quality of the imaging results. Next, measurements were processed with the underground SAR imaging algorithm and assuming \( \varepsilon_r = 1 \) for the sand (that is, free-space). Coherent combination of the measurements taken at each position was done using the coordinates provided by the RTK system. Underground SAR imaging results are shown in Fig. 7 (e) and (f), without and with average subtraction, respectively. Clearly the air-sand interface can be distinguished, as well as the buried metallic disc at approximately \( d_{echo} = 28 \text{ cm} \) depth, deeper than expected as free-space conditions were considered in the underground SAR imaging. Roughness of the air-sand interface results in a non-uniform backscattering, so the air-sand interface appears as a non-regular contour in the SAR image.

Underground SAR imaging results considering \( \varepsilon_r = 3.5 \) are depicted in Fig. 7 (g). In this case, the metallic disk is imaged at the correct depth of \( d_{echo} \approx d_{obj} = 15 \text{ cm} \), as the relative permittivity of the sand is taken into account in the underground SAR imaging.

**B. IN-FLIGHT TESTS AND RESULTS**

Once the payload was properly tested, it was mounted on-board the UAV for in-flight tests. Positioning subsystem then comprises RTK [46], LIDAR altimeter [47], and default UAV positioning systems (inertial sensors, barometer, and standard GNSS receiver). Combination of the positioning information provided by these sensors resulted in an accuracy better than 1.5 cm in \( x, y, \) and \( z \) axes. Radar measurements are provided at a rate of 50 samples/s, whereas positioning information is obtained at a rate of 10 Hz. This value determines the fastest scanning speed of the UAV, which for the flight test presented in this section is kept below 30 cm/s (1.1 km/h). At that speed, UAV position...
information is updated, on average, every time the UAV moves 3 cm in the horizontal plane (that is $0.5\lambda_{min}$). UAV coordinates are linearly interpolated in order to use all the radar measurements.

UAV can be operated manually (GNSS-assisted flight mode), where the operator controls UAV yaw, pitch, and roll axes. Another possible operation mode is based on waypoints: a flight path covering the area to be scanned is created, then uploaded into the UAV controller, so the UAV operator is just in charge of take off and landing operations. For the sake of simplicity, in-flight tests presented in this contribution were done in manual operation mode. Besides, in the case of straight line flight paths, no significant differences in the flight path were found between manual and waypoint-based flight operation.

In-flight tests were done at the airfield for UAVs of the University of Oviedo, located at (43.522, -5.624). Before taking off, it was verified that all the systems and subsystems worked properly. This verification was performed again after taking off. Measurement acquisition starts when taking off and finishes when landing. Furthermore, the acquisition can be remotely controlled from the ground station. To verify the capability of the system for in-flight SAR imaging (as done in [5], [6]), a 1-m long and 6 cm wide metallic bar was placed on the ground, perpendicular to the UAV flight path, as depicted in Fig. 8 (a). Several forward and backward flights following a straight path have been done, keeping a flight altitude of approximately 75 cm above ground (not too low to avoid turbulence due to the ground effect).

First, point-to-point backpropagation results are depicted in Fig. 8 (b), where it can be observed that the air-ground interface is fairly noticeable: again, the roughness of the ground and the grass create non-specular reflections. The metallic bar is clearly visible as it exhibits higher reflectivity than the ground, apart from the fact that the flat face of the metallic bar is parallel to the UAV flight path. The width of the metallic bar observed in Fig. 8 (b) clearly exceeds the true 6 cm width. Next, SAR imaging is applied to process the measurements, combining them coherently according to the positioning subsystem. Results depicted in Fig. 8 (c) show that, when applying SAR imaging techniques, the detected metallic plate is narrower, in agreement with the true width of 6 cm, proving the feasibility of performing SAR imaging with the implemented airborne-based radar system.

Assuming that cumulative geo-refering uncertainty still allows coherent combination of measurements along $L_{raw} = 1$ m, then theoretical cross-range resolution (Eq. 5) for $R = 75$ cm is $\Delta l = 2.25$ cm. This cross-range resolution is significantly smaller than the projected beam of the helix antenna on the ground ($\theta_{helix} = 51$ cm), consistent with the imaging results of the bar.

Next, the airborne GPR system was tested for detecting buried objects. A 78 cm x 56 cm x 43 cm plastic box was fully filled with sand (with $\varepsilon_r = 2.5$, as it has a different composition than the sandy soil of Section IV-A). As digging is not allowed in the airfield, the sandbox was placed on the ground. During flight operation, UAV tries to maintain a constant height over the ground, taking into account the distance to the ground measured by the LIDAR altimeter. Preliminary tests of the UAV when flying over the sandbox revealed that the sharp height variation from the ground to top of the sandbox caused the UAV to overoscillate in height. From a practical point-of-view, there will not be scenarios with such a sharp variation, so a setup to produce a smooth profile was implemented. The proposed solution is shown in Fig. 9: the sandbox was covered with a plastic canvas which is transparent to microwaves, but it creates a smooth interface for the LIDAR altimeter, avoiding the UAV to overoscillate when flying over it.

The first in-flight test for buried objects detection was devoted to evaluate the capability of detecting the $R = 8$ cm metallic disc shown in Fig. 10 (a) buried at $d_{target} = 12$ cm
For this test, several UAV overflights over the sandbox covered with the canvas were conducted. Imaging results for one of these overflights are depicted in Fig. 10 (b)-(d). Radar image corresponding to point-to-point backpropagation is shown in Fig. 10 (b), noticing that the air-sandbox interface and the buried metallic disc cannot be clearly identified. Next, SAR imaging is applied, first considering \( \varepsilon_r = 1 \) and without removing the average value of the measurements (Fig. 10 (c)). The improvement with respect to point-to-point backpropagation can be observed, as both the air-sand interface and the buried metallic disc can be better detected. Further improvement can be achieved by removing the average value of the measurements, Fig. 10 (d). Due to the slower propagation speed of the radio waves in the sand, the echo of the metallic disc appears at \( d_{echo} = 20 \text{ cm} \). When the sand permittivity (\( \varepsilon_r = 2.5 \)) is considered for underground SAR imaging (Fig. 10 (e)), the metallic disc is imaged at the correct depth (12 cm).

Underground SAR imaging improvement over point-to-point backpropagation results is more noticeable in this example (Fig. 10) than in Section IV-A (Fig. 7). The reasons are: i) in Section IV-A, the radar was moved manually in the horizontal plane, keeping constant the height. Thus, positioning and geo-referencing uncertainty are smaller than UAV-based measurements. ii) A sandbox is used for in-flight tests, that is, a finite domain. The fact of using a finite domain introduces reflections and echoes that eventually degrade the quality of the point-to-point backpropagation results in the case of complex geometry scenarios.

SAR imaging also provides a substantial improvement over metal detector-based techniques [27], as non-metallic objects can be detected as well. To prove this feature, a plastic (foam) disk having the same radius as the metallic one, Fig. 11 (a), has been buried 10 cm deep. SAR image from coherent combination of the geo-referred GPR measurements collected during an overflight, considering \( \varepsilon_r = 1 \) for underground SAR imaging, are depicted in Fig. 11 (b). In this case, not only the air-sandbox interface and the plastic disk are imaged, but also the reflection created by the sandbox-ground interface is visible. Introducing sandbox thickness \( h_{target} = 43 \text{ cm} \) and the location of the echo \( d_{echo} = 65 \text{ cm} \) in Eq. 6, sand permittivity is estimated as \( \varepsilon_r = 2.6 \), similar to the value estimated at the laboratory (\( \varepsilon_r = 2.5 \)).

A synthetic aperture of \( L_{Sy} = 70 \text{ cm} \) was considered in Fig. 11 (b). Flight height above the sandbox was around \( R = 50 \text{ cm} \), yielding \( \Delta l = 2.6 \text{ cm} \) cross-range resolution.
The impact of considering a larger synthetic aperture centered over the sandbox is shown in Fig. 11 (c), for \( L_{ap} = 230 \) cm. Although for this case theoretical cross-range resolution is \( \Delta l = 0.8 \) cm, in practice, cumulative geo-referring errors distort the SAR image, introducing some ripple and worsening cross-range resolution which is within the range of \( \Delta l = 2 - 2.5 \) cm. Note that PVC bars of the canvas frame are visible in the larger SAR imaging domain shown in Fig. 11 (c). The air-ground interface is also noticeable, as well as the sandbox-ground interface, delayed with respect to the true position as \( \varepsilon_r = 1 \) is considered in this case for SAR imaging.

In order to verify repeatability and reproducibility, SAR imaging result corresponding to measurements taken in another overflight over the sandbox is shown in Fig. 11 (d). The main features observed in Fig. 11 (b) are present, thus confirming that even manual flight operation mode is capable of providing highly-accurate SAR images along the vertical plane containing the flight path.

When the estimated permittivity of the sand (\( \varepsilon_r = 2.5 \)) is introduced in the underground SAR imaging algorithm, Fig. 11 (e), the plastic object and the sandbox-ground interface are imaged at the correct depth (10 cm and 43 cm respectively).

Last result presented in this contribution is devoted to prove the capability of the airborne-based GPR to detect two buried objects. For this experiment, a cylindrical metallic bar (of 2.5 cm radius) was buried 12 cm deep in one side of the sandbox (perpendicular to the UAV flight path), and a plastic box (with 8.5 cm \( \times \) 6.5 cm cross-section) was buried 9 cm deep in the other side of the sandbox. These two targets were 20 cm away in the horizontal plane. Imaging results are depicted in Fig. 12. In this case, point-to-point backpropagation results, Fig. 12 (a), allows identifying the air-sandbox interface and the two buried objects, although the echoes appear far from the correct position. The sandbox-ground interface is barely noticed. Resolution is improved when SAR imaging is applied, Fig. 12 (b)-(c), where the two targets and the sandbox-ground interface are clearly distinguishable. SAR imaging results considering \( \varepsilon_r = 1 \) and \( \varepsilon_r = 2.5 \) are depicted in Fig. 12 (b) and Fig. 12 (c) respectively.

V. CONCLUSIONS

A UAV-based underground SAR imaging system for the detection of buried objects has been presented. It aims primarily at detecting explosives such as antipersonnel landmines, but it can also be used for any other application where detection and identification of hidden objects is necessary. Results presented in this contribution have proved: i) that the radar range and cross-range resolution are \( \Delta R = 7.5 \) cm and \( \Delta l = 2 - 2.5 \) cm, respectively, ii) the capability of detecting buried nonmetallic objects, and iii) the repeatability and reproducibility of the measurements for SAR imaging. A 3 min video summarizing the features of the system (operating principle and description of the architecture) and a brief application example, can be watched at https://youtu.be/gsKptOPVARI.

The prototype and developed algorithms could be of interest in sectors where the detection of buried objects is essential, as the aforementioned detection of landmines, pipeline inspection, or archaeology work. The system can also be used in the detection of infrastructure defects, walls, roofs.
and road inspection. The added value, when compared with similar systems for non-destructive testing, comes from the fact that the GPR is mounted on a UAV which prevents physical contact with the ground during scanning. With respect to similar airborne GPR prototypes, this system is capable of creating SAR images with a few cm resolution, enabling detection of small metallic and dielectric objects buried in the ground. The system has been licensed under the patent [49].

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REFERENCES


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Improvement of GPR SAR-based techniques for accurate detection and imaging of buried objects

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Abstract—This contribution introduces three methodologies to improve Synthetic Aperture Radar (SAR)-based techniques used in Ground Penetrating Radar (GPR) systems. They consist of: i) equalization of the frequency response of the transmitting (Tx) and receiving (Rx) antennas, ii) processing of SAR images using partially overlapped frequency sub-bands, and iii) imaging domain clustering. The goal is to combine ground penetration capabilities of lower frequency bands with the resolution achieved when increasing the overall frequency band, resulting in enhanced detection and imaging capabilities. Validation of these techniques has been done at three levels: first using simulations, next by means of measurements in a controlled scenario and, finally, using a portable setup deployed in a realistic scenario.

Index Terms—Ground Penetrating Radar (GPR), subsurface sensing and imaging, Synthetic Aperture Radar (SAR).

I. INTRODUCTION

G round Penetrating Radar (GPR) is a non-invasive technique for subsurface sensing and imaging applications, which is based on the transmission and reception of electromagnetic waves using a radar system [1]. Transmitted radar waves are reflected on the interfaces between two media with different constitutive parameters (namely conductivity and permittivity). GPR exhibits several advantages over other Non-Destructive Testing (NDT) techniques (such as metal detectors, thermal cameras, or ultrasounds) for the detection of buried targets. Among others, it can be cited: i) capability of detecting both metallic and non-metallic objects, ii) possibility of obtaining high-resolution images of the ground and the buried targets, and iii) use of a mature, low-cost technology.

GPR has been extensively applied in several fields, such as inspection of civil infrastructure (e.g. bridges) [2], [3], location of underground tunnels [4], and landmine detection [5], [6]. In the latter, a novel technology based on an airborne GPR-Synthetic Aperture Radar (SAR) system has been developed, thanks to the advances in accurate positioning and geo-referencing sensors (such as Real Time Kinematics, RTK, and laser rangefinders) [7], [8], [9].

GPR image resolution depends on: i) the frequency bandwidth ($\Delta fW$), which determines range or depth resolution $\Delta R = v_{prop}/(2\Delta fW)$, being $v_{prop}$ the speed of light in a particular medium, and ii) the GPR antenna beamwidth, which is related to cross-range or lateral resolution. The latter can be improved by means of SAR techniques [10], based on the coherent combination of a set of measurements taken along a certain path (as done, for example, in airborne-based SAR systems [7], [8], [9], [11]). These measurements have to be accurately geo-referred so that the phase error due to position uncertainty does not distort the resulting image [8]. Although GPR-SAR-based techniques are not capable of recovering both the profile and constitutive parameters as accurately as inverse scattering techniques [12], [13], the former have much less computational complexity and are more robust against measurement uncertainties.

GPR-SAR images can also be improved (e.g. reducing false echoes and artifacts, improving the focusing) by taking into account the difference wave velocity in the air and in the ground. This requires the knowledge of the ground constitutive parameters [14]. In this sense, several GPR-SAR techniques have been developed for microwave imaging of the ground and the objects buried in it. Among them, it can be cited: 1) Delay-And-Sum (DAS): based on ray-tracing, it is one of the most extended techniques due to its ease of implementation [15]. 2) Phase Shift Migration (PSM): also known as $\omega$-k migration. It is based on the simplification of the electromagnetic wave equation, taking into account the constitutive parameters of the ground [16], [17]. 3) Piecewise Synthetic Aperture Radar (P-SAR): a modified version of PSM that takes into account the reflection and transmission coefficients of electromagnetic waves when passing through the different layers of the ground [18]. 4) Wiener filter-based GPR-SAR: this technique is based on Green functions for layered media [18], [19].

Several methodologies have been developed to enhance the quality of GPR images. For example, those ones conceived to mitigate the clutter due to the air-ground reflection, such as Singular Value Decomposition (SVD)-based projection methods [20], [21], time-gating [22], and average subtraction [21], [22].

A. Aim and scope

Novel GPR systems such as the one described in [8] require more robust GPR-SAR processing techniques capable
of providing high resolution images while keeping computational cost low. The use of cheap, off-the-shelf radiofrequency hardware allows reducing the overall cost of the GPR system, but at the expense of worsening the performance with respect to the use of GPR-specific hardware. For example, Ultra Wideband (UWB) antenna parameters such as directivity or return losses may vary significantly within the working frequency band, thus requiring these parameters to be taken into account in GPR-SAR processing techniques. Besides, UWB GPR systems allow increasing resolution and hence the capability of detecting smaller targets. However, constitutive parameters have a strong dependence with frequency, resulting in worse penetration as frequency increases. Efficient post-processing techniques for UWB GPR systems that make use of a proper characterization of the frequency response of the implemented GPR system have not been extensively developed in the current state-of-the-art of GPR techniques.

Aiming to improve the resolution of GPR-SAR images, to reduce clutter and artifacts, and to speed-up processing time, this contribution introduces three novel GPR-SAR processing techniques:

1) **Equalization of the frequency response of the Tx and Rx antennas**, so that the contributions of the scattered field at different frequencies have similar weight in the GPR-SAR image.

2) **GPR-SAR image processing in sub-bands**. The goal is to take advantage of lower frequency bands, which exhibit better penetration capabilities, and upper frequency bands, where resolution is better because of the larger electric size of the synthetic aperture.

3) **Imaging domain partitioning**, in order to take into account the respective antenna beamwidth at different working frequencies. The idea is to backpropagate, for each frequency, the scattered field to those clusters within the antenna beamwidth, thus minimizing reflections from non-desired contributions and speeding up the processing.

These techniques have been proposed to improve the airborne-based GPR-SAR system described in [8], where detection of non-metallic targets (e.g. Improvised Explosive Devices, IEDs, mainly composed by dielectric materials) is one of the target applications of the system. Nevertheless, these techniques are perfectly suitable for any GPR-SAR system.

The paper is structured as follows: Section II presents an overview of GPR-SAR-based techniques, focusing on DAS and PSM. The three methodologies introduced to improve GPR-SAR are explained in Section III. Validation by means of simulations and measurements (in laboratory and in a realistic scenario) is described in Section IV. Finally, conclusions are drawn in Section V.

## II. GPR-SAR Techniques

As mentioned before, taking into account the constitutive parameters of the soil in GPR-SAR processing techniques improves range resolution and helps to reduce the clutter. Thus, the techniques described in this Section are expressed in their multilayer form. If the soil permittivity cannot be estimated, it can be assumed a homogeneous medium (e.g. free-space propagation with $\varepsilon_r = 1$).

![Image](image-url)

**Fig. 1. General scheme of a multilayer evaluation for GPR-SAR techniques.**

In addition to these GPR-SAR techniques, several preprocessing methods mentioned in Section I can also be applied in order to reduce echoes coming from the impedance mismatching between the air and the ground. Average subtraction [22] can be used as long as the set-up measurement conditions are favorable for its implementation.

### A. Delay-And-Sum (DAS)

The basic principle of DAS GPR-SAR imaging is the coherent combination of the backpropagated scattered field collected on $M$ acquisition points at $N$ frequencies, $B_{\text{coast}}(r_{mn}, f_{\nu})$. Assuming a monostatic or quasi-monostatic configuration (i.e. Tx and Rx placed practically at the same position), the reflectivity at a single point $\rho_q(r^*)$ in the Q layer (Fig. 1) can be calculated as follows (Eq. 1):

$$\rho_q(r^*) = \sum_{m=1}^{M} \sum_{n=1}^{N} B_{\text{coast}}(r_{mn}, f_{\nu}) \prod_{\nu=1}^{q} e^{j2\pi q\phi_{\nu}}$$  \hspace{1cm} (1)$$

where $r_{mn}$ is the position of the $n$-th acquisition point, $f_{\nu}$ is the $n$-th frequency and $\phi_{\nu}$ are the phase-shifts due to the wave propagation in the p-th layer, as depicted in Fig. 1. These terms are defined in Eq. 2:

$$\phi_{\nu} = k_{p,\nu} \cdot \| r_{p} - r_{p-1} \|_2$$  \hspace{1cm} (2)$$

where $k_{p,\nu}$ is the wavenumber in the $p$-th layer for the $n$-th frequency, $r_p$ (for $p = 1, \ldots, q - 1$) is the refraction point at the $p$-th layer and $r^*$ is one of the points where the reflectivity is calculated (at layer Q), as indicated in Fig. 1. The refraction point can be derived from Snell’s law solving a 4th order equation. However, in order to reduce complexity and computational time, it is estimated using the approximation method proposed in [15].

This approximation method is expressed in Eq. 3 for a two-layer scenario as depicted in Fig. 2 (a), where $d_p$ are distances in x-axis referred to the antenna position (e.g. $d_1$ is the distance from the interface between $\varepsilon_{r1} - \varepsilon_{r2}$ to the
antenna). As DAS algorithm has been defined in its multilayer form, the refraction point at each layer is calculated by an extension of the approximation method given in [15]. This extension consists of solving the equation system derived from the previous two layer definition. A scheme of the refraction points of a typical three layer scenario is shown in Fig. 2 (b). After solving the equation system, refraction points for the three-layer scenario are given by Eq. 4, where \( \tilde{r}_p = r_p - \tilde{r}_0 = (\tilde{x}_p, \tilde{y}_p, \tilde{z}_p) = (x_p - x_0, y_p - y_0, z_p) \) and \( \Delta \lambda_{1,2}, \Delta \lambda_{2,3} \) are given by Eq. 5.

\[
\begin{align*}
\tilde{r}_1 &= r_{1,1} + \frac{2 \pi \lambda_{1,1}}{2 \pi \delta_c} (r_{1,1} - r_{2,1}) \\
\tilde{r}_2 &= r_{2,1} + \frac{2 \pi \lambda_{2,1}}{2 \pi \delta_c} (r_{2,1} - r_{2,2}) \\
\Delta \lambda_{1,2} &= 1 + \sqrt{\frac{2 \pi \delta_c}{2 \pi \delta_c} (d_1 + d_2)} \\
\Delta \lambda_{2,3} &= 1 + \sqrt{\frac{2 \pi \delta_c}{2 \pi \delta_c} (d_2 - d_3)}
\end{align*}
\]

**B. Phase Shift Migration algorithm (PSM)**

PSM algorithm also combines coherently the backpropagated scattered field. However, unlike DAS algorithm, it is based on the wave equation and the Exploding Reflector Model (ERM) from the seismic field [23]. In particular, it assumes that the medium is practically homogeneous along \( XY \) plane and the EM waves are generated by each point in the investigation domain rather than by the antennas. Therefore, the propagation velocity is assumed to be half its true value. In order to speed up calculations, the backpropagated scattered field is calculated in the \( f-k \) domain. Hence the reflectivity at a single \( XY \) plane (denoted as \( z' \) plane) in the \( Q \) layer \( \rho(z') \) is calculated as follows (Eq. 6):

\[
\rho(z') = \sum_{n=1}^{N} \sum_{p=1}^{P} r_{p} z' \left[ E_{\text{refl}}(k_x, k_y, f_n) \right] e^{j(k_x x + k_y y) + (z' - z_n - \Delta \lambda_{2,3})} \]

where \( d_s \) is the z-distance from the interface between layers \( p \) and \( p + 1 \) to the antennas (see Fig. 1). \( k_x, k_y \) are the wavenumber components in \( x \) and \( y \) directions, \( k_{p,n} \) is the wavenumber in \( z \) direction at the \( p \)-th layer and \( n \)-th frequency, and \( F_{\text{refl}}(\cdot) \) is the Fourier Transform in the \( x-y \) domain. The \( \Delta \lambda_{2,3} \) term is defined in Eq. 7 as:

\[
\Delta \lambda_{2,3} = \sqrt{(2 \pi \delta_c)^2 - k_x^2 - k_y^2}
\]

where \( \delta_c \) is half of the propagation velocity in the \( p \)-th layer.

As mentioned before, if the soil permittivity cannot be estimated, a homogeneous propagation velocity \( \delta_c = c/2 \) will be assumed.

**III. IMPROVEMENTS TO SAR TECHNIQUES**

With the purpose of obtaining high resolution GPR-SAR based images, an ultra wide frequency band from 0.1 to 6.5 GHz has been considered. The reason of this choice is because it is the same as the working frequency band of the radar used for experimental validation [24]. However, taking advantage of the entire frequency bandwidth (using the two aforementioned GPR SAR processing techniques) becomes challenging because the propagation losses and the direction of the transmitting and receiving antennas vary significantly with frequency. Thus, as mentioned in Section I, several methods are proposed in order to overcome these limitations.

**A. Equalization of the frequency response**

Two UWB Vivaldi antennas [25] have been selected for the implementation of the GPR-SAR system. These antennas exhibit a \( S_{11} \) parameter below -10 dB from 0.6 to 6 GHz. However, as observed in Fig. 3, their directivity fluctuates more than 7 dB along the working frequency band.

Fig. 4 shows the frequency response of the GPR system for a scenario where the antennas are 1 m above ground (normal incidence/reflection). Amplitude levels in the working frequency band exhibit a variation greater than 15 dB in addition to small multipath fluctuations. Consequently, SAR images are affected by these differences causing lowering frequencies to be dominant over higher ones, thus reducing the effective bandwidth and, in consequence, the resolution. Hence, the equalization of the frequency response, which consists of normalizing the SAR image for each discrete frequency, is proposed to take advantage of the entire frequency band.

Equalization of the frequency response is done as follows: for each \( n \)-th frequency of the working frequency band, the reflectivity image is calculated and saved. For example, for the DAS algorithm, Eq. 1 is recast as follows (Eq. 8):

\[
\rho(z', n) = \sum_{n=1}^{N} E_{\text{refl}}(r_{m}, f_n) \sum_{p=1}^{P} e^{j(2\pi f_n + (z' - z_n - \Delta \lambda_{2,3}))}
\]

Then, each \( n \)-th reflectivity image is normalized with respect to the maximum of its absolute value. This operation mitigates the influence of the frequency response of the Tx and Rx antennas (Eq. 9):
This technique uses the radiation patterns of Yagi antennas to increase signal-to-noise ratio and reduce calculation time. It consists of dividing the imaging domain into several angular sectors (as depicted in Fig. 5, a plan view of the reconstruction domain is defined in the $x$-$y$ plane, and the number of cells is $N_0 = a = b = c = d = 10$). The range bins $C_{ij}$ are defined as:

$$C_{ij} = \frac{a_i \cos(\theta_j)}{v}$$

The proposed solution is the one that maximizes the performance of the system. The parameters $a$, $b$, and $c$ are the dimensions of the antenna, and the parameters $\theta$ and $\phi$ are the angles between the propagation direction and the ground, respectively. The sampling rate is given by the formula:

$$\text{Sampling rate} = \frac{\text{frequency range}}{\text{range resolution}}$$

The SNR is then calculated as:

$$\text{SNR} = \frac{P_s}{P_n}$$

where $P_s$ is the signal power and $P_n$ is the noise power. The overall performance was evaluated by comparing the measurement results with the theoretical predictions.
performed at $z = 0$ cm and $x \in (-24, 24)$ cm with a step-size of 2 cm (about $\lambda/2$).

1) Analysis of GPR-SAR methods: The first part of this subsection is devoted to analyze the performance of the GPR-SAR methods (without improvements) and to show the influence of taking into account the soil constitutive parameters on the SAR images.

For these simulations, Hertzian dipoles arranged in a quasi-monostatic configuration are used as transmitter and receiver antennas. The first derivative of a gaussian pulse has been selected as transmitted signal with a center frequency of 3 GHz and a bandwidth of approximately 3.5 GHz.

The first analyzed scenario (Scenario A) is depicted in Fig. 7. This is a favorable scenario for detecting buried objects due to the low conductivity (and thus low losses) of dry sand. Scenario A results are presented in Fig. 8. In order to interpret the different images, the differences between monolayer and multilayer processing techniques must be remarked. Monolayer techniques do not take into account the permittivity of the ground (assuming the whole scenario is a unique homogeneous medium, in particular with $\varepsilon_r = 1$), whereas multilayer techniques consider different permittivities at each layer. Hence, both objects are displaced downwards and distorted after using the former techniques (Fig. 8 (a),(b)) whereas the objects appear at their actual depths using the latter ones (Fig. 8 (c),(d)). Furthermore, multilayer techniques have been complemented by the average subtraction method in order to remove reflections from the dry sand interface, as shown in Fig. 8 (c),(d). It can be noticed that the plastic object can be imaged with enough resolution to distinguish top and bottom sides. As expected, the metallic objects exhibits higher reflectivity than the plastic one.

Concerning PSM and DAS imaging techniques, it can be concluded that there are no remarkable differences in the SAR images, although PSM is about 30 to 50 times faster than DAS, thanks to the use of the FFTs (Fast Fourier Transforms).

In the second simulated scenario (Scenario B, see Fig. 9), the soil is composed by two layers of sand with different moisture levels. It must be noticed that the wetter the soil is, the greater the permittivity and conductivity are, thus being more difficult to detect buried targets. In this case, average subtraction method has not been applied in order to show that the air - dry sand and the dry sand - wet sand interfaces can be
clearly distinguished. Since both metallic objects have enough contrast with the surrounding medium, not using average subtraction does not affect their detection. As in scenario A, both the position and shape of the buried targets can be recovered (Fig. 10). Again, PSM and DAS imaging results are practically the same.

2) Preliminary analysis of improvements: The second part of this subsection is devoted to assess the effect of the proposed GPR-SAR improvements. As aforementioned, it must be noticed that these improvements are mainly needed due to frequency dependent behaviour of both the antennas and the soil.

In order to analyze the effect of the equalization of the frequency response, instead of ideal dipole antennas a pair of real bow-tie antennas (with central frequency of 1.5 GHz) have been used as Tx and Rx. The resulting SAR images obtained for DAS algorithm are shown in Fig. 11 with and without equalization (taken into account frequencies between 1 and 5 GHz). In general, an improvement in the range resolution can be noticed for both scenarios. In scenario A, the plastic object top interface is also better focused using equalization. In scenario B, the dry sand - wet sand interface is clearly distinguishable with equalization. However, if equalization is not applied, this interface and the cylindric object are more blurred. For this scenario, the maximum of the SAR images retrieved for each individual frequency is shown in Fig. 12. It can be noticed that the maximum decays with frequency. Thus, higher frequencies are masked by lower ones, and the effective range resolution is smaller than the theoretical one, as observed in Fig. 11 (c). Once the equalization of the frequency response is applied, range resolution increases (Fig. 11 (d)). Quantitatively, the range resolution obtained with and without equalization can be compared. This range resolution has been estimated calculating the 3-dB range-width of the air - soil interface, which is 3.9 cm without equalization and 2.7 cm with equalization. Nevertheless, the improvement is more clearly observed comparing the reflectivity images qualitatively.

As explained before, the propagation of EM waves, the
constitutive parameters of the materials and the behaviour of the antennas and RF equipment are frequency dependent. Therefore, some targets can be better detected considering only some frequencies (a sub-band) instead of the whole frequency band. To illustrate this effect, the scenario shown in Fig. 13 has been simulated considering a more realistic soil (Puerto Rico clay loams) with different levels of moisture. As at the beginning of this subsection, Hertzian dipole antennas have been used, transmitting the first derivative of a gaussian pulse centered at 3 GHz. This soil has been modeled using a two-term Debye model [28] so as to take into account its frequency-dependent behaviour. The relative permittivity at \( f = \infty \) (\( \varepsilon_{\infty} \)) and the static electric conductivity (\( \sigma_s \)) are shown in Fig. 13, and the parameters for the Debye poles are given in Table 1 of [28].

Three different frequency bands have been considered: 1 – 6 GHz (corresponding to approximately the whole useful bandwidth), 1 – 3 GHz and 4 – 6 GHz. The reflectivity images considering a 5% moisture are shown in Fig. 14. The targets exhibits higher reflectivity when considering the low frequency sub-band. In this simulation, it is clear that there is a buried target at around 54 cm. However, in real measurements some targets might be almost indistinguishable from the clutter (especially, when the soil is heterogeneous and lossy). In these cases, selecting a sub-band could help to decide whether there is a target or not.

In order to quantitatively assess the effect of selecting a sub-band, the difference between the reflectivity of the air - soil interface and of the target is given in Table I. As the soil losses increase, this difference also increases (being more difficult to detect the target). In this example, it must be noticed that this difference is greater when considering the high frequency sub-band, and smaller for the low one. Thus, the target can be better distinguished using the lower frequencies (at the expense of worse resolution because of using smaller bandwidth).

Regarding the use of image domain partitioning, the beamwidth of the antennas that are available in the simulation software is around 90°, so the antennas illuminate almost the whole imaging domain. In addition, the antenna patterns at each single frequency cannot be obtained (a measure of the total energy is given instead). Therefore, image domain partitioning cannot be applied to the simulations. The result of this technique will be shown in the measurements. It must be remarked that the benefits of all these improvements are more evident when processing the measurements, mainly due to the stronger frequency dependent behaviour of both the equipment and the inspected soil, as well as the soil heterogeneity.

### Table I

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>1.5 GHz</th>
<th>1.3 GHz</th>
<th>4.6 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>2.5%</td>
<td>-0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>5%</td>
<td>9.2</td>
<td>7.9</td>
<td>11.9</td>
</tr>
<tr>
<td>10%</td>
<td>33.4</td>
<td>11.6</td>
<td>15.7</td>
</tr>
</tbody>
</table>

### B. Measurement in a controlled environment

The proposed techniques have been validated using a XYZ measurement range [29], which has been modified to enable quasi-monostatic measurements. A NS244A PNA-X Vector Network Analyzer (VNA) [30] calibrated from 0.4 GHz to 7 GHz has been used together with the two Vivaldi antennas previously described [25] to measure the transmission coefficient \( S_{21} \). The \( S_{21} \) parameter is directly proportional to the scattered field, so DAS and PSM algorithms can be applied exactly as if the scattered field were acquired. The VNA has been calibrated at the edges of the coaxial cables connecting the VNA ports and the Vivaldi antennas,
III

Fig. 15. Picture of the $XYZ$ measurement range [29] configured for quasi-monostatic GPR measurements.

Fig. 16. Measurement scenario consisting of two buried objects (metallic and plastic) buried in a plastic box filled with dry sand.

Fig. 17. Reflectivity images, $YZ$ plane at $z = 3$ cm and $XZ$ plane at $y = 16$ cm of the scenario depicted in Fig. 16. (a)-(b) PSM multilayer, (c)-(d) DAS multilayer.

so the effects of the cables and connectors are removed from the measurements. The $XYZ$ measurement range is covered with APMY pyramidal absorber [31], which provides $-15$ dB reflectivity at 1 GHz, and $-29$ dB reflectivity at 4 GHz.

A rectangular acquisition grid of size $x = 70$ cm, $y = 80$ cm sampled every $\delta x = \delta y = 2$ cm (resulting in 1476 measurement points) and placed at $z = 120$ cm above the floor of the $XYZ$ measurement facility, has been considered. For this setup, measurement time is around 50 minutes. A scheme of the measurement setup is shown in Fig. 15.

The first measurement scenario is depicted in Fig. 16. It is composed by a rectangular plastic box filled with dry sand ($\epsilon_r = 2.5$) and two objects (metallic and plastic disks) buried at different depths. The absorbing material under the plastic box had to be removed, so the plastic box was placed on the metallic floor of the $XYZ$ measurement range.

DAS and PSM multilayer results, considering dry sand permittivity, are plotted in Fig. 17 without applying any of the improvements described in Section III. The following reflections can be identified in the reflectivity images: the air-sand interface ($z = 0.98$ m), the plastic disk ($z = 1.06$ m), the metallic disk ($z = 1.10$ m), and the sand-metallic floor interface $z = 1.30$ m. Besides, multiple reflections occur due to the finite size of the plastic box filled with sand, the air-sand impedance mismatching and the high reflectivity of the metallic floor, which result in the echo appearing at $z = 1.44$ m.

Amplitude differences between low and high frequency bands have different impact in PSM and DAS. In particular, less clutter is observed in PSM images. Regarding SAR image resolution (i.e. visualization of the interfaces between different media and reconstruction of the buried objects profile), both techniques perform similarly.

Some improvements are introduced in order to mitigate the clutter presence in DAS algorithm, which can be applied to PSM algorithm as well. First, sub-band processing is tested. Taking into account frequency dependence of propagation losses and directivity of the selected antennas [25], as discussed in Section III, it can be expected that lower sub-bands present more penetration capabilities, whereas higher sub-bands exhibit better resolution. These hypotheses are consistent with the results shown in Fig. 18: (a)-(b) correspond to the low frequency sub-band (1-3 GHz), and (c)-(d) to the high frequency sub-band (4-6 GHz).

It can be noticed that lower frequency sub-band results (Fig. 18 (a)-(b)) are similar to those obtained considering the entire band (Fig. 17 (c)-(d)). This is due to the fact that, as discussed in Section III, the frequency response of the GPR system at lower frequencies is higher, thus masking the response at higher frequencies. For this reason, the improvement consisting of the equalization of the frequency response is applied, resulting in greater range resolution and less clutter, as observed in Fig. 18 (e)-(f).

In a second scenario, five 10 cm thick blocks of concrete
 introduced together with the equalization of the frequency response. For this example, cell size is 2 cm, the same as the sampling rate of the acquisition domain grid. As explained in Section III, the number of cells is chosen as a function on the antenna beamwidth. Analysing Fig.5 it can be observed that the antenna beamwidth for frequencies below 2 GHz is greater than 50 degrees. That means that, for \( f = 2 \) GHz and at \( h = 1 \) m from the antenna (where the air - sand interface is located) the number of cells to be considered is (Eq. 10) \( C_{x,n} = 31 \) and \( C_{y,n} = 45 \), i.e. an area of 62 cm \( \times \) 90 cm. As a result, at low frequencies the whole area of the plastic box is fully illuminated by the beam of the antennas when these are centered over it.

Results for DAS algorithm are depicted in Fig. 21: (a)-(b) correspond to the equalization of frequency response, and (c)-(d) to both equalization and imaging domain partitioning. It can be observed that results are not improved significantly when introducing imaging domain partitioning, due to the use of antennas with broad beam at low frequencies together with the finite size of the scenario, which is fully covered by the beam for central positions of the scanning grid. Nevertheless, imaging domain partitioning reduces the calculation time as the backpropagated scattered field has to be evaluated in less points of the imaging domain (i.e. those corresponding to the selected cells for each frequency). For this example, calculation time is reduced around 25 %.

In this example it can be noticed that equalization of the frequency response to increase range resolution results in worse penetration capabilities. If Fig. 20 and Fig. 21 are compared, the metallic disk buried in sand is better detected in Fig 20 (for both DAS and PSM), where equalization of the frequency response was not applied. Low frequencies, capable of penetrating better in the concrete layer, contribute more to the radar image than high frequencies.

C. Measurement in a realistic scenario

Finally, the proposed techniques have been validated in an outdoor scenario. A portable setup has been deployed in a beach (coordinates 43.545, -5.694) close to the laboratory of the research group. A radar module [24] working from 100 MHz to 6.5 GHz connected to a Raspberry Pi controller and the previous Vivaldi antennas [25] (as transmitter and receiver antennas) have been used. Measurements have been done by
 manually sweeping the Vivaldi antennas every 2 cm along a 120 cm slider made of plastic pipes, and placed 140 cm above the ground, as depicted in Fig. 22. GPR measurements were sent to a laptop using a Wi-Fi connection, for later processing.

Concerning protection against electromagnetic interference that might occur in realistic scenarios, it must be remarked that the power transmitted by the radar module (-10 dBm) is expected to be higher than the level of potential interfering signals (such as those coming from broadcasting and mobile communications networks, for example). Moreover, the proposed GPR is an ultrawideband system (ranging from less than 1 GHz to up to 6 GHz). Thus, even high power narrowband signals will have little impact in the measured response of the radar, as it is integrated over the full bandwidth. Actually, robustness against narrowband interference is one of the main advantages of ultrawideband communications systems. Finally, it must be remarked that the Tx and Rx antennas are pointing towards the ground (downward-looking configuration) which reduces even more the possibility of capturing an interfering signal.

The sand of the beach was compacted by sea moisture, so it would be altered every time a hole is dug to bury an object. For this reason, a homogeneous volume of sand was created for the experiments by turning over the sand up to a depth of 25 cm. Next, two objects were buried in this homogeneous layer of sand: an empty plastic container and a metallic disk (Fig. 23 (b)). Imaging results for multilayer processing are shown in Fig. 24, considering $\varepsilon_r = 3$ for the sand of the beach. White dashed lines represent the cross-section of the limits of the ditch filled with sand, whereas black dotted lines indicate the placement and size of the buried targets.

Taking into account that i) the antennas were manually moved and ii) the air-sand interface is not perfectly flat, higher
levels of noise and clutter than in previous examples are expected. DAS results with no improvements are depicted in Fig. 24 (a),(d). Although stronger reflections at expected. DAS results with no improvements are depicted in levels of noise and clutter than in previous examples are expected. DAS results with no improvements are depicted in Fig. 24 (a),(d). Although stronger reflections at z = 56 cm and z = 64 cm can be observed in Fig. 24 (d), it is not possible to clearly distinguish the buried objects.

Next, equalization of the frequency response has been applied in Fig. 24 (b),(e). In the case of Fig. 24 (e), the reflection on the buried metallic disk can be clearly identified, but not the plastic container because its reflectivity is similar to the clutter level.

Finally, GPR-SAR processing, considering both equalization of the frequency response and imaging domain partitioning, is applied. In this case, h = 140 cm, so the number of cells to be considered in the XZ plane for f = 2 GHz is (Eq. 10) C x,n = 63. In other words, the antenna beam illuminates ± 63 cm along the x axis with respect to the position of the antennas.

Imaging results are depicted in Fig. 24 (c),(f), where the reduction of clutter can be noticed. In this case, both metallic and plastic objects can be distinguished from the remaining clutter. Furthermore, the reflection on the interface between the homogeneous sand in the ditch and the compact wet sand can be noticed at z = 67 cm in Fig. 24 (c) and partially in Fig. 24 (f) under the plastic object.

V. CONCLUSION

Three methodologies have been proposed for improving UWB GPR-SAR-based techniques, especially for those measurement setups where parameters such as frequency response and antenna directivity have a strong variation with frequency. It has been proved that the first one, equalization of the frequency response, allows increasing range resolution as the same weight is assigned to low and high frequencies contributing to the SAR image, but at the expense of worsening ground penetration. The second method, sub-band processing, takes advantage of the properties of each frequency sub-band (better ground penetration or better resolution) but cannot create a single SAR image that combines the advantages of each sub-band. Finally, imaging domain partitioning takes into account antenna beamwidth to reduce the number of points of the imaging domain where the backpropagated field has to be computed, thus reducing both the clutter and the calculation time.

 Depending on the characteristics of the area to be surveyed and the specifications of the GPR system, these improvement techniques may be combined and applied in UWB GPR-SAR systems for an accurate detection of buried metallic and non-metallic targets. For example, in a controlled scenario such as the one presented in Section IV-B, even at lower frequency bands it is possible to achieve sufficient resolution to distinguish the buried targets (as shown in Fig. 20). The use of equalization technique improves range resolution, but at the expense of worsening the reflectivity of the buried targets (Fig. 21). However, in a realistic scenario as the one shown in Fig. 24, if improvement techniques are not applied, it is almost impossible to distinguish anything due to the higher level of clutter and noise. The improvement in the reflectivity image after the equalization of the frequency response (and imaging domain partitioning) clearly makes the use of these techniques necessary to have enough resolution to distinguish the objects in harsh environments.

VI. ACKNOWLEDGEMENT

The authors would like to thank Prof. Fernando López Gayarre from the Department of Construction and Manufacturing Engineering at University of Oviedo for supplying the concrete blocks used in the second measurement setup of Section IV-B.

REFERENCES

Fig. 24. Reflectivity multilayer images (XZ plane). First row corresponds to the scenario of Fig. 23 (a) and second row, to the scenario of Fig. 23 (b). (a), (d) No improvements. (b), (e) Equalization. (c), (f) Equalization and imaging domain partitioning.
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Bistatic Landmine and IED Detection Combining Vehicle and Drone Mounted GPR Sensors

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Abstract: This work proposes a novel Ground Penetrating Radar (GPR) system to detect landmines and Improvised Explosive Devices (IEDs). The system, which was numerically evaluated, is composed of a transmitter placed on a vehicle and looking forward and a receiver mounted on a drone and looking downwards. This combination offers both a good penetration and a high resolution, enabling the detection of non-metallic targets and mitigating the clutter at the air–soil interface. First, a fast ray tracing simulator was developed to find proper configurations of the system. Then, these configurations were validated using a full wave simulator, considering a flat and a rough surface. All simulations were post-processed using a fast and accurate Synthetic Aperture Radar (SAR) algorithm that takes into account the constitutive parameters of the soil. The SAR images for all configurations were compared, concluding that the proposed contribution greatly improves the target detection and the surface clutter reduction over conventional forward-looking GPR systems.

Keywords: landmine detection; Improvised Explosive Device (IED); Ground Penetrating Radar (GPR); drone; bistatic radar

1. Introduction

The non-invasive detection of hidden or buried objects has attracted an increasing interest due to its practical applicability in several fields such as civil engineering (structural and road inspection), security and defense (landmine detection), and archeology, among others [1]. These techniques are able to detect the concealed objects without physically interacting with them or the surrounding medium. Furthermore, they can even be used to image the inspected area. Electromagnetic induction, thermal imaging, nuclear quadrupole resonance or Ground Penetrating Radar (GPR) are some well-known examples of non-invasive techniques.

Among these techniques, GPR has been widely used for subsurface imaging applications [2]. It is based on transmitting an electromagnetic wave and detecting the scattered waves at the air–soil interface and from the buried targets, providing a radar image of the underground. One of its main advantages is that it can detect both metallic and dielectric targets. However, this technique is quite sensitive to the soil heterogeneity, the soil surface roughness and the possible low contrast between the soil and a non-metallic target [3]. As a result, it requires careful configuration and advanced signal processing techniques to overcome these issues and improve the detectability of the system.

GPR systems can be classified using different criteria. According to the distance between the antennas and the soil, they can be classified as ground-coupled or air-launched systems. The former usually allow a better penetration into the soil and are less affected by the reflections at the air–soil interface.
interface (provided the antennas are well-matched to the soil impedance). However, they need to be in contact with the soil, which also slows down the scanning speed and should be avoided when searching for dangerous targets such as landmines and Improvised Explosive Devices (IEDs). The latter avoid the interaction with the soil, but the strong obscuring clutter (due to impedance mismatch at the rough air–soil interface) greatly compromises the detection of buried targets. GPR systems can also be classified as Forward-Looking GPR (FLGPR) [4] and Down-Looking GPR (DLGPR) [5]. In vehicle mounted FLGPR systems, the antennas look ahead of a vehicle, with an angle of incidence that helps to maximize TM (Transverse Magnetic) waves penetration into the soil and/or to minimize reflections from the air–soil interface backscattered to the receiver. However, they have lower resolution (being difficult to distinguish whether the targets are over or under the surface) and sensitivity (since much of a flat-topped target’s reflections are in the forward opposite direction from the transmitter). Concerning DLGPR systems, the antennas are perpendicular to the soil surface, which yields higher resolution at the expense of stronger clutter.

In landmine detection, the scanning system must keep a safety distance from the inspected area in order to avoid the threat of explosion, which thus strongly favors FLGPR. To address this issue, a GPR system on board an Unmanned Aerial Vehicle (UAV) or a drone has been recently presented for subsurface imaging [6,7]. This system provides high resolution subsurface images since it allows the coherent combination of measurements using a Synthetic Aperture Radar (SAR) algorithm. However, the strong clutter at the air–soil interface clearly degrades the detection capabilities, especially when the contrast between the target and the soil is low. It must also be noticed that, although bistatic SAR systems have gained an increasing interest in the last years [8], most GPR systems (both DLGPR and FLGPR) adopt a monostatic or a quasi-monostatic configuration.

It would be desirable to combine the advantages of FLGPR and DLGPR systems in order to obtain both good penetration into the soil and high resolution. This article is devoted to analyzing this novel GPR configuration. As shown in Figure 1, a transmitter is placed on a vehicle with the antenna looking ahead and a receiver is placed on a UAV with the antenna pointing straight down to the soil surface. A fast ray-tracing method has been developed to find feasible configurations of the system. Then, the resulting configurations were accurately analyzed with a Finite-Difference Frequency-Domain (FDFD) method. These configurations as well as the multimonostatic configuration (corresponding to just a DLGPR system on board a moving UAV) were compared by post-processing the simulated scattered field with a SAR algorithm.

2. Methodology

2.1. Scenario

Ray-tracing and FDFD methods are used to simulate a 2D GPR scenario, such as the one shown in Figure 2, with a target buried in the soil. In this scenario, there are $T$ transmitters (TX) placed at positions $r_t$ ($t = 1, ..., T$) and, for each transmitter, there are $R$ receivers (RX) at positions $r_r$ (where
subindex $r = 1, \ldots, R$ denotes the receiver and superindex $t$ the transmitter). The soil is characterized by its relative permittivity $\varepsilon_r$ and its conductivity $\sigma$. The target is assumed to have a circular shape, with radius $\delta_t$ and centered at coordinates $(x_{tg}, y_{tg})$. It is characterized by its constitutive parameters $\varepsilon_{tg}$ and $\sigma_{tg}$. The simulation is performed at $N$ frequencies, assuming either TE (Transverse Electric) or TM (Transverse Magnetic) polarization.

![Figure 2. 2D GPR modeling scenario.](image)

### 2.2. Ray-Tracing

Ray-tracing (RT) is a geometrical optics method that models propagation by following straight rays [9]. Although it is less accurate than conventional full-wave methods, it requires a much lower computational effort. Thus, it is useful for fast modeling of large scenarios at several frequencies and for several transmitter and receiver positions.

#### 2.2.1. Field Computation

The contribution to the electric field of a ray impinging a given receiver in air is calculated according to Equation (1) or Equation (2), depending on whether the ray comes from the reflection at the soil interface or from the target. In these equations $E_{\text{inc}}$ is the incident field amplitude; $A_t$ and $A_r$ are used to take into account the transmitter and receiver antenna beamwidths; $G_{in}$ and $G_{out}$ are the in-plane and out-of-plane geometrical spreading factors [10]; $\Gamma$ and $\tau$ denote the reflection and transmission coefficients; $R_m$, $\alpha_m$ and $\beta_m$ are the total ray path-length and the attenuation and phase constants in medium $m$ (where $m = 0$ is air and $m = s$ is soil). The ray-tracing method implemented in this contribution calculates the path length in each medium ($R_m$), which is then multiplied by the propagation constants so as to perform a multifrequency simulation.

$$E_{\text{soil}} = E_{\text{inc}} \frac{A_t A_r}{G_{in} G_{out}} \Gamma_{\text{air-soil}} \exp(-j\beta_0 R_0 \delta_t)$$

$$E_{\text{target}} = E_{\text{inc}} \frac{A_t A_r}{G_{in} G_{out}} \tau_{\text{air-soil}} \Gamma_{\text{soil-target}} \tau_{\text{soil-air}} \exp(-\alpha_s R_s) \exp(-j(\beta_0 R_0 + \beta_s R_s))$$

For these ray-tracing simulations, each transmitter and receiver is characterized by its angle of incidence with respect to the soil ($\theta_{it}$ and $\theta_{ir}$, respectively) and by its 3-dB beamwidth. The terms $A_t$ and $A_r$ model the antenna assuming a $\cos^q$ pattern (where $q$ is calculated according to the antenna beamwidth).
Assuming a moderately lossy soil, multiple reflections are not considered and the reflection and transmission angles are calculated using Snell’s law without taking into account the conductivity of the soil. These angles are then used to compute the reflection and transmission coefficients ($\Gamma$ and $\tau$), which do incorporate the conductivity of the soil.

2.2.2. Implementation

Usually, many rays are launched from each transmitter for proper illumination of the scenario [11]. However, to reduce the computational time required for multiple rays, only the rays that come from the specular reflection at the air–soil interface and the rays coming from the target are used. The former can be calculated directly using simple geometrical relations. For the latter, we estimate the angles of the incident rays that hit the left and the right sides of the target (i.e., the points $(x_{tg} - \delta_{tg}, y_{tg})$ and $(x_{tg} + \delta_{tg}, y_{tg})$). These estimations require first calculating the refraction points at the air–soil interface for those points on the target. Then, many rays are launched between the computed angles. If one of these rays (after its reflection at the target) is closer than a given threshold ($th$) to a receiver, it is assumed that ray hits that receiver and it is used to compute $E_{\text{target}}$. A detailed flowchart of the implemented approach is shown in Figure 3.

**Figure 3.** Flowchart of the ray-tracing implementation.
2.3. FDFD

The 2D Finite Difference Frequency Domain (FDFD) algorithm is well suited to nearfield analysis of dielectric or metal targets from about 0.1 to 30 wavelengths in size placed in lossy, rough dielectric backgrounds [12]. This algorithm simulates nearfield scattering from objects that are of electrical sizes that are particularly difficult to model (less than about 30 wavelengths), filling a desirable niche between geometric optics methods (high frequency or electrically large scatterers) [13] and Born approximation methods (low frequency or electrically small scatterers) [14]. The scattering objects and backgrounds can both be lossy dielectrics of any contrast and any loss tangent. The 2DFDFD algorithm subdivides space into uniform Yee cells and applies simple finite differences to describe the 2D partial differential Helmholtz wave equation for which one dimension, typically z, is invariant. Termination of the space is done by using a perfectly matched layer (PML) to minimize scattering from the computational boundaries [15]. Compared with 3DFDFD methods which require iterative (and slow) GMRES (Generalized Minimal Residual Method) or LGMRES (“loose” GMRES) solvers, the simpler 2DFDFD algorithm uses direct matrix inversion for both the TM and TE subclasses of problems. Computational time is relatively fast and complex geometries are easy to model.

2.4. Inversion

To compare the results for the different configurations, the simulated field is represented in the time-domain (B-scan) and post-processed with a SAR algorithm. SAR reflectivity at point \( r' \) of the investigation domain is given by Equation (3), where \( R_{t}^{r} \) is the path length between the \( t \)-th transmitter (located at \( r_t \)), the point where the reflectivity is calculated \( r' \) and the \( r \)-th receiver \( r_r \).

\[
\rho(r') = \sum_{n=1}^{N} \sum_{t=1}^{T} \sum_{r=1}^{R} E(f_n, r_t, r_r') \exp(+j\beta_0 R_{t}^{r})
\]  

(3)

Assuming free-space propagation, \( R_{t}^{r} \) would be equal to \( \| r_t - r' \| + \| r_r' - r' \| \). This assumption provides good results when the incidence angle is close to normal incidence and the permittivity and conductivity of the soil are low. When these conditions are fulfilled, it is possible to detect the object in the SAR image at approximately \( \sqrt{\epsilon_r s d} \) depth (being \( d \) the true depth of the buried target). To obtain better results and to detect the object at its real depth, the constitutive parameters of the soil must be taken into account. The common approach consists of calculating the refraction point at the air–soil interface (for each point \( r' \) in the investigation domain, and each combination of transmitter and receiver positions). This requires solving a fourth-order equation derived for Snell’s Law. However, instead of calculating the refraction point, \( R_{t}^{r} \) is modified so as to consider the permittivity of the soil [16,17]. Thus, \( R_{t}^{r} \) is given by Equation (4), where \( n_s = \sqrt{\epsilon_r s - 1} - \sqrt{\epsilon_r s} \) and the other parameters are defined according to the scheme shown in Figure 4.

\[
R_{t}^{r} = 2d \sqrt{\epsilon_r s - 1} + \frac{d_l(d_l - d_n s \cos(2\phi_l))}{d_l + d_n s \sin^2(2\phi_l)} + \frac{d_r(d_r - d_n s \cos(2\phi_r))}{d_r + d_n s \sin^2(2\phi_r)}
\]

(4)
3. Results

3.1. Scenario Configuration

The scenario simulated with these methods consists of a low moisture sandy soil (with $\varepsilon_r = 2.5$ and $\sigma_s = 0.0125 \text{ S/m}$) where a target of 2 cm radius is buried at 25 cm depth ($x_{tg} = 0 \text{ m}$ and $y_{tg} = -0.25 \text{ m}$). Both metallic and dielectric targets are considered. If the target is dielectric, it is modeled as trinitrotoluene (TNT) with $\varepsilon_{r,tg} = 2.9$ and $\sigma_{tg} = 0 \text{ S/m}$. Simulations are performed between 3.5 and 5.5 GHz at 10 MHz steps considering TE polarization. Although these frequencies are higher than those commonly used in GPR, they have been chosen so that the radar could be light enough to be mounted on board a UAV (as it has been already proved in the prototype shown in [6]). In the ray-tracing simulation, the antenna beamwidth is 30° and the results are contaminated with white Gaussian noise, resulting in a signal to noise ratio of 30 dB. It must be noted that the direct signal between the TX and RX has not been included in the simulations, since it is expected to be removed from the received signal in a real implementation of the system (thanks to the fact that it will arrive earlier than the signal coming from the soil reflection and it will likely to be stronger).

Three different configurations have been simulated:

- **Multimonostatic**, where the TX–RX (drone mounted transceiver) is placed at 65 different positions between down-track positions $x = -0.8 \text{ m}$ and $x = 0.8 \text{ m}$ at $y = 1 \text{ m}$ height. The angle of incidence is 0° (i.e., the antennas are aligned perpendicular to the soil surface, with main beam pointing straight down).

- **Multistatic**, where the TX is placed at a fixed position (on a vehicle, at down-track position $x = -20 \text{ m}$ and height $y = 2.5 \text{ m}$) with main beam pointing at an angle of incidence of 83° with the nominal ground surface, and the drone-mounted RX is looking downward and is moved to the same positions as in the multimonostatic case.

- **Multibistatic**, where the vehicle-mounted TX is placed at $y = 2.5 \text{ m}$ height and is moved between down-track positions $x = -20.8 \text{ m}$ and $x = -19.2 \text{ m}$ and the drone-mounted RX is moved between the same positions as in the multimonostatic case. Thus, both TX and RX are moved coherently. The angles of incidence are 83° for the TX and 0° for the RX.

The positions of the TX–RX in the multimonostatic configuration were set according to those already used in previous experimental work. The positions of the TX–RX and the angle of incidence in the multistatic and multibistatic configurations were found using ray tracing simulations, so as to be able to detect dielectric targets. The performance of all configurations were then verified with FDFD.
3.2. Initial Comparison: Scattered Field and B-Scan

Before applying the inversion algorithm, the simulated scattered fields obtained with each method were compared, in both the frequency and time domains. This comparison is shown in Figures 5–7 for the multimonostatic scenario with a metallic target buried in the soil. The normalized scattered field in the frequency domain is shown for two observation domain positions: \( x = -0.8 \) m (Figure 5) and \( x = 0 \) m (Figure 6). The inverse Fourier Transform is used to compute the scattered field in the time domain (B-scan), as shown in Figure 7. The agreement between the scattered field simulated with RT and TE FDFD modeling \( E_z \) (or TM\(_z\), relative to z-axis) is good. The main difference is that in FDFD the amplitude at the air–soil interface is larger than the amplitude at the target, whereas in RT both amplitudes are similar. This might be due to the fact that RT only considers the specular reflection at the air–soil interface. This fact also explains that the scattered fields in the frequency domain are more similar at \( x = -0.8 \) m (left side of the observation domain) than at \( x = 0 \) m (center of the observation domain, exactly over the target).

Figure 5. Normalized scattered field at the first transmitter-receiver position (\( x = -0.8 \) m): multimonostatic scenario with a metallic target. Real part (a) and imaginary part (b).

Figure 6. Normalized scattered field in the middle of the observation domain (\( x = 0 \) m): multimonostatic scenario with a metallic target. Real part (a) and imaginary part (b).
3.3. SAR Image Comparison

The final goal was to compare the SAR images for each configuration (multimonostatic, multistatic and multibistatic) to determine the best configuration. First, the SAR images were obtained from the RT simulations and then the results were verified with the FDFD simulations.

3.3.1. Multimonostatic Simulations

The SAR image of the multimonostatic scenario with a buried metallic target is shown in Figure 8. Both the interface and the object are clearly detected. The reflectivity at the interface is larger in the FDFD simulation, as expected from the previous discussion.

When the buried target is dielectric (TNT), it is hardly detected in the SAR image (as shown in Figure 9). Thus, in accordance with the initial hypothesis, the antenna configuration must be improved to be able to detect non-metallic targets.
3.3.2. Multistatic and Multibistatic Simulations

Since the goal is to detect non-metallic targets, the multistatic and multibistatic simulations comparison was performed when the buried target is dielectric. SAR images are shown in Figures 10 and 11 for the multistatic and multibistatic scenarios, respectively. In RT simulations, the specular reflections from the soil surface do not reach the receiver. Therefore, in FDFD simulations, the known flat ground background is removed, thus showing only the target-scattered response. The results are almost the same for both configurations, where the dielectric object is clearly distinguishable. There is also a good agreement between the RT and FDFD simulations, thus it can be concluded that RT is a useful tool for designing new GPR configurations.
3.3.3. Effect of Inversion Path Length

As aforementioned, the permittivity of the soil must be known or estimated in order to obtain an accurate SAR image. If the permittivity is not taken into account, the object is detected deeper and bigger than expected, as shown for the multimonostatic case in Figure 12a. Furthermore, if the permittivity or the angle of incidence is high, the resulting SAR image is considerably distorted, as shown for the multibistatic scenario in Figure 12b.

3.4. Computational Performance

The computational time required by the forward wave modeling (RT and FDFD) for each scenario is shown in Table 1. It was measured running the codes in a conventional laptop with 16 GB of RAM and Intel Core i7-6700HQ. As expected, RT is much faster than FDFD. It must be noticed that the pathlength is computed only once for each ray, since it is independent of the frequency. Furthermore, RT can be parallelized, which would reduce the computational time even more.

<table>
<thead>
<tr>
<th>Method</th>
<th>Multimonostatic</th>
<th>Multistatic</th>
<th>Multibistatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>6.1 s</td>
<td>0.5 s</td>
<td>9.2 s</td>
</tr>
<tr>
<td>FDFD</td>
<td>28.5 h</td>
<td>32.2 min</td>
<td>32.7 h</td>
</tr>
</tbody>
</table>
Regarding the inversion step, the SAR algorithm takes 5.1 s to run. It must be noticed that it can also be easily parallelized to reduce the computational time.

3.5. Effect of Rough Surface

One of the main difficulties for detecting buried objects with GPR is the strong random clutter produced by the reflection at the rough air–soil interface (due to impedance mismatch). If the interface is rough, this reflection cannot be easily removed and it clearly worsens the detection capability of the system. Therefore, it was necessary to analyze the performance of the different configurations with a rough surface. This analysis was performed with FDFD, considering a rough surface with an average height of 2 cm and a correlation length of 60 cm.

The SAR images for the monostatic and bistatic configurations with a buried dielectric target are shown in Figure 13. In the monostatic configuration, the target is hardly detected (similarly as for the flat surface). In the bistatic configuration, the target is still detected, although there are some stronger reflections at the air–soil interface, which worsens the quality of the SAR image. The inversion results for the bistatic configuration are similar to the bistatic arrangement. The target detection is improved relative to the monostatic configuration because, in the bistatic and multistatic configurations, rays specularly reflected from the ground surface do not reach the receiver. Using a forward-stationed drone receiver also offers advantages of higher signal strength and closer angular proximity to the maximum target-scattered response, relative to a vehicle-mounted receiver [16]. Thus, it can be concluded that the proposed multibistatic configuration allows to detect dielectric targets even under rough surfaces.

![Figure 13. SAR image from FDFD simulations with a dielectric target buried under a rough surface (dashed line indicates the soil interface) for monostatic (a) and bistatic (b) configurations.](image)

3.6. Effect of Polarization

All previous simulations were performed considering TE polarization. Since the reflection coefficient is smaller for TM polarization (which provides better penetration into the soil), an improvement in the results could be expected with TM. However, when the surface is rough, there is not only better penetration, but also slightly higher clutter levels with TM. As a result, the contrast between the target and the soil remains almost the same, as shown in Figure 14 for the multibistatic configuration. Nonetheless, there is less clutter below the soil surface, which helps to facilitate the detection.
4. Analysis

As mentioned above, the target detection and surface clutter reduction in the proposed distributed GPR configuration are better than conventional GPR architectures. The previous analysis was performed for a small generic target (both dielectric and metallic), whose behavior is similar to a point source.

To further analyze this system for the proposed application (landmine and IED detection), a target with characteristics similar to a plastic PMN-type landmine was considered. In particular, the target, which is fully composed by TNT, has a cross-section of 10 cm × 4 cm and it has been buried at 25 cm depth under the same rough surface used previously. This is one of the most challenging scenarios for this application mainly due to the major part of the reflected signal from the target being specularly-reflected away from the receiver, the low-contrast between the target and the soil, and the clutter due to the soil surface roughness.

The SAR images obtained from FDFD simulations for the configurations previously compared (multimonostatic DLGPR, multistatic and multibistatic FLGPR–DLGPR) as well as the multimonomostatic FLGPR configuration were compared in this scenario. In the multimonostatic FLGPR configuration (shown in this section for comparison purposes), the TX–RX is moved between down-track positions \( x = -20.8 \) m and \( x = -19.2 \) m at \( y = 2.5 \) m height, with main beam pointing at an angle of 83°.

The results for all these configurations are shown in Figure 15. As explained above, the multistatic and multibistatic FLGPR–DLGPR configurations show similar results (Figure 15c,d, respectively). In the multimonostatic configurations (Figure 15a,b), the target cannot be detected at all. Furthermore, in the multimonomostatic FLGPR case (Figure 15b), it can also be seen that there is poor resolution in vertical position, which implies that it is not possible to distinguish even whether the target is above or below the surface (in case it was detected) [16]. For this configuration, the bright high-intensity bands shown in the SAR image are generated entirely from the rough surface scattering, and their extended lengths are due to poor synthetic focusing in the down range direction. Their change of direction is due to the fact that the refraction at the soil surface is taken into account in the inversion. However, in the proposed multibistatic FLGPR–DLGPR configuration (Figure 15d), two reflections coming from the target (at \( -15 \) dB mainly from its left and right sides) can be clearly distinguished, thus allowing the detection of the target.
Figure 15. SAR image from FDFD simulations with a flat-top dielectric target buried under a rough surface (dashed line indicates the soil interface) for: multimonostatic DLGPR (a); multimonostatic FLGPR (b); multistatic FLGPR–DLGPR (c); and multibistatic FLGPR–DLGPR (d) configurations.

5. Conclusions

A novel GPR system architecture was designed using a fast ray tracing algorithm. The proposed architecture was validated using FDFD, even taking into account the surface roughness. This new system exploits the advantages of FLGPR (with the transmitter looking ahead of a vehicle) and DLGPR (with the receiver on a drone), mainly in terms of less clutter and good penetration and resolution. Compared to a monostatic FLGPR (on a vehicle at a stand-off distance), it provides higher signal strength and resolution, since the receiver is closer to the investigation domain. Compared to a multimonostatic DLGPR (on board a UAV), it helps to mitigate the strong clutter from the air–soil interface. For the analyzed aperture size and TX–RX distance, it was also shown that the results with the transmitter stationary (multistatic) or moving synchronously with the receiver (multibistatic) are almost the same.

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Autonomous Airborne 3D SAR Imaging System for Subsurface Sensing: UWB-GPR on Board a UAV for Landmine and IED Detection

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Abstract: This work presents an enhanced autonomous airborne Synthetic Aperture Radar (SAR) imaging system able to provide full 3D radar images from the subsurface. The proposed prototype and methodology allow the safe detection of both metallic and non-metallic buried targets even in difficult-to-access scenarios without interacting with the ground. Thus, they are particularly suitable for detecting dangerous targets, such as landmines and Improvised Explosive Devices (IEDs). The prototype is mainly composed by an Ultra-Wide-Band (UWB) radar module working from Ultra-High-Frequency (UHF) band and a high accuracy dual-band Real Time Kinematic (RTK) positioning system mounted on board an Unmanned Aerial Vehicle (UAV). The UAV autonomously flies over the region of interest, gathering radar measurements. These measurements are accurately geo-referred so as to enable their coherent combination to obtain a well-focused SAR image. Improvements in the processing chain are also presented in order to deal with some issues associated to UAV-based measurements (such as non-uniform acquisition grids) as well as to enhance the resolution and the signal to clutter ratio of the image. Both the prototype and the methodology were validated with measurements, showing their capability to provide high-resolution 3D SAR images.

Keywords: Ground Penetrating Radar (GPR); Unmanned Aerial Vehicles (UAVs); Synthetic Aperture Radar (SAR); Real Time Kinematic (RTK); Ultra-Wide-Band (UWB); landmine and IED detection; non-destructive testing

1. Introduction

In the last years, there has been a massive development of new applications using Unmanned Aerial Vehicles (UAVs) [1–4]. A considerable amount of these applications is based on integrating electromagnetic sensors on board the UAVs (e.g., power detectors for antenna measurement [5], or radars for earth observation [6] and subsurface sensing [7]). Safety, measurement speed and the ability to fly over difficult-to-access areas are some of the advantages that have contributed to widely increase the usage of UAVs for security and defense applications, such as landmine and Improvised Explosive Device (IED) detection.

Several Non-Destructive Testing (NDT) techniques have been employed for subsurface sensing applications, since they allow extracting information of the subsurface and detecting possible buried targets without interacting with them. Focusing on the field of landmine and IED detection, the most common NDT techniques are, according to their physical principle [8]: electromagnetic induction, Nuclear Quadrupole Resonance (NQR), thermal imaging and Ground Penetrating Radar (GPR). GPR has been found to be a useful strategy for this application since it is able to provide high resolution images from the subsurface and, as a result, it makes possible the detection of both...
metallic and dielectric buried targets [9,10]. However, GPR capabilities are considerably affected by the soil heterogeneity, the roughness of the air–soil interface and the possible low signal to clutter ratio (especially for non-metallic targets) [11].

There are several criteria to classify GPR systems. The first criterion takes into account whether the GPR antennas are placed directly in contact with the ground (ground-coupled) or above the ground (air-launched). The former architecture usually provides a better signal to clutter ratio, due to a higher penetration into the ground and weaker reflections from the air–soil interface (assuming a well-matching between the antennas and the soil impedance). The main drawback of this configuration is that the antennas are directly over the soil, which prevents the use of ground-coupled systems in applications which require a safety stand-off distance such as the aforementioned landmine and IED detection. The latter architecture avoids the contact with the ground, but suffers from stronger clutter, which makes the target detection more difficult. Another criterion classifies GPR systems according to the orientation of the antennas with respect to the soil surface, distinguishing between Forward (or Side)-Looking GPR (FLGPR, SLGPR) and Down-Looking GPR (DLGPR). In FLGPR [12] and SLGPR [13], the antennas are usually oriented looking ahead, which contributes to minimize the reflection coming from the air–soil interface. Nevertheless, they suffer from lower sensitivity and resolution (compromising the distinction between targets under or above the ground). On the other hand, in DLGPR [14], the antennas are placed looking downwards, providing higher resolution but receiving stronger reflections from the air–soil interface.

As aforementioned, in landmine and IED detection, the scanning system must be placed at a safe stand-off distance to prevent accidental detonations, thus FLGPR architectures have been usually proposed due to the difficulties to keep a safe distance with a DLGPR system. However, in the last years, a new approach based on a UAV-mounted radar has been proposed [7,15], allowing the use of a DLGPR configuration in safe conditions.

Although several UAV-mounted GPR systems have been presented [7,16,17], the system and processing techniques presented in this contribution have several novelties with respect to existing state-of-the-art systems. The most important feature is its ability to provide high resolution well-focused 3D images of the underground from radar measurements gathered during autonomous flights. This requires integrating a high accuracy real-time positioning system on board the UAV because: (i) the UAV needs accurate positioning to follow the predefined flight path; and (ii) the radar measurements are coherently combined using a Synthetic Aperture Radar (SAR) algorithm, which imposes a geo-referring accuracy several times lower than the smallest working wavelength. Furthermore, the positions of the radar measurements are carefully processed to discard data that could cause unfocusing or resolution degradation in the SAR image (for instance, due to oversampling in some areas [18], since it is very difficult to perform a uniformly sampled acquisition with the UAV). Regarding the processing of the radar data, some improvement steps are also proposed to enhance the resolution and the target discrimination. In addition, the lowest working frequency of the selected radar has been notably decreased (down to Ultra-High-Frequency, UHF, band), allowing the detection of targets buried in higher loss soils. Both the prototype and the processing techniques were tested with experimental flights, comparing the resulting 3D SAR images with the ground-truth. A video summarizing the features of the system and a brief application example is provided as supplementary material.

2. System Architecture

The main goal of the proposed system is that the UAV autonomously flies over a region of interest collecting radar measurements, which are geo-referred and sent in real-time to a ground control station, to produce high-resolution 3D SAR images. The UAV-mounted GPR prototype, which is shown in Figure 1, comprises the following subsystems:
The flight control subsystem is composed of the UAV flight controller and common positioning sensors on board UAVs. These sensors are: an Inertial Measurement Unit (IMU), a barometer, and a Global Navigation Satellite System (GNSS) receiver.

The enhanced positioning system consists of a laser rangefinder and a dual-band Real Time Kinematic (RTK) system.

The radar subsystem includes the radar module, and the transmitter and receiver antennas.

The communication subsystem has a receiver at 433 MHz for the link with the pilot remote controller and a wireless local area network (WLAN) transceiver at 5.8 GHz to exchange data with the ground station. Both frequencies were selected to minimize possible interferences with the radar subsystem during the experimental campaigns.

The architecture of the system is similar to the one adopted by the prototype proposed in [7]. The main improved features are: (i) the radar subsystem, which works at considerably lower frequencies; and (ii) the enhanced positioning system, whose accuracy has been greatly increased. As a result, with the prototype presented in this contribution, targets buried in soils with higher losses can be detected and, due to the enhanced positioning accuracy, well-focused 3D SAR images of the underground can be obtained.

Regarding the radar subsystem, an M-sequence Ultra-Wide-Band (UWB) radar covering a frequency range from 100 MHz to 6 GHz was selected [19]. This radar transmits a type of pseudo-random binary signal called Maximum Length Binary Sequence (MLBS) periodically, thus the received backscattered signal must be correlated with the ideal MLBS to obtain the impulse response. Two UWB Vivaldi antennas, working from 600 MHz to 6 GHz, were selected for transmitting and receiving. For the experimental validation shown in this contribution, only the frequency band from $f_{\text{min}} = 600$ MHz to $f_{\text{max}} = 3$ GHz was selected for processing since the soil losses in the measured scenario produce too much attenuation at higher frequencies. As shown in Figure 1, 3D printed structures were designed and fabricated to properly mount the radar and the antennas on board the UAV.

Concerning the enhanced positioning system, to coherently combine all the measurements gathered with the prototype, they must be accurately geo-referred. To avoid artifacts and obtain a well-focused SAR image, this accuracy should be better than $\lambda_{\text{min}}/4 = 2.5$ cm in the horizontal plane (i.e., in cross-range) and $\lambda_{\text{min}}/8 = 1.25$ cm in the vertical direction (i.e., in range), where $\lambda_{\text{min}} = 10$ cm

![Figure 1. UAV-mounted GPR prototype.](image-url)
is the smaller wavelength. A dual-band multiconstellation RTK system was selected to fulfill this requirement. This system is composed of two RTK beacons [20], one mounted on the UAV and another one working as base station static on the ground. The latter sends real-time correction data to the former to achieve cm-level positioning accuracy. The reason a dual-band RTK was chosen is to obtain better accuracy and availability (that is, percentage of time that corrected coordinates are provided), more robustness (especially when working in challenging environments, e.g., with limited sky view) and faster deployment time (since less time is required to resolve carrier phase ambiguity), compared to single-band RTKs previously used. The selected dual-band RTK was integrated into the UAV to provide these accurate coordinates in real time for both the UAV navigation and the measurements geo-referring. The expected accuracy is 0.5 cm in the horizontal plane and 1 cm in the vertical direction, which corresponds to $\lambda_{\text{min}}/20$ and $\lambda_{\text{min}}/10$, respectively. Nevertheless, even better relative positioning accuracies were observed during the measurement campaigns.

3. Methodology

The data acquired with the prototype (composed by the georeferred radar measurements) are processed according to the flowchart shown in Figure 2. The boxes in gray correspond to the processing of the geo-referring data gathered with the positioning subsystem, blue boxes represent the basic GPR-SAR processing, and green ones highlight the steps corresponding to improvements in the GPR-SAR processing. The final result is a 3D high-resolution SAR reflectivity image (yellow box).

![Flowchart of the data processing.](image)

**Figure 2.** Flowchart of the data processing.

3.1. Positioning Data Processing

The flowchart of the positioning data processing is shown in Figure 2 (left). The positioning data to be processed is composed by: latitude (lat), longitude (lon) and height from the RTK system, and roll, pitch and yaw from the IMU. Due to the high accuracy of the RTK system in both horizontal and
vertical directions, the laser range finder is not used in the processing. It is used, however, in the UAV navigation to help the UAV to keep an approximately constant distance to the soil surface.

This geo-referring data are processed mainly: (i) to select which measurements will be processed (discarding those that do not provide valuable information); (ii) to compute the position of the radar antennas in a cartesian coordinate system; and (iii) to define the investigation domain (i.e., where the SAR image is obtained) according to the flight path.

As explained above, the UAV autonomously flies over the region of interest. The flight path (i.e., the measurement grid) is a planar rectangular surface at a constant height and heading, where geo-referred radar measurements are continuously collected. However, it must be noticed that the proposed positioning data processing does not require prior knowledge of the predefined measurement grid, thus allowing the processing of measurements gathered in planar grids with both autonomous and manual flights.

The first step consists of transforming the coordinates from the geodetic system (latitude, longitude and height) to a local ENU (East–North–Up) system \((x_r, y_r, z_r)\). This requires selecting a reference point as origin of the ENU system. In particular, the position of the UAV when it is first turned on is used as reference: the latitude and the longitude are given by the RTK, and the height is given by the physical distance from the RTK antenna to the ground (so that at the reference position, \(z_r = 0\) m).

Then, the main course over the ground or main ground track (denoted as \(c_{og}\)) is estimated and the flight path is rotated according to this value. After the rotation, the flight path will be almost aligned with the \(x\) and \(y\)-axis, which helps to facilitate the visualization of the measurements and the definition of the investigation domain. \(c_{og}\) will also be used in the next step (data selection) to discard measurements acquired when the course over the ground is too far from its main value.

The main ground track estimation is obtained from the set of UAV positions as follows: (i) the course over the ground \(c_{og}\) (discarding the sense) is estimated according to Equation (1), where \(v_n\) and \(v_e\) are the velocities in the north and east directions and \(\text{mod}\) denotes the modulo operation; (ii) \(c_{og}\) is discretized in bins of \(1^\circ\)-width and the mode is computed to obtain a rough estimation of the main course over the ground \(\hat{c}_{og}\); and (iii) the estimation is improved by computing the mean of all measurements in the range \(
abla c_{og} \leq \pm 10^\circ\), yielding \(\hat{c}_{og}\).

If the flight path is performed autonomously (as in this contribution), this value is almost the same as the desired course defined with the waypoints. It must be noticed that the mean of \(c_{og}\) is a worse estimation of the main course over the ground than \(\hat{c}_{og}\), since it is greatly influenced by the course of the UAV when it changes sense or when it is almost still.

\[
c_{og}[\text{rad}] = \text{mod} \left( \text{atan} \left( \frac{v_n}{v_e} \right), \pi \right) \approx \text{mod} \left( \text{atan} \left( \frac{\partial y_s}{\partial x_r} \right), \pi \right) \quad (1)
\]

Figure 3 shows the histogram of \(c_{og}\) of an autonomous flight defined with waypoints (with a desired course of \(65^\circ\)). The mode gives the rough estimation of \(\hat{c}_{og} = 65.5^\circ\). After improving this estimation as explained before, \(\hat{c}_{og} = 65.09^\circ\), which is almost the same as the desired course. The original and rotated flight paths are shown in Figure 4. As expected, the rotated path \((x_{nr}, y_{nr}, z_{nr})\) is now aligned with the \(x\) and \(y\)-axis.

The next step aims to discard the data that do not provide valuable information (e.g., when there is a sudden change in attitude) or that could degrade the SAR image. Regarding the latter, it must be noticed that the spatial sampling should be as uniform as possible to avoid artifacts in the SAR image. If there is an oversampled region (where much more measurements were taken), the SAR image pixels close to this region will have a high amplitude, thus masking the detection of targets in other parts of the image. In measurements taken with UAVs, it is very difficult to perform a uniform acquisition, since the UAV deviates from the ideal flight path mainly due to wind conditions and positioning systems uncertainties. Furthermore, in the experimental flights, it was observed that, when the UAV changes sense of movement (i.e., when it changes from moving in one direction to moving in the opposite one), the speed usually decreases, thus resulting in oversampling. It must be remarked that
the UAV heading is fixed to a constant value (making it coincident with the desired main course over the ground).

The data that are kept for further processing must satisfy the following constraints, where $th()$ denotes a fix threshold:

- $\Delta_{xy} = \sqrt{\Delta x^2 + \Delta y^2} > th_{\Delta}$, where $\Delta x$ and $\Delta y$ are the differences between adjacent values of $x$ and $y$, respectively. This condition ensures that the UAV is actually moving.

- $|\text{roll} - \text{roll}| < th_{\text{roll}}$, $|\text{pitch} - \text{pitch}| < th_{\text{pitch}}$, and $|\text{yaw} - \text{yaw}| < th_{\text{yaw}}$, where $[\cdot]$ denotes the mean value. These conditions are used to filter out the positions where there was a noticeable change in attitude.

- $|\text{rem}(c_{og} - \hat{c}_{og}, \pi)| < th_{\text{c}}$, where rem denotes the remainder operator. Only measurements with the course over ground close to the main one are kept. This means that, if the UAV path deviates noticeably from the main path, these measurements are discarded.

- $|\text{zur} - \text{zur}| < th_{\text{z}}$. This condition helps to get rid of considerable changes in height.

The following thresholds were employed: $th_{\Delta} = \lambda_{\text{min}}/6 \approx 0.017$ m (where $\lambda_{\text{min}}$ is the smaller wavelength), $th_{\text{att}} = \text{att} + 3\text{std}(\text{att})$ where std is the standard deviation and att is each of the attitude angles (roll, pitch and yaw), $th_{\text{c}} = 20^\circ$ and $th_{\text{z}} = 0.25$ m. They were found to provide a good compromise to avoid oversampling and discard unnecessary data, while keeping enough measurements to obtain a well-focused SAR image.
In the flight used for illustrating the positioning data processing, the UAV is mainly moving back and forth between $y = 1$ m and $y = 5$ m. If only one of each four consecutive UAV positions are plotted (Figure 5a), it can be clearly seen the oversampling when the UAV changes sense of movement (at $y = 1$ m and $y = 5$ m). Figure 5b shows the full flight path (after the rotation performed in the previous step) and the selected flight path. Most of the discarded data correspond to these oversampled regions (as can be inferred from Figure 5c), whereas the rest of discarded data mainly correspond to sudden changes in movement due to wind.

![Image](image.png)

**Figure 5.** One of each four consecutive UAV positions (a); full and selected UAV positions (in blue and red, respectively) (b); and one of each four consecutive selective UAV positions (c).

This data selection step also helps to reduce the number of measurements that are processed, thus helping to decrease the computational time. In the previously shown example, the full flight path contains 4993 measurements points, whereas the selected path has 3118 points. This means that only 62.5% of the measurements will be processed.

As a result of this step, the indexes of the measurements that will be processed ($\text{ind}_\text{obs}$) are stored in a vector. Thus, the observation domain coordinates (i.e., the positions where these measurements were taken) are: $r = (x, y, z)$, where $x = x_{\text{er}}(\text{ind}_\text{obs})$, $y = y_{\text{nr}}(\text{ind}_\text{obs})$ and $z = z_{\text{ur}}(\text{ind}_\text{obs})$.

Finally, the investigation domain, $r' = (x', y', z')$, where the 3D SAR image will be calculated must be defined. The investigation plane ($x'$ and $y'$ coordinates) is defined according to the observation plane ($x$ and $y$ coordinates) as follows:

- First, the minimum area bounding rectangle that encloses the observation plane (called bounding box) is retrieved. To find it, the convex hull of the observation plane coordinates (i.e., the smallest convex polygon containing the observation plane) is computed. Then, the bounding box can be easily obtained since it always contains an edge of the convex hull.
- Then, the maximum axis-aligned rectangle inside the bounding box is computed, since it is easy to define and work with an axis-aligned investigation domain and the observation domain is almost aligned (due to the rotation according to the main course over the ground previously performed).
- Finally, the investigation plane is defined by shrinking this rectangle by a scale factor of $s_f_t$ and $s_f_{ct}$ in the track and across-track directions (to avoid edge effects in the SAR image) and sampling it every $\delta_t$ and $\delta_{ct}$, respectively.

An example of the computation of the investigation plane following this procedure is shown in Figure 6, where the bounding box is depicted with a solid black line, the maximum axis-aligned
rectangle inside it is drawn with a dash-dot red line and the edges of the investigation plane are shown in solid red. For the results shown in this contribution, the investigation plane is obtained by shrinking the rectangle with the scale factors $s_f = 0.95$ and $s_{fr} = 0.85$ (which prevents edge effects in the SAR image) and sampling it every $\delta t = \delta_{fr} = \lambda_{min}/4 = 0.025$ m. Since the soil surface is around $z = 0$ m, $z'$ is defined between $-0.6$ m and 0.4 m, and is sampled every $\delta z = 0.02$ m. These values can be adjusted by the user as desired (e.g., if coarse sampling of the investigation domain is considered enough for the specific application considered).

![Obs. domain, Bounding box, Max. rectangle, Shrunk rectangle](image)

**Figure 6.** Definition of the investigation plane edges (in solid red line) from the observation plane coordinates (in dotted blue line).

It is worth noting that the investigation domain coordinates, $r'(x', y', z')$, where the 3D SAR image is calculated, can be transformed back to the geodetic system of coordinates by applying the inverse of the previous operations (i.e., rotating them an angle $-\hat{c}_{og}$ and then applying the transformation from the local east–north–up system to the geodetic system).

### 3.2. Radar Data Processing

The flowchart of the radar data processing is shown in Figure 2 (right). As aforementioned, the boxes in blue correspond to the basic processing and the boxes in green are optional steps to improve the resulting SAR image quality.

Since the radar used in this contribution transmits a pseudorandom binary sequence, the first step consists of cross-correlating the raw radar data $E_{raw}(t_r)$ with the ideal transmitted binary sequence to obtain an approximation of the impulse response function $E_{scatt}(t_r)$ (where $t_r$ is the time axis). As explained above, it must be noticed that only the selected measurements (given by $ind_{obs}$) will be processed.

The next step deals with adjusting to a common time-zero and selecting the time-window of interest. Estimating the time-zero is important in order to remove the effect of the wires and the radar internal delays as well as to obtain a well-focused image. The estimation is performed with a calibration measurement at the beginning of the experimental campaign. The prototype is placed over the ground at a known distance $(d_{rg})$ and this distance is also estimated with the radar $(d_{rg} = c t_g/2$, where $c$ is the light speed and $t_g$ is the time instant where the ground is detected). Therefore, the time-zero is given by $t_0 = 2(d_{rg} - d_{rg})/c$, the corrected time-axis is $t_c = t_r - t_0$ and the measurements at $t_c < 0$
will be discarded. Besides, the time window of interest is selected so as to reduce the data size (since measurements at larger range do not provide valuable information). In particular, the used criterion selects the time-window $t$ that corresponds to a range of $r_0 \pm 1$ m, where $r_0$ is the mean distance between the radar antennas and the soil. It must be remarked that the time-zero is estimated only once, and then the same time-zero correction is applied to all measurements (discarding the data at $t_c < 0$).

The radar measurements of the flight shown in Section 3.1 after applying this step are depicted in Figure 7, where the range axis is given by $r_{ng} = ct/2$.

![Figure 7](image.png)

**Figure 7.** Normalized radar measurements ($E_{scatt}(r_{ng})$) after time-zero correction and time-window selection. The distance between the radar antennas and the soil is depicted in black on top of the measurement.

To improve the signal to clutter ratio $[21]$, the background should be estimated and removed from the radar measurements. In this contribution, the background is estimated as the average of all measurements and thus, the average is subtracted from each measurement. This helps to reduce the clutter, such as the coupling effects between the antennas.

The resulting improved radar measurements $\hat{E}_{scatt}(t)$ are shown in Figure 8, where a clear improvement can be noticed comparing this image with the original radar data. This enhancement can be better observed taking a closer look to both original and improved radar measurements (Figure 9). Furthermore, there is a good agreement between the location of the air–soil interface in the radar measurements and the distance between the radar antennas and the soil provided by the positioning system. The small discrepancies are mainly due to the soil being not perfectly flat (besides the scattering effects due to the presence of grass on the ground), and the errors in the positioning system.

After this step, a height correction can be applied to the data to enhance the SAR image quality (mainly focusing and resolution). This correction consists of first shifting the radar measurements by $z - z_0$, so that the resulting data $\hat{E}_{scatt}(t)$ look as if the measurements were taken at constant height.

The radar measurements after the height shifting are shown in Figure 10 and a closer look is depicted in Figure 11. As expected, the strong reflection at the air–soil interface is now almost at the same range for all measurements. In addition, it can also be concluded that there is a target at around 15 cm over the ground.
Figure 8. Normalized radar measurements ($\tilde{E}_{\text{scatt}}(r_{bg})$) after background subtraction. The distance between the radar antennas and the soil is depicted in white on top of the measurement.

Figure 9. Closer look to the radar measurements before (a) and after (b) background subtraction.

Figure 10. Normalized radar measurement ($\tilde{E}_{\text{scatt}}(r_{bg})$) after height shifting.
After the shifting, a second background subtraction is applied to mitigate the reflection from the air–soil interface and further enhance the signal to clutter ratio.

The next step consists of applying the Fourier transform to obtain $E_{\text{scatt}}(f)$ since the SAR processing will be performed in the frequency domain. Before the SAR processing, the positions of the transmitter and receiver antennas, denoted as $r_t = (x_t, y_t, z_t)$ and $r_r = (x_r, y_r, z_r)$, must be calculated since the observation domain coordinates are given with respect to the RTK antenna. These positions are computed through translation and rotation operations taking into account the attitude angles, the observation domain coordinates and the distances between the RTK antenna, the radar antennas and the IMU. If height correction has been applied, this must also be taken into account since in this case $z = \pi$.

Then, a SAR algorithm [22] is applied to coherently combine the measurements and obtain a well-focused image. SAR reflectivity at pixel $r'_p$ is given by Equation (2), where $f_n$ are the selected frequencies of interest; $r''_t$ and $r''_r$ denote the position of the transmitter and receiver antennas, respectively, at the $m$th measurement point; $k_{0,n}$ is the wavenumber in free-space at the $n$th frequency; and $R_{p,m}$ is the total path length between the transmitter antenna, the pixel where the SAR reflectivity is computed and the receiver antenna.

$$\rho(r'_p) = \sum_{n=1}^{N} \rho(r'_p, n) = \sum_{n=1}^{N} \sum_{m=1}^{M} E_{\text{scatt}}(f^n, r''_t, r''_r) \exp(+j k_{0,n} R_{p,m})$$

If free-space propagation is assumed (i.e., the soil composition is not taken into account), then $R_{p,m} = \|r''_t - r'_p\| + \|r''_r - r'_p\|$. Thus, if an object is buried at $d_{obj}$ depth and the soil permittivity is $\varepsilon_r$, it will be detected at $\sqrt{\varepsilon_r}d_{obj}$ in the SAR image. To consider the soil composition when calculating the path length for $z'_p < 0$ m (i.e., under the soil surface), $R_{p,m}$ is computed according to (3), where $n_s = \sqrt{\varepsilon_r - 1} - \sqrt{\varepsilon_r}$ and the other parameters are shown in Figure 12 [23].

$$R_{p,m} = 2d\sqrt{\varepsilon_r - 1} + \frac{d_s(d_s - d_{ns} \cos(2\phi_t))}{d_1 + d_{ns} \sin(2\phi_t)^2} + \frac{d_s(d_s - d_{ns} \cos(2\phi_r))}{d_r + d_{ns} \sin(2\phi_r)^2}$$

To improve the resolution of the SAR image, an equalization of the frequency response can be performed. When working with UWB radars and antennas, the amplitude levels of the SAR image show a great variation across the whole frequency band (mainly due to the fact that the antenna behaviour notably changes with the frequency) [19]. Usually, the data at lower frequencies mask the data at higher frequencies, yielding a SAR image with worse resolution than expected. To overcome this issue, instead of computing the SAR image for all the frequencies directly, the SAR image is computed for each $n$th frequency and is normalized by the maximum of its absolute value. Then, all $n$th SAR images are added to obtain the final SAR image, according to Equation (4).

$$\rho(r'_p) = \sum_{n=1}^{N} \frac{\rho(r'_p, n)}{\max\{\rho(r'_p, n)\}}$$
Figure 12. Main parameters involved in the estimation of the path length when the soil permittivity is taken into account (dashed line represents the true ray path).

4. Results and Discussion

The proposed system was validated at the airfield of the University of Oviedo (Figure 13). Two measurements were performed with the setup shown in Figure 14. In both cases, a metallic disk (of 9 cm radius) was placed on top of a plastic briefcase (with 14 cm height). In the first measurement, an open cylindrical metallic box (of 9.5 cm radius) was placed inside of a small hole of 8 cm depth (without soil covering it). For the second measurement, the box was covered with soil (i.e., the box was buried 8 cm under the soil surface).

Figure 13. Measurement scenario.
Figure 14. Setup for the measurement (a); first with the 9.5 cm radius metallic box uncovered (b); and second with this box buried and covered with soil (c).

In both measurements, the flight was performed autonomously. The predefined flight path was a rectangle of dimensions $\Delta x_p = 1$ m and $\Delta y_p = 4$ m sampled at $\delta x_p = 0.03$ m and $\delta y_p = 0.25$ m to define the waypoints positions, where $x_p$ denotes the cross-track direction and $y_p$ the along-track directions. The height was fixed at 2.3 m distance to ground (from the laser rangefinder). It must be remarked that radar measurements are continuously acquired during the flight (i.e., they are acquired not at each waypoint, but all over the flight path). The resulting flight path for the second measurement was used to illustrate the processing of the position data described in Section 3. To facilitate the comparison of the results shown in this section, both flights were rotated according to the same $\hat{\epsilon}_c$ (in particular, $\hat{\epsilon}_c = 65.09^\circ$ as estimated for the second measurement) and the same investigation domain was used ($x' \in [-0.4, 0.6]$ m, $y' \in [1, 5]$ m and $z' \in [-0.6, 0.4]$ m).

In the following subsections, different slices of the resulting SAR images are depicted. Please note that a $YZ$ plane is an along-track view (i.e., an along-track vs. depth slice), a $YX$ plane is a top view (i.e., an along-track vs. across-track slice) and an $XZ$ plane is an across-track view (i.e., across-track vs. depth slice).

4.1. Basic Processing

Both measurements were processed according to the procedure explained in Section 3, but first only applying the basic radar processing steps (without the improvement steps and without taking into account the soil composition). The resulting 3D SAR images were compared and the most relevant slices are shown in Figures 15 and 16. These slices were normalized by the maximum value of the full 3D SAR image to facilitate the comparison between different slices of the same measurement.

First, the slices at the position where the cylindrical box is detected are depicted in Figure 15, on the left for the first measurement (where the box is not covered by soil, Figure 14b) and on the right for the second measurement (where the box is covered by soil, i.e., buried under the ground, Figure 14c). In the former, the box is detected at approximately its true position, at $(x, y, z) = (-0.05, 4.55, -0.08)$ m. In the latter, as expected, the box is detected deeper (at $z = -0.14$ m) since the soil composition had not been taken into account yet. In addition, in the along-track view (i.e., $YZ$ plane), it can also be noticed that the target is not clearly distinguished from the soil surface interface, due to the strong reflection at the soil interface and the resolution in the $z$-axis not being high enough. This issue is overcome with the improvement steps in the radar processing. Furthermore, the amplitude of the SAR image at the box position is around 10 dB smaller when the box is buried, due to the high losses of the soil.
Figure 15. Slices of the 3D SAR image at the position where the buried metallic cylindrical box is
detected. Results for the first measurement (uncovered buried metallic box) are depicted on the left:
along-track view at $x = -0.05$ m (a); top view at $z = -0.08$ m (b); and across-track view at $y = 4.55$ m
(c). Results for the second measurement (buried metallic box covered with soil) are depicted on
the right: along-track view at $x = -0.05$ m (d); top view at $z = -0.14$ m (e); and across-track view at
$y = 4.55$ m (f).

Then, the slices at the position where the disk (placed on top of a briefcase) is detected are
depicted on the left part of Figure 16. Only the slices of the second measurement are shown since
the 3D SAR images of both measurements are almost the same in all the investigation domain except
in the area where the cylindrical box is buried. The disk is detected at its true position, at $(x, y, z) = \(-0.075, 3.4, 0.14\)$ m.

Finally, the slices of a region without targets at one position at the air–soil interface are represented
on the right part of Figure 16. The air–soil interface is clearly detected and, as the actual physical
air–soil interface, it is not perfectly flat.
Figure 16. Slices of the 3D SAR image for the second measurement at the position where the cylindrical disk on top of a briefcase is detected (along-track view at $x = -0.075$ m (a); top view at $z = 0.14$ m (b); and across-track view at $y = 3.4$ m (c)) and at a position at the soil surface interface without targets (along-track view at $x = 0.3$ m (d); top view at $z = 0$ m (e); and across-track view at $y = 2$ m (f)).

4.2. Enhanced Processing

As explained above, the SAR images obtained with the basic processing should be improved mainly to obtain a better resolution and a higher signal to clutter ratio. In particular, this is especially important in order to detect shallow buried targets and distinguish them from the air–soil interface. The slices of the SAR image obtained for the second measurement at the position where the cylindrical box is detected are shown to analyze the effect of the proposed improvements.

4.2.1. Height Correction

The results obtained applying the height correction described in Section 3.2 are shown on the left part of Figure 17. Comparing them with the results without the height correction (right part of Figure 15), the cylindrical metallic box has become clearly distinguishable from the air–soil interface. Furthermore, the reflection of the air–soil interface has been mitigated thanks to the second background subtraction applied in the height correction step. This mitigation results in less amplitude in the SAR image around $z = 0$ m, which is especially evident in the YZ slice (where some areas corresponding to the interface have a normalized amplitude smaller than $-30$ dB). As a result, there is an improvement in the signal to clutter ratio. As a side effect, there is also a considerable amplitude in the SAR image approximately under the metallic disk, which might be due to some secondary reflections.
Figure 17. Slices of the 3D SAR image at the position where the cylindrical box is detected when height correction is applied (on the left) and when the SAR image is equalized (on the right): (a,d) along-track views at $x = -0.05$ m; (b,e) top views at $z = -0.14$ m; and (c,f) across-track views at $y = 4.55$ m.

4.2.2. Equalization

The effect of applying the equalization can be observed comparing the SAR image slices when equalization is applied (right part of Figure 17) with the results of the basic processing (right part of Figure 15). As explained above, the goal of the equalization is to effectively use the whole bandwidth, preventing the low frequency data masking the high frequency one. Thus, the range resolution, which corresponds in this case to the resolution in the $z$-axis, should improve with the equalization. This improvement is clearly visible since the width of the high reflectivity areas corresponding to the disk, the box and the air–soil interface is narrower. As a result, the buried box can be now distinguished from the air–soil interface.

4.2.3. Height Correction and Equalization

If both height correction and equalization are applied, the resulting SAR image (shown in left part of Figure 18) has better resolution and higher signal to clutter ratio than the one obtained with the basic processing. Furthermore, the equalization also helps to remove the artifact that appears under the metallic disk after applying the height correction. Thus, the combination of these improvements helps to enhance the range resolution (especially the equalization) and the signal to clutter ratio (mainly by reducing the reflection at the air–soil interface with the height correction).
Figure 18. Slices of the 3D SAR image at the position where the cylindrical box is detected when height correction and equalization are applied. Results on the left are obtained without taking into account the soil composition, whereas results on the right are obtained assuming $\varepsilon_r = 3$: (a,d) along-track views at $x = -0.05$ m; (b,e) top views at $z = -0.14$ m and $z = -0.08$ m, respectively; and (c,f) across-track views.

4.2.4. Soil Composition Consideration

Finally, the soil composition must be taken into account in order to obtain a well-focused SAR image with the buried targets detected at their true depth. Soil permittivity can be estimated from the radar measurements or from the characteristics of the scenario (temperature, soil material components and volumetric water content). A relative permittivity of $\varepsilon_r = 3$ has been assumed, based on previous soil characterization results from [24]. This agrees with the fact that, when free-space propagation is considered, the box is detected at a depth of approximately $d_{\text{box}}\sqrt{\varepsilon_r} = 0.14$ m (being $d_{\text{box}} = 0.08$ m the true depth).

The resulting SAR images are shown in Figure 18b. The box is now detected around its true depth (that is, the depth where the box is detected when it is not covered by soil).

4.3. Comparison

To further compare the results, the histograms of the 3D SAR images amplitudes when using basic and enhanced processing (height correction, equalization and soil composition consideration) are shown in Figure 19 (in blue and orange respectively) for the second measurement (i.e., when there is a buried target). In this figure, the vertical lines indicate the maximum amplitude of the buried target in the corresponding 3D SAR images. This representation allows quantitatively assessing the influence of the proposed enhanced processing. When applying this enhanced processing, the distance between the target amplitude (depicted in the vertical line) and the clutter is increased, which helps to improve the detection capabilities of the system and to reduce the false alarm rate.
5. Conclusions

An enhanced UAV-mounted SAR imaging system to obtain 3D high-resolution radar images (where both underground and overground targets can be detected) is presented. The ultimate goal is the detection of buried hazards, mainly landmines and IEDs, although it can be used for a wide range of application involving both subsurface sensing and terrain observation.

First, several improvements have been implemented in the proposed prototype, mainly to increase the accuracy of the positioning system and the penetration of the electromagnetic waves into the soil. As shown in the results, this allows the coherent combination of measurements gathered at arbitrary positions (3D measurement grid), providing high-resolution radar images, and it also enables the detection of targets buried in higher losses soils.

Concerning the methodology, the processing chain for both the positioning and radar data is thoroughly explained. This methodology can be used to process data collected in both manual and autonomous flight mode, since it selects which measurements will be processed and the location of the investigation domain taking into account the set of UAV positions where measurements were acquired during the flight (i.e., the observation domain). Furthermore, several enhancements in the radar processing are presented to improve the resulting 3D images (mainly in terms of resolution and target discrimination).

Both the prototype and the methodology were experimentally validated with autonomous measurement flights, proving the capability of the system to provide high-resolution 3D SAR images even when using a basic processing strategy. In addition, the effectiveness of the enhanced radar processing was also proved, showing that it yields better resolution and signal to clutter ratio. As expected, results also confirm that, when an estimation of the soil composition is taken into account the buried targets are detected at their true depth.

6. Patents

Supplementary Materials: A video of the system is available online at http://www.mdpi.com/2072-4292/11/20/2357/s1.


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References


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In-situ antenna diagnostics and characterization system based on RFID and remotely piloted aircrafts

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Abstract

A cost-effective solution for in-situ antenna characterization and diagnostics based on Radio Frequency Identification technology and Remotely Piloted Aircrafts is presented. The cost-effectiveness of the proposed solution is achieved by replacing the radio frequency equipment on-board the small aircrafts with Radio Frequency Identification tags, while the Antenna Under Test is connected to a Radio Frequency Identification reader, thus reducing the weight and complexity of the payload of the aircrafts dedicated to antenna measurement task. Received Signal Strength measurements are geo-referred with centimeter-level accuracy thanks to a Real Time Kinematic system. An iterative phase retrieval technique based on the Sources Reconstruction Method is used to recover an equivalent magnetic currents distribution on the Antenna Under Test aperture plane. The reconstructed currents distribution provides antenna diagnostics information and enables the calculation of the antenna radiation pattern. The presented method has been validated by means of measurements in the UHF band for two different antenna arrays with excellent results.

Keywords: Antenna diagnostics, Received Signal Strength (RSS), Radio Frequency Identification (RFID), Antenna radiation pattern, Remotely Piloted Aircraft (RPA), Real Time Kinematic (RTK).

1. Introduction

The great cost reduction of the fabrication technology of small Remotely Piloted Aircrafts (RPAs) has motivated the development of new types of applications in fields such as civil engineering [1, 2], agriculture [3, 4], mining [5], etc.

Although less accurate than anechoic-chamber measurements, in-situ antenna characterization can provide useful information about antenna performance in its final environment while being a less expensive
technique. Thanks to the advances in RPA instrumentation and the availability of Real-Time Kinematic (RTK) hardware capable of providing centimeter-level positioning accuracy, the use of RPAs for in-situ antenna characterization has proven to be more accurate than traditional land-based solutions or manned aircraft-based surveys for in-situ antenna characterization [6].

There are several RPA-based systems available in the literature that have been successfully validated for antenna characterization. In [6] an antenna and a receiver (RX) are installed on-board an RPA for the direct far-field (FF) characterization of high-powered broadcast antenna systems by means of amplitude-only measurements. The weight of the complete system is 9 kg and its autonomy is 25 minutes in wind speeds up to 30 km/h approximately. A similar system has been presented in [7] for the characterization of cellular and multimode networks. The instrumentation on-board the RPA for the antenna characterization is generally composed by a RX antenna and a spectrum analyzer; the RPA control and telemetry system is composed by a mini-computer, a flight controller and GPS systems. Data are sent to the ground control station, composed by a dedicated computer and several TX/RX systems for the telemetry and measurement data reception.

A system for the characterization of the FF of low frequency antenna arrays has been presented in [8, 9, 10]. The instrumentation is slightly different in this example, where the RPA has been equipped with a continuous-wave transmitter (TX) and an antenna which operates as source while the Antenna Under Test (AUT) can register the amplitude data for different positions of the source. Telemetry and flight control instrumentation is similar to the one in the first presented system although in this case, the RPA is equipped with a differential GPS system in order to achieve centimeter positioning accuracy. However, the main limitation of the previous presented systems is that they work in the FF of the AUT and perform direct acquisition of the power emitted by the AUT (i.e. signal strength) for obtaining its radiation pattern and thus, antenna diagnostics cannot be conducted. This limitation has been partially overcome in [11], where the use of navigation and geo-referring systems providing centimeter-level accuracy enable NF acquisition.

Antenna diagnostics [12, 13, 14, 15, 16] is a non-destructive method based on computing an equivalent magnetic currents distribution that, according to the Second Equivalence Principle [17], corresponds to the extremely near field (NF) on the antenna aperture. From the aperture fields antenna diagnostics can be conducted, allowing the detection of failures which prevent the AUT from achieving its expected performance. This is especially interesting for detecting deformations in the antenna structure [14] or antenna array elements malfunction [16]. From the NF acquired data, the FF radiation pattern of the AUT can also be computed by means of NF-FF transformation techniques [18, 19, 20, 21].

In order to perform NF-FF transformations or antenna diagnostics, amplitude and phase information is generally required. Thus, when performing amplitude-only acquisitions, phase retrieval algorithms must be applied.

There are two main approaches for phase retrieval. On the one hand, there are interferometric techniques,
which are based on creating an interference pattern by means of a known source and the AUT [16, 18]. These techniques are accurate and iteration-free, although they require additional hardware to create the interference pattern. On the other hand, there are iterative techniques, which rely on the information provided by the spatial variation of the NF with distance. They require the acquisition of the field on two or more surfaces [19, 20, 21] and their main limitation is the risk of stagnation due to the use of iterative solvers for non-linear system of equations. In the case of iterative techniques based on the Sources Reconstruction Method [21], the field could be acquired as well in an arbitrary cloud of points around the AUT.

Other important limitation of the existing systems for antenna in-situ characterization based-on RPAs is that it requires using an RPA with high maximum takeoff weight in order to cope with the size and weight of the RF payload [6]. This implies, as well, an increase in the required power and size.

Radio Frequency IDentification (RFID) systems have multiple applications in access control, identification, tracking and monitoring goods, vehicles [22] and persons [23]. These systems consist of RFID tags (active, semi-passive or passive [24],[25]), which are inexpensive, and RFID readers, which are significantly more expensive than the former. Among the different RFID standards, in this contribution we will focus on the EPCglobal Gen2 Air Interface Protocol [26] defined for UHF frequency bands, which is also the most widespread and the most suitable for this application. The allocated frequencies for its operation in Europe range from 865.7 to 867.5 MHz in 4 channels. In addition to the extremely low cost of passive RFID tags (euro cents), this technology was selected for this application since the low weight of the tags allows mounting them on a low cost commercial RPA with a limited payload.

Concurrently, RFID technology has been already employed for antenna characterization [27] and gain measurements [28] as well as for indoor tracking and location of RPAs [29] with successful results.

This contribution proposes a novel approach for antenna characterization based on an RFID system. Several tags are fixed to the RPA, avoiding the need for expensive and delicate RF instrumentation onboard, and the RFID reader is connected to the AUT. The reader and the RPA position data are registered while the RPA flights over a set of points surrounding the AUT. The centimeter-level accuracy positioning is achieved using RTK, which is a differential Global Navigation Satellite System (GNSS) that makes use of the GNSS carrier phase [30]. In particular, two GNSS have been used: Global Positioning System (GPS) and GLONASS. A post-processing algorithm whose inputs are the RFID reader lectures and the RPA position data, is implemented in order to process the acquired data and perform the phase retrieval and NF-FF transformation to obtain the antenna radiation pattern. The proposed solution allows for in-situ antenna NF phaseless characterization over a non-regular grid with reduced costs at the RFID frequency bands.

The rest of the manuscript is organized as follows: In Section II, the complete system is described in-depth focusing on the instrumentation, the data acquisition process and the developed algorithms for phaseless antenna diagnostics from NF data, and NF-FF transformation. In Section III two application examples are presented for the characterization of a log-periodic antenna array and an RFID antenna array...
in the UHF band. A discussion about the feasibility and performance of the proposed technique is presented in Section IV. Finally, main conclusions are drawn in Section V.

2. System description

2.1. Overview of the measurement system

The proposed system for antenna characterization based on RFID and RPAs is composed by the following devices:

- An RPA, that includes an array of RFID tags attached to it, and an RTK beacon.
- An RFID reader, which is connected to the AUT.
- A second RTK beacon on a fixed position, which is used as a base station for the RTK system.
- A ground station (e.g. a laptop) connected to the RFID reader. The ground station receives RSS data and RTK positioning information, and processes this information to map RSS measurements with an accuracy of 3-4 cm.

The ground station also runs an iterative phase retrieval technique based on the Sources Reconstruction Method [21] that recovers an equivalent magnetic currents distribution on the aperture plane of the AUT. From this equivalent currents distribution it is possible to identify the radiating sources of the AUT as well as estimating the radiation pattern.

RPA flight path around the AUT can be defined using waypoints. Sometimes waypoints definition is restricted to a minimum distance between two consecutive points. Thus, the RPA can be manually piloted around the AUT in order to acquire sufficient amount of samples of the field radiated by the AUT.

Communication between RPA, RTK beacons, and the ground station can be easily achieved by means of a Wireless Local Area Network (WLAN). For this purpose, a wireless router with a battery is the cheapest and easiest solution. Radio controller works in the 5.8 GHz band.

A block diagram of the system and a flowchart are depicted in Fig. 1. First, the RFID reader is connected to the AUT and the RPA takes off. The RFID reader sends an interrogation signal that is received by all the RFID tags in the AUT coverage area. In this case, the RFID tags are onboard the RPA. These RFID tags will respond to the RFID interrogation signal, which will be received by the RFID reader. The RFID response signal will be forwarded to the ground station together with a time stamp. In parallel, the RTK base station beacon will forward the corrections that must be applied to the GNSS signal to the RTK beacon placed in the RPA. The latter will use these corrections to improve the position accuracy down to centimeter-level. It will also send the calculated geodetic coordinates (Latitude, Longitude and Height) with
a time stamp to the ground station. Therefore, RFID measurements can be geo-referred thanks to the fact that both the position information and the RFID measurements have time stamps.

Geo-referred RFID measurements containing signal strength information (RSS) are introduced in the iterative phase retrieval technique based on the Sources Reconstruction Method. From the reconstructed equivalent currents, AUT diagnostics information and AUT radiation pattern are obtained.

A picture of the devices selected for the measurement setup implementation is shown in Fig. 2. The RPA is a Phantom II model that has 400g maximum payload weight (close-up picture shown in Fig. 3). Three DogBone RFID tags [31], separated λ/8 (4.3 cm at the RFID frequency of 868 MHz), are mounted on a plastic and cardboard structure attached to the landing gear of the RPA (see details on Fig. 3). The reason of this layout is to introduce some spatial diversity, taking advantage of the fact that the RPA will be facing the AUT during the flight tests.

Two Reach units from Emlid [32] are used as RTK beacons. One RTK beacon is mounted inside a 3D printed case at the bottom of the RPA and the GNSS antenna is placed in a mast over a ground plane at the top of the RPA, as shown in Fig. 3. The RTK beacon working as base station is placed on a tripod at a known position.

An Impinj Speedway RFID reader is used, connecting it to the ground station (laptop) using an Ethernet cable.

Concerning the RPA flight path, the main restriction is that acquisition points should be spaced less
Figure 2: Picture of the implemented measurement system. Dashed lines represent wireless links between the RPA, grounded RTK beacon, and the laptop for data gathering and processing. Dotted line represents RPA flight path.

Figure 3: Picture of the RPA (Phantom II model) with the three RFID tags attached and the GNSS antenna on top.
than $\lambda/4$ (8.7 cm at 868 MHz RFID frequency band). RTK provides centimeter-level positioning accuracy so this condition can be easily fulfilled. The use of waypoints allows defining the flight path in advance. However, the autopilot unit of the RPA chosen for this setup (DJI Phantom 2 [33]) uses an internal GPS unit and the coordinates obtained with the chosen RTK beacons cannot be transferred to this autopilot. Besides, the software tool for waypoints and paths definition [34] does not allow placing waypoints closer than 1 m, which is about 3 $\lambda$. Therefore, since RTK information cannot be included for placing waypoints at centimeter-level accuracy, manual flight mode has been selected for the initial tests of the system. Position given by the RTK can be plotted in real-time so the person flying the RPA can visualize the points where RSS samples have been acquired as well as those areas in front of the AUT that have not been measured yet.

The proposed system requires two wireless data links: one for connecting RTK beacons and the ground station, and another for RPA telemetry. As mentioned before, the former works in the 2.4 GHz frequency band, whereas for the selected RPA (DJI Phantom 2) telemetry uses 5.8 GHz frequency band. As RFID operates at 868 MHz (European band), this frequency planning minimizes the risk of electromagnetic interference even when working in the vicinity of the AUT in order to conduct NF measurements.

2.2. Phaseless antenna diagnostics from near field measurements

The RFID reader provides, among other parameters, a time stamp of each measurement, the RSS indicator at the RFID reader side, and the phase of the signal backscattered by the detected RFID tags. In this regard, it should be noted that the amplitude and phase values computed by the reader account for both the direct and the return path, so the round-trip propagation path has to be taken into account. In addition, the chip of the Speedway Revolution Reader [35], which is widely employed among other commercial RFID readers, randomly adds 180 degrees to the measured phase values. Hence, it is not possible to know whether the retrieved phase values are the true ones or the true phase values plus 180 degrees.

To avoid this phase ambiguity introduced by the RFID reader, this contribution makes use of an iterative phase retrieval technique based on the SRM for antenna diagnostics and characterization [21]. The idea is to recover an equivalent magnetic currents distribution on the AUT aperture plane, so that they radiate the same field as the AUT.

The flowchart of the iterative phase retrieval technique is depicted in Fig. 4. It is based on minimizing a cost function $F$ that relates a vector containing the RSS measurements (i.e. amplitude of the electric field, $|E|)$ taken on the RPA flight path with a vector containing the values of the electric field radiated by the equivalent magnetic currents, $Mx$, $My$, on the AUT aperture plane, updated at each iteration. An initial guess for the equivalent currents can be set based on a-priori knowledge of the AUT external geometry (e.g. $Mx = My = 1$ on the area covering the antenna aperture).

Electric field integral equations relate the equivalent magnetic currents with the radiated electric field
(Eq. (2) of [21]). As explained in Section II of [21] these integral equations can be numerically evaluated and stored in two matrices, $Z_{E,Mx}$ and $Z_{E,My}$, whose size is $N \times M$, with $N$ the number of RSS (electric field) samples, and $M$, the number of points in which the AUT aperture is discretized. Thus, the multiplication of $(Z_{E,Mx}, Z_{E,My})$ and $(Mx : My)$ gives the electric field radiated by the equivalent magnetic currents.

Different numerical techniques can be implemented for minimizing the cost function $F$. In this problem, $F$ is non-linear, so non-linear optimization techniques, such as inexact Newton-Raphson [36] or Levenberg-Marquardt [36], must be used. The latter will be considered in this contribution as it has been proved to converge monotonically.

As shown in Fig. 4, at each $k$-th iteration the cost function $F$ is evaluated. If the cost function value is equal to or smaller than a certain pre-defined residual $\epsilon$ (typically $\epsilon = 0.01$) or if the number of iterations $k$ reaches a pre-defined maximum number of iterations $K$, the iterative algorithm is stopped. Convergence is achieved when the algorithm stops before reaching the maximum number of iterations $K$. In that case, it can be stated that the root mean square error of the amplitude of the field radiated by the equivalent currents and the RSS measurements is equal to or less than $\epsilon$.

As mentioned in Section 1 equivalent magnetic currents correspond to the electric field on the antenna
aperture [17]. The field distribution on the antenna aperture can be used for antenna diagnostics, to identify malfunctioning elements in antenna arrays or deformations in the antenna structure (e.g. reflector antennas [14]). It is worth mentioning again the immediate applicability of a system and method capable of providing in-situ antenna diagnostics.

From the reconstructed equivalent currents, the field at any point of the space in front on the antenna aperture plane can be computed, and hence its radiation pattern [13],[21].

Concerning antenna radiated field sampling requirements, phase retrieval methods require the measured field to be sampled at a rate of, at least, $\lambda/4$ [16],[18] (in case of amplitude and phase measurements, the sampling rate can be relaxed to $\lambda/2$ [13]). The use of an iterative phase retrieval technique based on the SRM [21] also overcomes the restriction of using a regular acquisition grid. This feature is a key issue in order to perform antenna diagnostics from a set of measurements taken at arbitrary positions, provided these measurements fulfill the aforementioned sampling rates.

3. Application examples


The proposed RFID-based system for in-situ antenna measurement and characterization has been validated by means of the characterization of two different AUTs. The AUT for the first test consists on an array of two log-periodic antennas whose working frequency band ranges from 400 MHz to 3.6 GHz [37]. These antennas are mounted as shown in Fig. 5, so that the separation is $1.3\lambda$ at 868 MHz. These antennas are fed though a power combiner/divider connected to port 1 of the RFID reader.

The flight path is shown in Fig. 6 together with the measured RSS at each position. For each flight path position, three RSS values are collected, each corresponding to the three RFID tags onboard the RPA. Several RSS combination strategies have been tested, such as taking the average or the maximum envelope of the three RSS values, although the way in which RSS values are combined does not impact significantly antenna diagnostics and FF pattern results. An example of measured RSS values is depicted in Fig. 7.

It can be noticed that the flight path fits a 5 m x 3 m aperture placed on average 3 m in front of the AUT. As the separation between the two log-periodic antennas is $1.3\lambda$ it can be expected the presence of grating lobes in the radiated field, as observed also in Fig. 6 (grating lobes placed at $x = -2$ m and $x = +2$ m). Flight took around 5 minutes, collecting an overall amount of 5500 samples at an average rate of 20 samples per second.

RSS measurements are matched with the positions given by the RTK system using time stamp information. Next, the 5500 geo-referred RSS samples are introduced in the iterative phase retrieval technique based on the SRM. The equivalent magnetic currents are recovered on a 2 m x 2 m plane placed on the antenna aperture plane, discretized into 41x41 points. In this example the Levenberg-Marquardt algorithm stopped
after reaching the condition of maximum number of iterations ($K = 30$) achieving a residual $\epsilon = 0.051$ (larger than the targeted residual of $\epsilon = 0.01$). The error between the measured field amplitude (i.e. RSS values) and the field amplitude radiated by the reconstructed equivalent magnetic currents is depicted in
Figure 7: RSS values (300 samples) for the three RFID tags onboard the RPA. Averaged and maximum values are depicted.

For comparison purposes, the log-periodic antenna array has been measured at spherical range in anechoic chamber, using a SH400 probe antenna [38] (Fig. 9). AUT - probe distance is 5.25 m. Measured field has
been sampled every 2 degrees in $\theta$ and every 3 degrees in $\phi$.

![Image](image-url)

Figure 9: Measurement setup of the log-periodic antenna array at spherical range in anechoic chamber. Probe antenna SH400 is visible in the right side of the picture.

The amplitude of the equivalent magnetic currents on the aperture plane is plotted in Fig. 10 (a)-(c) considering different ways of combining RSS values from the three RFID tags onboard the RPA. In all the cases, the two log-periodic antennas separated 45 cm can be identified. Slightly better diagnostics results are obtained (Fig. 10 (c)) when the maximum envelope of the RSS measurements is taken as input in the iterative phase retrieval technique. As a reference, the reconstructed equivalent magnetic currents from anechoic chamber measurements are depicted in Fig. 10 (d). The relative radiation level of each antenna can be also assessed, which is of special interest for detecting malfunctioning elements in antenna arrays. In this case, both antennas are identically manufactured and the feeding is symmetric, so the difference in the aperture fields for each log-periodic antenna is hardly -2 dB.

From the reconstructed equivalent currents the radiation pattern can be calculated. For this example, the radiation pattern is depicted in Fig. 11 (UV plot) and Fig. 12 ($\varphi = 0^\circ$ and $\varphi = 90^\circ$ cuts). Results for RSS measurements (Fig. 11 (a)-(c)) and anechoic chamber measurements (Fig. 11 (d)) are compared: in both cases, the main lobe and the grating lobes can be clearly identified.

Focusing on the FF pattern main cuts (Fig. 12), for $\varphi = 0^\circ$ the position and width of the main lobe and array factor grating lobes calculated from RSS measurements fit the FF pattern calculated from anechoic chamber measurements. In the case of $\varphi = 90^\circ$, the radiation pattern of each log-periodic antenna element is not affected by the antenna array factor, so the radiation pattern is less directive. As in the case of antenna
diagnostics results, taking the maximum envelope of RSS measurements provides more accurate results than
the rest of the tested RSS values combinations.

3.2. Example 2: RFID antenna array.

For the second validation example, an array of two UHF RFID antennas [39] has been chosen. These
antennas have been placed at different heights aiming to test an array of two antennas arbitrary placed. As in
Section 3.1 RFID antennas are connected to the port 1 of the RFID reader through a power divider/combiner.
For this example 6500 samples have been collected in a 7-minutes flight. RSS measurements and RTK
positions are depicted in Fig. 13. A 30 s video of the RPA flight showing geo-referred RSS measurements
in real-time can be watched at https://youtu.be/94hjel_S1DI.

Geo-referred RSS measurements have been processed again with the iterative phase retrieval technique
based on the SRM, taking the maximum envelope of the three RFID tags onboard the RPA. As in the
example of Section 3.1, the equivalent magnetic currents are recovered on a 2 m x 2 m planar surface placed
on the antenna aperture plane, discretized into 41x41 points. For this example the Levenberg-Marquardt

Figure 10. Reconstructed equivalent currents on the log-periodic antenna array aperture. (a) From RSS measurements, one
RFID tag. (b) From RSS measurements, maximum envelope of two RFID tags. (c) From RSS measurements, maximum envelope
of three RFID tags. (d) From measurements (amplitude and phase information) at spherical range in anechoic chamber.
algorithm stopped again after reaching the maximum number of $K = 30$ iterations with a residual of $\epsilon = 0.065$ (larger than the targeted residual of $\epsilon = 0.01$). The amplitude of the reconstructed equivalent currents as well as a picture of the RFID antenna array is plotted in Fig. 14. It can be noticed that the maximum intensity of the reconstructed equivalent currents fits the position of the RFID antennas. As both antennas are of the same model and the feeding is symmetrical, aperture fields present the same amplitude level.

From the reconstructed equivalent magnetic currents, the antenna array radiation pattern is calculated (Fig. 15 (a)). It can be noticed that, as the two RFID antennas are spaced more than $1\lambda$ over the array axis, radiation pattern also exhibits grating lobes in such axis (Fig. 15, $\phi = -40^\circ$) similarly to the radiation pattern of the log-periodic antenna array analyzed in Section 3.1. The radiation pattern calculated from measurements at spherical range in anechoic chamber is depicted in Fig. 15 (b), confirming the presence of the aforementioned grating lobes.
Figure 12: Log-periodic antenna array radiation pattern main cuts. (a) $\varphi = 0^\circ$. (b) $\varphi = 90^\circ$. Solid black line: radiation pattern calculated from the reconstructed equivalent currents using anechoic chamber measurements. Solid red line: radiation pattern calculated from the reconstructed equivalent currents using RSS measurements (one tag). Dash-dotted blue line: radiation pattern calculated from the reconstructed equivalent currents using RSS measurements (maximum envelope of two tags). Dashed green line: radiation pattern calculated from the reconstructed equivalent currents using RSS measurements (averaging three tags). Solid green line: radiation pattern calculated from the reconstructed equivalent currents using RSS measurements (maximum envelope of three tags).

4. Discussion

The technical specifications and capabilities of the proposed RFID-based system for antenna characterization using RPAs has been compared in Table 1 with those already presented in the literature. In this contribution, the main advantage from a hardware point-of-view is the fact that the RPA payload is reduced thanks to the use of RFID technology, avoiding boarding a receiving probe antenna and a power detector [11]. Minimizing the payload weight also enables using smaller RPAs. This issue is of special interest in the case of NF measurements for antenna characterization and diagnostics, as flying larger RPAs in the vicinity of the AUT increases the risk of damaging the AUT in case of an accidental collision. Thus, the use of smaller, low-weight RPAs provides safer operating conditions. Even when flying hundreds of meters away from the antenna as in [6], [8], [9], [10] for direct FF measurements, piloting larger RPAs requires higher...
Figure 13: RFID antenna array. Measured RSS levels in the RPA flight path. (a) XY view. (b) 3D view.

Figure 14: Reconstructed equivalent currents on the RFID antenna array aperture. Picture of the RFID antenna array overimposed.
degree of expertise. Furthermore, civil regulations and required licenses for RPA operation in non-controlled airspace are related to RPA take-off weight, typically RPAs $< 2$ kg, RPAs $< 25$ kg, and RPAs $> 25$ kg [40]. Heavier RPAs require additional licenses and are subject to more restrictive regulations, which eventually impacts on the overall cost of the system.

The main drawback of the proposed system is the fact that the AUT can be tested only at RFID frequency bands, apart from requiring the AUT to be connected to the RFID reader. It must be noticed the higher uncertainty of the proposed technique concerning AUT radiation pattern characterization. This is due to the fact that small measurement uncertainties in the NF (such as multipath propagation, RFID tag pattern) affect the phase retrieval technique and thus the NF-FF transformation, as also happens in [11] when operating in the NF region. In the case of [6],[8],[9],[10], FF pattern is directly measured, so FF uncertainties are mainly due to RPA positioning errors.
Table 1: Comparison of antenna measurement techniques using RPAs.

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<tbody>
<tr>
<td>Frequency range</td>
<td>9 kHz - 12 GHz</td>
<td>30 - 900 MHz</td>
<td>2 - 5 GHz</td>
<td>RFID frequency bands (868 MHz in Europe).</td>
</tr>
<tr>
<td>Positioning system. Accuracy</td>
<td>GPS, Angular resolution 1°</td>
<td>GPS. Up to 1 cm with a tracking station.</td>
<td>RTK and laser altimeter (1-2 cm).</td>
<td>RTK (3-4 cm).</td>
</tr>
<tr>
<td>Measurement region</td>
<td>Far field</td>
<td>Far field</td>
<td>Near field / Far field</td>
<td>Near field / Far field</td>
</tr>
<tr>
<td>Radiation pattern uncertainty</td>
<td>+/- 3 dB</td>
<td>1 dB</td>
<td>+/- 4 dB</td>
<td>5 - 6 dB</td>
</tr>
<tr>
<td>AUT diagnostics capabilities</td>
<td>None</td>
<td>None</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Onboard receiving unit</td>
<td>Required</td>
<td>Required</td>
<td>Required</td>
<td>Not required</td>
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5. Conclusions

A simple, low-cost in-situ antenna diagnostics system based on RFID technology has been presented. Thanks to the use of RTK, RFID measurements are geo-referred with centimeter-level accuracy, which enables the use of an iterative phase retrieval technique based on the Sources Reconstruction Method to recover the electric field distribution on the antenna aperture plane. This distribution provides information about the AUT radiating elements, and it can be also used for AUT radiation pattern calculation.

From the results presented in this contribution, the system has been proved to be quite effective for antenna diagnostics, even when flying the RPA in manual mode without a pre-defined path using waypoints. Further work will be devoted to integrate RTK information in the RPA flight controller to create waypoints with centimeter-level accuracy, which will provide more accurate acquisition paths, as well as measurements repeatability. Besides, the use of a RFID reader capable of providing phase without 180°-ambiguity will be also assessed enabling direct acquisition of the phase of the radiated field.

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Antenna Diagnostics and Characterization using Unmanned Aerial Vehicles

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Abstract— This contribution presents a compact, low-cost Unmanned Aerial System for Antenna Measurement (UASAM). The proposed system overcomes existing limitations in terms of Unmanned Aerial Vehicle (UAV) positioning and data geo-referencing accuracy using a Real Time Kinematic (RTK) positioning system to achieve cm-level accuracy. Amplitude-only measurements acquired using a low-cost power sensor are processed by means of the phaseless Sources Reconstruction Method (pSRM). This is an iterative phase retrieval technique that allows recovering an equivalent currents distribution which characterizes the Antenna Under Test (AUT). From these equivalent currents, Near-Field to Far-Field (NF-FF) transformation is applied to calculate the AUT radiation pattern. This contribution also analyzes probe antenna characterization, and the impact of positioning and geo-referencing accuracy on the radiation pattern. Two application examples of antenna measurement at S and C bands using the implemented system are presented.

Index Terms—Unmanned Aerial Vehicles (UAVs), antenna measurement, antenna diagnostics, Real Time Kinematic (RTK), phaseless measurements, Near-Field to Far-Field transformation (NF-FF), Sources Reconstruction Method (SRM).

I. INTRODUCTION

In the last years Unmanned Aerial Vehicles (UAVs) have experienced a great cost reduction while improving technical capabilities such as avionics and propulsion systems [1], batteries capacity, obstacle avoidance methods [2], multiband communications [3], and sensor integration. These achievements have fostered the introduction of UAVs in a wide field of applications such as archaeology [4], environmental monitoring [5], civil engineering [6], and assistance in natural disasters [7].

In the field of electromagnetic emissions and antenna measurement, UAVs have enabled the possibility of performing in-situ evaluation of radiating systems [8],[9]. This kind of measurements, although less accurate than those performed in anechoic chambers or outdoor ranges, allow the evaluation of the antenna radiation pattern in realistic conditions, as well as assessing the influence of the environment in the radiation pattern (e.g. distortion due to multipath contributions in ground, surrounding buildings, etc.).

Current UAV-based antenna measurement systems are mostly based on an antenna connected to a power detector or a spectrum analyzer onboard the UAV, which transmits the measured data and UAV position to a ground station. A waypoint path defined around the Antenna Under Test (AUT) is pre-defined prior operation [8],[10]. In some implementations, the UAV is equipped with a continuous wave transmitter, being the AUT the receiver [11].

UAV-based antenna measurement systems have been introduced for practical applications and projects such as testing the antennas for the Square Kilometer Array (SKA) project [12], assessing the integrity of radionavigation signals (VHF omni-directional range, VOR) [13], and characterizing cellular and multimode networks [8]. These results prove the accuracy and cost effectiveness of UAV-based systems over traditional land-based solutions or manned aircraft based surveys for in-situ antenna characterization.

The aforementioned UAV-based antenna measurement systems are based on direct measurement of the radiation pattern, with the UAV acquiring data in the far field (FF) region of the antenna. For low frequencies or electrically large antennas, the far field region can be hundreds of meters from the AUT. This fact has two main advantages: i) positioning errors are less critical as acquisition points can be separated tens of meters, and ii) Near-Field to Far-Field (NF-FF) transformation is not required to obtain the AUT radiation pattern. However, there are some drawbacks: i) longer flight path for full pattern measurement, which might require several flights due to UAV flight autonomy, ii) flight restrictions that may limit the scan zone (e.g. flying over crowded areas, restricted zones, beyond visual line of sight). These constraints may limit the practical implementation of the method.

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To overcome these limitations, and thanks to the improvements in UAV positioning and data geo-referring accuracy, Near Field (NF) measurements have been proposed. [14],[15] describe a NF antenna measurement technique using airborne NF-probes onboard UAVs, and a laser tracking system for accurate positioning, whereas in [16] an analysis of different scanning strategies (definition of acquisition grids using waypoints) is presented.

The concept of performing antenna diagnostics from NF measurements is already mentioned in [15],[16]. Yet, Near-Field to Near-Field (NF-NF) transformation to recover the field in the vicinity of the AUT (e.g. aperture fields) enables antenna diagnostics capabilities, which is of great interest in order to detect malfunctioning elements or distortions in the antenna structure [17]. When dealing with complex AUT geometries, the use of an equivalent current distribution reconstructed from NF measurements on a surface fitting the AUT geometry has been proved to be a successful methodology for antenna diagnostics [18]-[20]. Besides, once the equivalent currents are reconstructed, NF-FF can be applied to obtain the AUT radiation pattern.

In order to keep the cost and the complexity of the UAV-based antenna measurement system low, amplitude-only acquisition is preferred, avoiding the need of coherent receivers for phase measurements. Thus, in order to perform NF-NF and NF-FF transformations, phase retrieval methods [21] have to be considered. In addition to this, aiming to keep the hardware complexity onboard the UAV as low as possible, iterative phase retrieval techniques based on equivalent currents [22] are used instead of indirect holographic techniques [23].

This contribution presents a UAV-based system for antenna diagnostics and characterization (Unmanned Aerial System for Antenna Measurement, UASAM) which tries to overcome some of the limitations in current state-of-the-art systems.

A. Highlights

The main advantages and novelties of the system presented in this contribution (UASAM) with respect to similar systems are:

i) Use of a compact, low-cost UAV, thanks to the fact that the payload is reduced to a low profile antenna and a power detector.

ii) Centimeter-level accuracy data geo-referring achieved by means of a Real Time Kinematic (RTK) system, which is a differential Global Navigation Satellite System (GNSS) that makes use of the GNSS carrier phase [24]. A laser altimeter is integrated to improve accuracy in height.

iii) Capability of AUT diagnostics and characterization from NF phaseless measurements, thanks to the use of the phaseless Sources Reconstruction Method (pSRM) that can handle arbitrary-geometry NF grids [23] (details in Section III).

iv) Low sensitivity to UAV positioning (as it will be explained in Section IV), which can be of interest in windy operating conditions.

An overview of the UASAM features can be watched in the video accompanying this contribution.
Fig. 2 shows a picture of the UAV with the RTK and the probe printed monopole antenna onboard.

The UAV frame is composed by the F550 model of DJI [25], with a total 2400 g payload capacity. The UAV is controlled with a Navio2 board [26] attached to a Raspberry Pi running ArduCopter [27].

A printed monopole antenna is selected as a probe. The choice of this kind of antenna and its characterization is explained in Section III. The onboard probe antenna is connected to a compact, low-cost power sensor based on the AD8318 chip [28], which has a dynamic range of 50 dB. The analog output is digitalized and passed to the Raspberry Pi, then sent to the ground station together with the RTK positioning information.

The RTK system consists of two units based on the u-blox NEO-M8T chip [29] acting as RTK beacons. One is designed as the mobile RTK beacon, placed onboard the UAV. As depicted in Fig. 2, the RTK antenna is placed over a ground plane in a pole at the top of the UAV. The RTK beacon working as base station is placed on a tripod at a fixed, known position. This base station beacon forwards the corrections that must be applied to the GNSS signal to the RTK beacon placed in the UAV (as depicted in Fig. 1). The latter applies these corrections reducing the position uncertainty down to cm-level.

A compact laser altimeter [30] is also mounted at the bottom of the UAV frame to improve the accuracy of height positioning. The flight controller combines the positioning and attitude information data provided by the positioning systems (RTK, laser altimeter, inertial sensors, standard GNSS and barometer) to obtain the geodetic coordinates (Latitude, Longitude and Height), which are sent to the ground station together with a time stamp.

The ground station runs the algorithms that process the georeferred amplitude-only field measurements to calculate the antenna radiation pattern and to obtain antenna diagnostics information.

B. Phaseless Sources Reconstruction Method

One of the drawbacks of using power detectors for antenna measurement is that phase information cannot be directly measured, thus requiring phase retrieval methods [21]-[23]. The UASAM makes use of the phaseless Sources Reconstruction Method (pSRM), an iterative phase retrieval technique where an equivalent electric and magnetic currents distribution is recovered on a surface enclosing the AUT [22]. Iterative phase retrieval techniques require the measurement of the NF on two or more acquisition surfaces, as the spatial variation of the field distribution with distance in the AUT NF region contains sufficient information to allow for phase recovery [22].

As a simplified scheme but without losing generality, an infinite plane can be considered as the enclosing surface (reconstruction domain); then, the Second Equivalence Principle [31] can be established to reconstruct the magnetic equivalent currents that radiate the same field as the AUT outside the reconstruction domain. As explained in [22], the enclosing surface can be truncated in some cases to a plane placed on the AUT aperture.

The reconstructed equivalent currents provide antenna diagnostics and, by means of NF-FF transformation, the AUT radiation pattern can also be calculated.
The flowchart of the pSRM is shown in Fig. 3. The inputs are the measured amplitude of the radiated field, geo-referred with cm-level accuracy thanks to the RTK system, and an initial guess for the equivalent currents (e.g., a uniform distribution on the area covering the antenna aperture, \( I_{eq} = 1 \), and \( I_{eq} = 0 \) elsewhere).

Then, a non-linear cost function relating the measured amplitude and the amplitude of the field radiated by the equivalent currents is minimized. For this purpose, non-linear optimization techniques, such as Newton-Raphson and Levenberg-Marquardt, have been considered. The iterative algorithm stops if the cost function value is smaller than a certain threshold \( \varepsilon \), or if a maximum number of iterations \( K \) is reached. Finally, from the equivalent currents, the field at any point of the space as well as the AUT radiation pattern can be evaluated.

An important feature of the SRM [19] (and also the phaseless version pSRM) is the capability of handling arbitrary-geometry field acquisition and equivalent currents reconstruction domains, provided that they are properly sampled, i.e., adjacent points spaced \( \Delta r \leq \lambda/2 \) in the case of amplitude and phase measurements, and \( \Delta r \leq \lambda/4 \) for amplitude-only acquisitions [32].

To reduce the calculation time of the pSRM, the algorithm has been coded using Graphics Processing Units (GPU) [33].

III. PROBE ANTENNA CHARACTERIZATION

A key component of the UASAM is the probe antenna. During the design stage several options already used in related works, such as dipole antennas [11], log-periodic antenna arrays [10], biconical probes, or horn antennas [14], were considered. However, the use of directive antennas would require probe correction techniques. Besides, UAV attitude uncertainties will have a higher impact in NF measurements when considering directive probes due to AUT-probe orientation misalignments. For this reason, low-directive antennas have been widely considered as probes for UAV-based antenna measurement systems, and so for the UASAM.

![Printed monopole antennas](image1)

![Normalized radiation pattern](image2)
Besides directivity, there are other parameters, such as working frequency band, bandwidth, weight, size, and polarization purity that must be taken into account for probe antenna selection. In this contribution, S and C bands will be considered.

Printed monopole antennas fulfill the requirements of low directivity, low weight and compact size. Two printed monopole antennas, shown in Fig. 4, are considered. The first one is a commercial antenna [34] working in the 4 to 7 GHz band (S\textsubscript{11} depicted in Fig. 5), and the second one is a customized hexagon-shaped printed monopole antenna [35], working in the 2.5 to 5 GHz frequency band (2.6 to 4.7 GHz if a -17 dB S\textsubscript{11} threshold is considered, Fig. 5).

![Customized hexagon-shaped printed monopole antenna radiation pattern](image)

Radiation patterns of such probes have been measured at the spherical range in anechoic chamber of the University of Oviedo at the frequency of 4.65 GHz. From Fig. 6 it can be concluded that the commercial monopole antenna exhibits better symmetry with respect to the H plane (XZ plane in Fig. 6). In the case of the customized hexagon-shaped printed monopole antenna, it has better rotation symmetry around y axis than the commercial monopole antenna.

Next, the accuracy of the measurements when considering these monopoles as probes has been benchmarked against a Standard Gain Horn (SGH) antenna at 4.65 GHz. For this test, a second hexagon-shaped printed monopole antenna has been chosen as the AUT. Measurement results at the spherical range in anechoic chamber for the commercial printed monopole antenna are depicted in Fig. 7. It can be noticed the agreement in the copolar component for both probes. However, in the case of the crosspolar there are some discrepancies. This is due to the fact that the crosspolar level of the printed monopole antenna is 15-20 dB higher than the SGH.

**IV. ACCURACY ANALYSIS**

One of the most critical parameters concerning UAV-based NF measurements is UAV positioning. Inertial navigation systems, GNSS uncertainties, and weather conditions introduce deviations in the flight path of the UAV with respect to the pre-defined one.

UAV positioning error is defined as the distance between the targeted and real flight path, whereas geo-referring error is the distance between the true UAV position and the UAV position estimated by the RTK, laser altimeter, and inertial sensors.

In the case of FF measurements, where the separation between waypoints can be tens of meters, positioning errors with current UAV positioning and navigation systems can be around 1 m, having little impact in the measurements [8]-[12].

![Flowchart of the procedure to evaluate the impact of positioning and geo-refering errors in the far field pattern](image)

In the case of NF measurements, the use of NF-NF techniques capable of handling arbitrary-geometry acquisition domains [18],[19] overcomes the requirement of accurate positioning provided that the positions where data is acquired are accurately geo-referred. To address this problem, [15] proposes the use of a laser-tracker system, that provides mm-level accuracy (enabling measurements up to 40 GHz) but at the...
expense of increasing the complexity of the system and its cost. UASAM uses a RTK module and a laser altimeter for positioning and data geo-referring with cm-level accuracy. That limits the upper working frequency to approximately 5-6 GHz ($\frac{c}{4} = 1.5 - 1.9$ cm), but still covers the working frequency band of a wide variety of wireless communications systems (e.g. radio and television broadcasting, and/or mobile networks, radionavigation systems).

An analysis of the impact of positioning and geo-referring errors is conducted next, following the procedure depicted in Fig. 8. For this purpose, an AUT consisting of a linear array of two horn antennas working at 4.65 GHz (for further details please refer to Section V.B) has been measured at the spherical range in anechoic chamber. Then, an equivalent currents model has been calculated to have an electromagnetic equivalent model of the AUT which allows the evaluation of the field radiated by the AUT at the positions of interest [22].

Two cylindrical acquisition domains of radius $R = 3$ m and $R = 4$ m and height $h = 2$ m have been defined. The coordinates of the cylindrical acquisition domain are the targeted UAV flight path. The targeted flight path is compared against the true UAV flight path (Fig. 9) in order to quantify the positioning errors. The probability density function of the error (Fig. 9 (b)) shows that the positioning error in $x$ and $y$ axes is around 15-30 cm, whereas in $z$ it is reduced to less than 10 cm.

The geo-referring uncertainty of the RTK system has been measured by placing the UAV at a fixed location, then recording RTK geolocation data for ten minutes. The same experiment has been done in a different day, placing the drone in another position. In the horizontal plane ($x, y$ axes), RTK geo-referring standard deviation is approximately $\sigma_{x,y} = 1-1.5$ cm. However, in height ($z$ axis), RTK geo-referring standard deviation increases up to $\sigma_z = 3-4$ cm. This uncertainty is reduced to $\sigma_z = 1-2$ cm thanks to the use of the laser altimeter [30].

In order to evaluate the impact of geo-referring errors in the radiation pattern, random errors following a normal probability density function $N(0, \sigma)$ are introduced in the true UAV flight path coordinates.

![Fig. 9. (a) Targeted and true flight paths in the XY plane. (b) Probability density function of the positioning errors in x, y, z axes, and combined.](image)

![Fig. 10. Impact of positioning and geo-referring errors in the far field pattern (H plane, $\phi = 0^\circ$) when considering amplitude-only NF data. FF pattern form NF amplitude and phase data (black line) is depicted as a reference.](image)

From the equivalent currents model of the AUT, NF has been calculated at: i) targeted UAV positions, ii) true UAV positions with no geo-referring error, and iii) true UAV positions with geo-referring error. Next, the pSRM is applied to calculate the AUT FF pattern from the amplitude of the calculated NF, considering positioning and geo-referring errors.

Results depicted in Fig. 10 show that positioning errors (with no geo-referring error) have little impact in the radiation pattern (less than 1 dB difference). However, even when considering the low measured geo-referring uncertainty of the UASAM ($\sigma_{x,y} = 2$ cm, $\sigma_z = 1$ cm), differences in the sidelobe levels can be noticed. Increasing the geo-referring uncertainty to $\sigma_{x,y} = 4$ cm, $\sigma_z = 2$ cm increases these differences.

To sum up, the capability of the pSRM to handle arbitrary-geometry acquisition domains minimizes the impact of UAV positioning errors in the calculation of the FF pattern from amplitude-only NF measurements. However, the true
coordinates of the measurement positions must be precisely known.

V. VALIDATION

Aiming to test the UASAM upper frequency limits for antenna measurement, two application examples at S and C bands respectively are presented. Tests have been conducted at the airfield authorized by the Spanish Agency of Air Safety (AESA) located at the Technical School of Engineering of Gijón (coordinates 43.521698, -5.623983).

Antenna diagnostics and FF pattern results have been benchmarked against measurements at a spherical range in anechoic chamber. Measurement uncertainties have been assessed by comparing the measured NF with the field radiated by an equivalent currents model of the AUT at the UAV positions, as depicted in the flowchart of Fig. 11.

A. S-band horn antenna array

The first AUT consists of an array of two horn antennas working in the 2.5 – 4 GHz frequency band, measured at the frequency of 2950 MHz using the customized hexagon-shaped printed monopole antenna. The separation between the two horn antennas is 2.6\(\lambda\) (26 cm), resulting in a radiation pattern with several grating lobes.

The power of the signal generator is +10 dBm. The output is connected to a power divider to feed both horn antennas. The AUT is placed in the center of the airfield, at the top of a 3 m height pole (see Fig. 12). The ground RTK unit is deployed around 10 m away from the AUT. The ground station (a laptop) is set at one of the edges of the airfield. For this AUT, the FF region starts at \(R_{FF} = 2D^2 / \lambda = 4.9\) m [32] (with \(D = 0.5\) m, the AUT size).

Different acquisition domains can be considered (planar, cylindrical, spherical). The UAV is capable of flying around the vertical axis of the AUT while keeping the orientation towards that axis. Thus, a cylindrical acquisition path has been found to be the NF measurement domain most suitable for this case, as it only introduces truncation error in the vertical axis. Two cylinders of R = 3 m and R = 4.5 m, and height ranging from 2 m to 4 m have been considered, sampling every 15 cm in height.

UASAM deployment and setup time took around 15 min for this example. Measurement time for each cylindrical surface was approximately 10 min (R = 3 m) and 15 min (R = 4.5 m), with the UAV moving at 1.2 m/s. Measurements are taken every 25 ms, so the spacing between two consecutive positions in the horizontal plane is 3 cm (0.3\(\lambda\)). An average of 750 samples per ring (\(z = \text{constant}\)) of the cylindrical domains are taken. Results, for this example, in around 22500 NF samples.
Measurements were geo-referred using the information provided by the different sensors (RTK, laser altimeter, inertial sensors). As observed in Fig. 13, the main lobe and the sidelobes (actually, grating lobes) can be noticed.

For validation purposes, the AUT has been measured at the spherical range in anechoic chamber, then applying the SRM to obtain an equivalent model of the AUT to evaluate the NF at the UAV measurement positions. A comparison between the amplitude of the measured NF and the NF radiated by the electromagnetic equivalent model of the AUT at UAV positions is depicted in Fig. 14 (XZ plane projection) and Fig. 15 (H plane). Differences are mainly due to orientation misalignment between the AUT and the probe antenna (wind gusts and positioning errors influence the UAV steering towards the AUT).

![Fig. 14. NF amplitude at UAV positions, f = 2950 MHz (targeted flight path: R = 4.5 m radius cylinder). (a) Simulated from AUT equivalent currents model. (b) UASAM measurements.](image)

![Fig. 15. NF amplitude, H plane. f = 2950 MHz. Comparison between simulation from AUT equivalent currents model and UASAM measurements.](image)

Geo-referred NF measurements are post-processed by the pSRM. Equivalent magnetic currents (that is, aperture fields) are recovered on a 70 cm x 70 cm plane placed in front of the AUT aperture. For comparison purposes, equivalent magnetic currents using simulated NF at the UAV flight path positions are also recovered. The inverse problem to be solved involves 22500 equations (NF samples at the two measurement domains) and 225 unknowns. Thanks to the use of the GPU version of the pSRM [33], equivalent currents are recovered in less than 10 s.

![Fig. 16. Reconstructed aperture fields (equivalent magnetic currents), f = 2950 MHz. (a) From simulated NF at UAV positions, considering amplitude and phase information. (b) From simulated NF at UAV positions, phaseless reconstruction. (c) From measured NF amplitude.](image)

Reconstructed equivalent currents are depicted in Fig. 16, showing that the placement of the two horn antennas as well as the relative emitted power level of each of them can be identified. As expected, in the case of UASAM, measurements uncertainties (geo-referring errors, AUT-probe in-flight misalignments) degrade the quality of the reconstruction. It must be pointed out that the use of amplitude-only information also impacts the results, as it can be noticed when comparing Fig. 16 (a) and Fig. 16 (b).

From the aperture fields, the AUT radiation pattern can be calculated. Taking into account the height of the cylinder (2 m, from 2 m to 4 m) and the radius (4.5 m) of the outer cylinder, the valid angular margin in the vertical plane (E plane) is just 25º [32]. In the horizontal plane (H plane), no truncation errors occur. FF pattern comparison is depicted in Fig. 17. As in the case of aperture fields, geo-referring errors and AUT-probe in-flight misalignments are the main sources of error that results.
in 4-5 dB discrepancies between FF pattern from NF measurements at spherical range in anechoic chamber, and FF pattern from NF measurements using the UASAM. These differences are in agreement with the ones depicted in Fig. 10, where the impact of geo-referring errors was analyzed.

![Fig. 17. AUT far field pattern comparison (H plane). \( f = 2950 \text{ MHz} \)](image1)

**B. C-band horn antenna array**

In this example, the S-band horn antennas of Section V.A have been replaced by two horn antennas working at 4 – 6 GHz. Measurements were conducted at 4650 MHz using the commercial printed monopole antenna as probe. The AUT is fed with a Voltage Controller Oscillator (VCO) plus a RF amplifier that delivers up to +10 dBm. As in the previous example, the AUT is placed on top of a 3 m height pole (see Fig. 18). The two horn antennas are separated also 26 cm, but as the wavelength is smaller, the electrical distance is 4 \( \lambda \), expecting more lobes in the radiation pattern. Given the AUT size, \( D = 0.5 \text{ m} \), FF distance is \( R_{FF} = 7.8 \text{ m} \).

For this example, two cylindrical grids at \( R = 3 \text{ m} \) and \( R = 4 \text{ m} \) have been considered, extending the height of the cylinders from 1.5 m to 4.5 m. Amplitude of the measured NF at the geo-referred UAV positions for the \( R = 4 \text{ m} \) grid is plotted in Fig. 19. The presence of several sidelobes can be observed.

For validation purposes, the methodology depicted in Fig. 11 flowchart has been followed. Thus, a comparison between the measured NF and the NF radiated by an equivalent currents model of the AUT is plotted in Fig. 20. With respect to Example V.A (Fig. 15) it can be noticed a better agreement between simulated and measured NF. This is due to: i) the fact that the commercial printed probe antenna has a more symmetric pattern that the customized hexagon-shaped printed monopole antenna (see Section III), ii) UAV had a more stable flight (weaker wind gusts).

![Fig. 18. Picture of the UASAM measurement setup. AUT: array of two horn antennas at 4650 MHz.](image2)

![Fig. 19. Measured amplitude of the NF radiated by the AUT at the UAV flight path positions. Targeted flight path: cylindrical domain of radius \( R = 4 \text{ m} \). \( f = 4650 \text{ MHz} \). Axes centered at the AUT position.](image3)
Fig. 20. NF amplitude, H plane. Comparison between simulation from AUT equivalent currents model and UASAM measurements.

Fig. 21. Reconstructed aperture fields (equivalent magnetic currents), \( f = 4650 \) MHz. (a) From simulated NF at UAV positions, considering amplitude and phase information. (b) From simulated NF at UAV positions, phaseless reconstruction. (c) From measured NF amplitude.

Next, the pSRM is applied to recover the equivalent magnetic currents on the AUT aperture plane (100 x 60 cm, discretized in 714 points). For this example, the number of NF field samples is around 19200. As in the Example of subsection V.A, the placement of the two horn antennas as well as the relative emitted power level of each can be identified (Fig. 21).

Finally, FF pattern is calculated from the reconstructed equivalent magnetic currents on the AUT aperture plane. Results depicted in Fig. 22 show 4-5 dB difference between FF patterns calculated from simulated NF at UAV positions and from amplitude-only measurements. Again, the error level is in agreement with the one observed in Fig. 10, for a geo-referring error of \( \sigma_x = 2 \text{ cm}, \sigma_y = 1 \text{ cm} \).

Fig. 22. AUT far field pattern comparison (H plane). \( f = 4650 \) MHz.

VI. DISCUSSION

Table I compares the technical specifications of the presented UASAM with other UAV-based antenna measurement systems described in Section I. Concerning the question about which system provides better performance, the answer is that it depends on the application. For example, [15] is suitable for accurate antenna measurement up to 40 GHz where the cost and complexity of the system does not matter. For fast, simple evaluation of far field patterns, either [10],[11] or UASAM provide similar performance. UASAM distinctive feature is the capability of working in the NF region and performing antenna diagnostics.

It must be remarked that smaller, low-weight UAVs provide safer operating conditions when flying in the vicinity of the AUT, as in the case of NF measurements. The use of small UAVs minimizes the risk of damaging the AUT in case of an accidental collision. Even when flying hundreds of meters away from the antenna for direct FF measurements, piloting larger RPAs requires higher degree of expertise. Furthermore, practical limitations of FF measurements due to flight restrictions should be taken into account.
Besides, civil regulations and required licenses for UAV operation in non-controlled airspace are related to UAV take-off weight [36]: heavier UAVs require additional license degree and are subject to more restrictive regulations (e.g. regarding beyond line of sight operation), which eventually impacts on the overall operation cost.

### TABLE I

<table>
<thead>
<tr>
<th>Comparison of UAV-Based Antenna Measurement Systems</th>
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<tbody>
<tr>
<td><strong>Frequency range</strong></td>
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<tr>
<td>----------------------</td>
</tr>
<tr>
<td>9 kHz - 12 GHz</td>
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</tbody>
</table>

*Ground Station (laptop) not included in the estimated cost.*

### VII. CONCLUSION

Results presented in this contribution prove the feasibility of the USASM for antenna diagnostics and characterization. The combination of a cm-level accurate geo-referencing system and an algorithm capable of handling NF amplitude-only measurements taken at arbitrary-geometry acquisition domains have contributed to simplify the hardware and sensors required onboard the UAV, resulting in a compact, low-cost, and accurate antenna measurement system. Quick deployment time and ease-of-operation make USASM of interest for rapid in-situ antenna testing of a wide variety of wireless communications systems such as radio and television broadcasting, mobile networks, radionavigation systems.

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On the use of Unmanned Aerial Vehicles for Antenna and Coverage Diagnostics in Mobile Networks

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Abstract—The capability of in-situ antenna measurement and diagnostics using a compact low-cost Unmanned Aerial System is presented. An onboard power sensor collects amplitude-only measurements, which are processed by means of an iterative phase retrieval technique. This technique allows recovering an equivalent currents distribution which characterizes the Antenna Under Test (AUT). These currents can be used for antenna diagnostics as well as to evaluate the field radiated by the AUT. In the field of mobile networks, the proposed system is of interest for rapid assessment of the antennas operational conditions providing radioelectric coverage within the mobile network cells and allowing the evaluation of antenna failures, such as incorrect tilt or beamforming/feeding network malfunction. Proof-of-concept of the system is conducted for testing a commercial Base Transceiver Station (BTS) antenna under normal and malfunctioning operation conditions, discussing the extension of the system to allow measurements at millimeter-wave frequency bands.

Index Terms—Radio coverage, antenna measurement, antenna diagnostics, Unmanned Aerial Vehicles (UAVs), phaseless measurements, Near-Field to Far-Field transformation (NF-FF), Sources Reconstruction Method (SRM).

I. INTRODUCTION

The development of 5G standards have put together efforts from different institutions in order to define the radio access and core network architectures capable of facing the challenge of connecting billions of heterogeneous end-user devices, while keeping backward compatibility with existing wireless networks [1]. 5G radio access network seems to rely mainly on new multiple access schemes, based on massive MIMO (Multiple Input Multiple Output) and beamforming technologies [2], that will require the replacement or upgrading of existing Base Transceiver Station (BTS) antennas.

Concerning the deployment of 5G technologies and networks, several working frequency bands have been proposed, focusing primarily in the 24 – 28 GHz frequency band [3]. Traditional lower frequency bands such as 700 MHz, 2.6 GHz, and 3.4-3.8 GHz are also of interest for 5G deployment thanks to the lower free space propagation losses with respect to mm-wave frequency bands.

Network densification is expected to be another strategy for a successful deployment of 5G networks [4]. This strategy will result in an increase in the number of cells, reducing propagation path losses especially for mm-wave frequency bands [5]. Taking into account the aforementioned challenges and requirements, one of the fields of interest for the deployment of 5G networks is the improvement of the methods for radioelectric coverage prediction and calculation, aiming to optimize the placement of the antennas. In this sense, techniques based on antenna characterization using an equivalent currents model [6,7] or modal expansion [8] provide accurate estimation of the radiated field, not only for coverage evaluation, but also for exposure to radiated fields compliance assessment.

Besides, the increase on the number of coverage cells and thus, the number of antennas, will require the development of new techniques for the assessment of parameters such as power level and radioelectric coverage, as well as for quick, low-cost detection of anomalies in the radiofrequency front-end. Due to the large scale number of cells in 5G networks, the development of such techniques would result in operational and maintenance cost savings.

Thanks to the development of Unmanned Aerial Vehicles (UAVs) in terms of cost reduction and improvement of technical capabilities, they have been successfully introduced in different areas related to communications networks, such as network coverage extension [9,10] and in-situ antenna measurement and testing [11,12,13]. The latter allows the evaluation of the antenna radiation pattern in realistic conditions, analyzing the impact of the surroundings (e.g. multipath contributions in ground, buildings, etc.). The price to pay is the loss of accuracy with respect to anechoic chamber facilities.

In-situ UAV-based antenna measurement in large open areas can be conducted directly in the far field (FF) region of the antenna, which can be hundreds of meters away in the case of...
electrically large antennas or at lower operation frequencies (typically less than 1 GHz). In the scope of 5G networks it would be the case of macro cell antennas, whose coverage area can range up to 2-3 km. But for micro and nano cell antennas, testing will be likely to occur in the near field (NF) region of the antenna, especially those working at millimeter-wave frequency bands.

The main advantages of FF over NF measurements are:

i) Maximum separation between measurement points is proportional to the distance from the Antenna-Under-Test (AUT). Thus, positioning and data geo-referring errors has more impact in NF measurements.

ii) Radiation pattern has to be measured in the AUT FF region. Otherwise, Near-Field to Far-Field (NF-FF) transformation is required.

However, NF measurements are of interest under the following circumstances:

i) Reducing issues regarding flight autonomy (and thus the number of acquisition points), as FF measurements result in longer flight paths.

ii) Overcoming flight restrictions that may limit the scan zone (e.g. flying over crowded areas, restricted zones, beyond visual line of sight) and therefore, the practical application of FF systems.

iii) Antenna diagnostics cannot be conducted using amplitude-only information collected in the FF region, as explained in [7].

A UAV-based antenna measurement system capable of operating not only in the FF region, but also in the NF of the AUT combines the advantages of AUT measurement in these regions.

Furthermore, antenna diagnostics techniques have been proved to be a quite efficient way of detecting malfunctioning elements in antenna arrays [6],[7],[14]. As mentioned before, it is expected that 5G networks will implement MIMO and beamforming techniques, which require the use of antenna arrays. Once these antennas are in their final placement within the mobile network, in case of antenna or feeding/beamforming network failure, it is not possible to assess the impact on the cell coverage. Although in most cases the solution is just the replacement of the antenna by the mobile network operator, in some scenarios this is not straightforward. Thus, the possibility of having a-priori diagnostics of the problem would allow the company to decide whether the antenna has to be replaced, it can be fixed in-situ, or the degraded operational conditions are sufficient to maintain the service.

A UAV-based system for antenna diagnostics and characterization (Unmanned Aerial System for Antenna Measurement, UASAM) capable of performing NF antenna measurement and diagnostics has been presented and described in [11]. In this contribution the goals and novelties are: i) to prove the successful application of UASAM for rapid assessment of mobile networks commercial antennas, not only for diagnostics, but also for evaluating the impact of the failure in the antenna coverage; ii) to validate the capability of UASAM to conduct measurements at millimeter-wave frequency bands.

II. PROOF OF CONCEPT: IN-SITU ANTENNA MEASUREMENT SYSTEM

The proof-of-concept for in-situ measurement and diagnostics of mobile networks antennas using unmanned aerial vehicles will be based on the hardware and post-processing techniques of the system developed in [11] (UASAM), conceived for general-purpose antenna measurement. Fig. 1 provides an overview of UASAM subsystems and post-processing algorithms, which will be briefly described in this section.

Onboard the UAV there is a monopole probe antenna connected to a power detector, and a Real Time Kinematic (RTK) beacon acting as a rover station for the RTK system. A second RTK beacon acting as a base station system is placed at a fixed position. The RTK system, together with a laser rangefinder for accurate positioning in height, are in charge of providing centimeter-level in-flight navigation and data geo-referring accuracy.

The data sent by the UAV (geo-referred radiated field measurements and flight path positions coordinates) are post-processed in a ground station (a laptop).

![Diagram of UASAM](image)

**Fig. 1.** Block diagram of the Unmanned Aerial System for Antenna Measurement (UASAM).

UASAM makes use of pre-defined flight paths around the AUT, created using waypoints, so the flight path can be repeated if needed. This is of interest in case of in-situ mobile
network antenna measurements, as the network operator can store the coordinates of these antennas, thus making the procedure of antenna inspection easier.

Communications system between UAV, RTK beacons, and the ground station of the implemented prototype is based on Wireless Local Area Network (WLAN) operating in the 2.4-2.5 GHz and/or 5.7-5.8 GHz frequency bands, whereas a 433 MHz radio transmitter and receiver is used for UAV flight control. The use of these frequency bands avoids overlapping with those used by mobile networks, especially for future 5G communications at millimeter-wave frequencies.

Thanks to the development of both Global Navigation Satellite Systems (GNSS) and RTK technology, multi-constellation and dual-band RTK systems are capable of providing positioning and geo-referencing accuracy up to 5 mm, enabling measurements up to 30 GHz (to ensure that geo-referencing uncertainties are not greater than half wavelength). There are other possible solutions for mm-level accuracy data geo-referencing such as laser trackers, as already proposed in [13] for crane-assisted antenna measurement at mm-wave frequency bands. For this proof-of-concept, UASAM makes use of a low-cost RTK system providing 1-2 cm geo-referencing and positioning uncertainty.

Radiated field measurements conducted with power sensors do not allow direct measurement of the phase of the field. Thus, phase retrieval methods are applied to reconstruct the phase from amplitude-only measurements of the radiated field collected on two or more acquisition surfaces around the AUT. UASAM makes use of the phaseless Sources Reconstruction Method (SRM), an iterative phase retrieval technique where an equivalent currents distribution is recovered on a surface enclosing the AUT [7]. These phase retrieval techniques have been successfully tested at frequencies as high as 140 GHz, also in the field of antenna measurement for 5G communications [15].

In addition to this, it must be pointed out that the SRM is capable of handling arbitrary-geometry acquisition domains, thus overcoming the restriction of requiring accurate UAV navigation. As proved in [11], UAV flight path deviation with respect to the pre-defined one has negligible impact in the measurements, as long as they are accurately geo-referenced. This feature is of special interest as operational conditions (e.g., wind, propellers vibrations) restrict UAV capability to follow the pre-defined path with cm-level accuracy, which would have prevented the use of UAV for antenna measurement at mm-wave frequency bands.

The reconstructed equivalent currents provide an accurate electromagnetic model of the AUT, which can be used for evaluating the radiated field at any point of the space. Immediate applications are radiation pattern calculation and prediction of the radioelectric coverage. Besides, these equivalent currents can be used to determine the presence of malfunctioning elements in the case of antenna arrays. Thus, if an element of the antenna array is not fed, the equivalent currents distribution over this element will exhibit low or zero amplitude.

A monopole antenna is selected as a probe for the proof-of-concept presented in this contribution. The reason of this choice is due to the low directivity and the rotation symmetry of its pattern, which minimizes AUT measurement distortion due to the probe antenna pattern. The selected monopole antenna operates at 900, 1800, and 2350 MHz (in agreement with the working frequency bands of UASAM), having 3% bandwidth. Similar low-cost monopole or monopole-like antennas are available and ready-to-mount on the UAV for antenna measurement at higher frequency bands.

![Fig. 2. UAV with the RTK and the probe monopole antenna onboard. Labels in red color: antenna measurement subsystem; Labels in blue: UAV positioning and geo-referencing subsystem. Labels in green: communications and UAV controller subsystem.](image)

Technical details and specifications of the rest of devices onboard the UAV are given in [11]. A picture of the UAV with the RTK and the probe printed monopole antenna onboard is shown in Fig. 2.

**III. MOBILE NETWORK ANTENNA CHARACTERIZATION**

Practical assessment of UASAM capabilities for mobile network antenna measurement and diagnostics is described in this section. For this purpose, a 1.3 m length commercial BTS antenna for GSM and UMTS mobile networks, working at 1800, 2100, and 2300 MHz has been selected (Fig. 3(a) and Fig. 4(a)) to ensure that the positioning and geo-referencing error is less than half wavelength at the working frequency. Measurements have been conducted at the airfield located at the Technical School of Engineering of Gijón (coordinates 43.521698, -5.623983).

The BTS antenna has been mounted on top of a 3.5 m height mast. RTK base station (ground beacon) is deployed 20-25 m away from the base of the mast. Fig. 3(a) shows the placement of the BTS antenna with the UAV in operation, the RTK base station, and the ground station (laptop). For this setup, the WLAN connecting ground RTK beacon, UAV, and the ground station is set to 5.8 GHz to minimize the risk of interferences.

Aiming to simulate antenna malfunctioning, e.g. a failure in one of the elements of the BTS antenna, a sheet of aluminum foil has been wrapped around the lower section of the BTS antenna radome (depicted in Fig. 4(e)). The placement of the
aluminum foil has been selected so that it does not impact BTS antenna return losses with respect to normal operation conditions.

BTS antenna is fed with a RF signal generator, as shown in Fig. 3(a), tuned at 2350 MHz, in order to test UASAM measurement capabilities at the highest working frequency band of the selected BTS antenna.

In order to set up the flight path around the BTS for radiated field measurement, first the coordinates of a reference point in the base of the BTS antenna are taken [11]. Due to the fact that the expected BTS antenna radiation pattern will cover less than 180° in the horizontal plane, with little back radiation, the UAV flight path can be fitted to a 180°-arc cylindrical surface. This cylindrical grid ranges from 2. m to 4.5 m in height. As mentioned before, iterative phase retrieval techniques require the field to be measured in, at least, two acquisition surfaces around the AUT [7], so two arc cylindrical surfaces with radius \( R_1 = 3.7 \) m and \( R_2 = 4.5 \) m have been considered. Taking into account the electric size of the BTS antenna, these measurement surfaces are well within the NF region of the BTS (which starts at around 25 m from the antenna).

Once the flight paths have been defined and uploaded into the UAV controller, the UAV operator takes it off. Then, UAV flight mode is changed from GPS-assisted manual flight mode to autonomous mode so the UAV can follow the pre-defined flight path while taking radiated field measurements. Flight time required to complete the pre-defined path ranges from 12 to 14 minutes for each 180°-arc cylindrical surface. Around 7000 to 8000 geo-referred measurements are collected. A video showing the UAV in operation can be watched at https://youtu.be/4C5G4MrdJ3Q.

Geo-referred BTS antenna NF measurements (depicted in Fig. 3(b)) are then processed with the iterative phase retrieval technique based on the SRM to recover an equivalent currents distribution on the BTS antenna aperture plane [7]. That implies minimizing a non-linear cost function that has around 7500 equations and 600 unknowns. With the development of computational capabilities, it can be done with a conventional laptop, requiring not more than 2 minutes calculation. Results for the BTS antenna in normal operation conditions are shown in Fig. 4(b), noticing that the equivalent currents exhibit uniform amplitude along the entire length of the BTS antenna.

In order to provide a reference framework to assess the accuracy of antenna diagnostics from in-situ measurements, the selected BTS antenna has been measured at the spherical range in anechoic chamber of the University of Oviedo. Anechoic chamber measurements have amplitude and phase information, so either amplitude and phase or phaseless NF-NF backpropagation techniques based on the SRM [7] can be applied to obtain an equivalent currents model of the BTS antenna.

Fig. 4(c) shows the reconstructed equivalent currents from measurements in anechoic chamber using amplitude and phase information, whereas Fig. 4(d) corresponds to the reconstructed equivalent currents considering only the amplitude of anechoic chamber measurements.

The same methodology has been applied to the measurements corresponding to the malfunctioning BTS antenna depicted in Fig. 3(c). Results from in-situ measurements are depicted in Fig. 4(f). Fig. 4(g) and Fig. 4(h) correspond to the reconstructed equivalent currents from measurements in anechoic chamber considering amplitude and phase, and amplitude-only information, respectively. In all the three compared cases, equivalent currents vanish in the area where the aluminum foil is placed.
IV. Radioelectric Coverage Analysis

The equivalent currents reconstructed from AUT radiated field measurements can be used not only for antenna diagnostics [7],[6], but also for evaluating the field radiated by the AUT at any point, allowing far field pattern calculation, and radioelectric coverage analysis. The latter feature is of special interest to evaluate the impact of commercial BTS antenna failure or misalignment.

Fig. 4. Reconstructed equivalent currents on the BTS antenna aperture: (a) from in-situ amplitude-only NF measurements; (c,g) from amplitude and phase NF measurements at spherical range in anechoic chamber; and (d,h) from amplitude-only NF measurements at spherical range in anechoic chamber. A picture of the BTS antenna is displayed on the left side of the figure without (a) and with (e) aluminum foil.

To illustrate this, the field radiated by the BTS antenna in a 100 m x 100 m area in front of the antenna has been calculated from the reconstructed equivalent currents using in-situ measurements. Calculation is done with a full wave-based electromagnetic simulation software that takes the equivalent currents as an input. As the BTS antenna is completely characterized by its equivalent currents model, such model can be placed at a different height or orientation, e.g. 20 m above ground.

Fig. 5. Radioelectric coverage calculated from the reconstructed fields on the BTS antenna aperture. BTS antenna placed at height of 20 m. (a) Reference BTS antenna. (b) Malfunctioning BTS antenna.

Predicted electric field levels are depicted in Fig. 5(a) for the BTS antenna in normal operation conditions, and in Fig. 5(b) for the malfunctioning BTS antenna. It can be noticed that the malfunctioning BTS antenna results in lower field levels than the reference antenna, due to the fact that its radiation pattern is less directive. Besides, the blockage due to the aluminum foil can still be noticed when evaluating the radiated field in a vertical plane in front of the BTS antenna aperture (Fig. 5(b)). From these results, mobile network operator can decide if the
malfunctioning BTS antenna still provides enough coverage or if the radiated field levels are too low so it is better to replace the BTS antenna.

Concerning the accuracy of the proposed methodology, the Root Mean Square Error (RMSE) between the coverage level calculated from anechoic chamber measurements and from in-situ UASAM measurements is 0.2 %.

V. EVALUATION OF THE SYSTEM PERFORMANCE AT MILLIMETER-WAVE FREQUENCY BANDS

In order to evaluate UASAM capabilities for antenna diagnostics and characterization at 5G mm-wave frequency bands, an application example consisting of a 4-element antenna array with non-uniform excitations working at 25 GHz has been selected. The elements of the array are horn antennas, with a 3-cm space between each of them.

For the sake of clarity, the methodology followed in this application example is summarized in the flowchart shown in Fig. 6.

As the upper frequency limit of the power sensor currently onboard the UAV is 8 GHz, in this example the NF radiated by the AUT at the acquisition points had to be calculated from an equivalent magnetic current model of the AUT measured at anechoic chamber (Fig. 6(b)), adding noise according to a Signal-to-Noise ratio of 30 dB (a level worse than the noise response of power detectors working up to 30 GHz).

Two planar measurement domains of 4 m x 2 m, placed at 2.5 and 4 m in front of the AUT aperture have been considered. Next, UAV flight path is defined, resulting in 7108 acquisition points on each domain. Once the UAV flight path is created, the UAV is taken off and set up to autonomous flight mode, recording the coordinates of the acquisition points. Then, the NF is calculated (using the AUT model) at the geo-referred positions, as depicted in Fig. 6(a).

Next, equivalent magnetic currents on the AUT aperture plane are recovered. When comparing the reference currents (Fig. 6(b)) with the reconstructed ones (Fig. 6(c)) it can be observed that the amplitude distribution of the array elements is recovered.

The impact of geo-referring errors has been assessed, modeling them as a normal probability distribution (being σ is standard deviation). σ = 1 cm and σ = 1.5 cm geo-referring errors, which are within the degree of geo-referring uncertainty of the RTK system [11], have been introduced in the x, y, and z coordinates of the acquisition points. Results are depicted in Fig. 6(d) and Fig. 6(e) respectively, where the antenna array elements can be still detected.

Finally, from the reconstructed equivalent currents, the AUT radiation pattern can be retrieved. Radiation pattern calculated from the equivalent currents depicted in Fig. 6(b)-(e) is plotted in Fig. 6(f). Even for a geo-referring error of σ = 1.5 cm, discrepancies between the calculated radiation pattern and the reference one are less than 3 dB.

VI. CONCLUSION

Results presented in this contribution has proven the viability of using compact low-cost UAV-based antenna measurement systems for in-situ diagnostics and characterization of mobile network antennas. Quick deployment and ease-of-operation are two additional advantages of the proposed methodology.

The capability of conducting in-situ measurements for rapid assessment of the status of mobile networks commercial antennas will become a helpful tool for mobile network infrastructure maintenance tasks, especially in the case of denser networks as expected with 5G. Here the disruptive
improvement is given by measurements post-processing, that allows not only the detection of malfunctioning elements in mobile network antennas, but also the evaluation of the radioelectric coverage, enabling predictive maintenance of the mobile network infrastructure.

USAM geo-refering accuracy is currently limited to 1-2 cm, which has been shown to be sufficient for antenna diagnostics and characterization up to 25 GHz. In any case, sub-cm accuracy can be achieved by complementing the USAM navigation system with an accurate geo-refering system (e.g. a laser tracker).

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BIographies

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Unmanned aerial system for antenna measurement and diagnosis: evaluation and testing

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Abstract: This contribution analyses the performance of an unmanned aerial system for antenna measurement (UASAM) for different kinds of measurement scenarios. UASAM is conceived for antenna diagnostics and characterisation at the operational location of the antenna under test (AUT). The system measures the amplitude of the near field radiated by the AUT. Then, these measurements are post-processed using phase retrieval techniques and equivalent current methods to obtain an electromagnetic model of the AUT. This model can be used for antenna diagnostics and for evaluating the far field pattern. Similar to antenna measurement systems, UASAM allows defining different acquisition grids depending on the type of AUT (planar, cylindrical, arc cylindrical), which also influences the flight time. In addition to this, the capability to measure circularly polarised antennas from amplitude-only measurements is presented, discussing the limitations found during the tests, and comparing the results with those from measurements at a spherical range in an anechoic chamber.

1 Introduction

Advances in unmanned aerial vehicles (UAVs) technology have resulted in a burgeoning amount of disruptive applications that make use of their capabilities for accessing remote areas, exploration speed, and ease of operation. Earth observation and mapping [1], infrastructure inspection [2], crops monitoring [3], detection of buried improvised explosive devices such as landmines [4], and acting as hotspots for extending wireless networks coverage [5], are just some of the areas where UAVs, commonly known as drones, have been successfully introduced.

In the area of telecommunication networks, where the front-end infrastructure can be located in remote access places (e.g. on top of a building or a mountain), additional costs for inspection a repair task can be derived with respect to the case of such devices located in accessible places. Even more, in the case of the antennas, they are usually placed several meters above ground. Thus, it is clear that UAV-based systems would be of help for monitoring these elements.

Airborne-based systems for antenna measurements were already developed in 1963 using manned aircrafts [6]. In recent years, developments on small, low-cost consumer UAVs, have made possible the use of these platforms for in-situ antenna measurement and testing at a fraction of the cost of those systems based on manned aircrafts. One of the advantages of using airborne-based systems for antenna measurement is that the antenna can be tested in operational conditions, taking into account how the surrounding environment affects its performance (e.g. reflections in nearby buildings). This kind of test cannot be conducted in antenna measurement facilities such as anechoic chambers, where the antenna is characterised alone. Although the technology maturity of airborne-based antenna measurement systems cannot offer the same accuracy as anechoic chamber measurements, the aforementioned possibility of evaluating the influence of the antenna surroundings on its performance is an added feature of special interest for forthcoming 5G communications systems which will rely on multipath and MIMO techniques [7, 8].

Although different UAV-based systems for antenna testing have been developed recently, the majority are based on a radio-frequency transmitter [9–11] or receiver (a power sensor [12, 13] or a compact spectrum analyser [14]) on board the UAV. Signal levels recorded at each position of the UAV flight path are then geo-referenced and latter post-processed (e.g. converting spatial coordinates in polar ones) in order to obtain the radiation pattern of the antenna under test (AUT). In the case of electrically large antennas, or low-frequency communications systems, far-field (FF) distance can be located tens or hundreds of metres away from the AUT, so measuring even a single cut of the radiation pattern could become challenging due to the resulting long flight path for antenna measurement in the FF region. Apart from limitations in the flight autonomy of most UAVs (up to 15–20 min), flight regulations over restricted areas (e.g. crowded places) may add additional constraints. For these reasons, UAV-based systems capable of operating in the near-field (NF) region of the AUT have been proposed [15–19], so that the distance from the AUT to the UAV-based antenna measurement system is not greater than several metres, then applying NF–FF transformation techniques to obtain the AUT radiation pattern.

This contribution reviews recent advances in the validation and testing tasks of an unmanned aerial system for antenna measurement (UASAM), capable of working in the NF region of the AUT, extending the aim and scope of the contribution presented at EuCAP 2018 [16]. The system has been experimentally validated up to C band [15], although simulations emulating realistic flight conditions and measurement uncertainties have proven UASAM capability to operate at millimetre-wave frequency bands [17]. The novelties with respect to the state-of-the-art are: (i) evaluation of different measurement grids in the NF region of the AUT, assessing their impact in antenna measurement, and (ii) capability of UASAM for testing circularly polarised antennas based on the independent acquisition of two linear components. For all the tested antennas, fields recovered on the aperture plane of the AUT as well as the radiation pattern will be compared with results from measurements conducted at a spherical range in an anechoic chamber.

2 Description of the proposed system

2.1 UASAM hardware architecture

UASAM prototype, depicted in Fig. 1, is composed by the following subsystems:

- Flight control subsystem (Fig. 1, text in green colour), containing the flight controller, the communication devices and the usual positioning sensor on board the majority of small consumer UAVs. These sensors are a barometer, inertial
measurement units (IMUs), and a Global Navigation Satellite System (GNSS) receiver.

- Accurate positioning subsystem (Fig. 1, text in blue colour), consisting of a laser rangefinder and a real-time kinematic (RTK) system. The latter has two elements: one RTK beacon on board the UAV and the other RTK beacon at a fixed position in ground. The ground beacon acts as base station sending GNSS corrections to the rover beacon.
- Antenna measurement subsystem (Fig. 1, text in red colour), which includes a probe antenna and a power sensor.
- Ground control station (e.g. a laptop) where the geo-referred amplitude-only measurements are post-processed.

Fig. 2 shows a scheme of the main components of the UASAM prototype together with the connections between them.

The flight path of the UAV is created using waypoints, taking as input a pre-defined AUT measurement grid: a cylinder, a cylindrical arc, or a plane. It must be indicated that the UAV heading points towards the AUT in the case of cylindrical grids (as in cylindrical measurement ranges), whereas the heading is perpendicular to the AUT aperture plane in the case of planar grids. The UAV coordinates and the measurements of the power detector are sent to the ground station, where they are post-processed to perform antenna diagnostics and to obtain the radiation pattern.

2.2 Measurements post-processing

Geo-refered amplitude-only NF measurements need to be processed in order to calculate the AUT radiation pattern as well as to obtain antenna diagnostics information (e.g. detection of malfunctioning elements). NF-FF transformation and antenna diagnostics techniques [20-24] require information of both amplitude and phase of the NF. Thus, phase retrieval techniques from amplitude-only NF measurements have been considered in UASAM.

Phase retrieval techniques can be classified into two main groups. On the one hand, indirect off-axis holography is based on the knowledge of a reference field and an interference pattern with the field radiated by the AUT [25]. Recent advances on indirect off-axis holography allows for independent phase recovery at each measurement point in the case of broadband antennas [26], complemented with scalar calibration techniques [27]. On the other hand, iterative phase retrieval techniques consist of a minimisation of a cost function relating the amplitude of the NF measured on two or more acquisition surfaces, with the amplitude of the NF radiated by an electromagnetic equivalent model of the AUT on such surfaces. This model can be, for example, an equivalent currents distribution or extremely NF on the AUT aperture plane [28-30]. Iterative techniques require less hardware than indirect off-axis holography, but at the expense of longer acquisition and processing time. Also, the ill-conditioning nature of the inverse problem to be solved influences the convergence of the iterative method. Nevertheless, the requirement of cheap, low-cost hardware on board the UAV has conditioned the choice of an iterative phase retrieval technique over off-axis indirect holography.

In the case of UASAM, the phaseless sources reconstruction method (pSRM) for antenna diagnostics and NF-FF transformation [30] has been considered for processing geo-refered NF measurements acquired in two measurement surfaces. A flowchart of this iterative method is shown in Fig. 3, whereas a discussion about how geo-referring uncertainties and positioning errors affect pSRM performance is presented in [15].

2.3 Comparison flowchart

To validate the antenna diagnostics and the radiation pattern calculated using UASAM, antennas tested in this contribution have been measured at a spherical range in an anechoic chamber as well. As depicted in Fig. 4, two methodologies for validation of the results are proposed: (i) calculation of aperture fields and FF pattern from complex NF measurements in anechoic chamber (Fig. 4, green path), and (ii) using an equivalent model of the AUT from these NF measurements [22], the amplitude of the NF is calculated at the geo-referred flight path positions of the UAV. Then, these measurements are processed with the pSRM in-situ measurements (Fig. 4, yellow path). The goal is to have an assessment of different sources or error, such as positioning and geo-referring uncertainties, and the nonlinearity of the power sensor.

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Fig. 1 UASAM prototype. Main subsystems are highlighted in different colours: flight control subsystem (green), accurate positioning subsystem (blue), antenna measurement subsystem (red).

Fig. 2 Overview of UASAM architecture: main components and connections between them.

Fig. 3 Flowchart of the phaseless sources reconstruction method. \( E_0 \) is the impedance matrix relating the radiated field \( k \) with an equivalent currents distribution (electric and/or magnetic) \( I_0 \) that radiates the same fields as the AUT.

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3 Evaluation of different measurement grids

In this section, the influence of different acquisition grids in the FF pattern and in the aperture fields of the AUT, is evaluated. For this example, a two horn antenna array working at C band (from 4 to 6 GHz) has been selected as AUT [15]. It is fed with a voltage controller oscillator (VCO) and an RF amplifier which provides a +10 dBm signal at 4.65 GHz. The AUT is fixed to a mast at 3 m height and the distance between the horn aperture centres is approximately 4l. The measurement setup is shown in Fig. 5.

Concerning the probe antenna on board the UAV, a commercial printed monopole working from 4 to 7 GHz with vertical polarisation and an omnidirectional pattern in azimuth (±1.5 dB accuracy) has been chosen [15, 31]. For this example, only the copolar component (vertical polarisation) is measured, which also simplifies the integral equation formulation of the pSRM algorithm [30], as the s-component of the equivalent magnetic currents on the

Fig. 6 Grid #1: cylindrical grid of radius $R_1 = 3\, \text{m}$ and $R_2 = 4\, \text{m}$, with the scanning height going from 1.5 to 4.5 m in 0.15 m steps

Fig. 7 Grid #2: arc cylindrical surfaces of radius $R_1 = 3.7\, \text{m}$ and $R_2 = 4.5\, \text{m}$, with the scanning height going from 2 to 4.5 m in 0.1 m steps

Fig. 8 Grid #3: parallel planes of 10 m width at $R_1 = 3.7\, \text{m}$ and $R_2 = 4.5\, \text{m}$, with the scanning height going from 1.8 to 4.5 m in 0.1 m steps

AUT aperture plane, $M_a$, is calculated from the measured z (vertical)-component of the NF, $E_z$.

3.1 Measurement grids

Measurement grids are defined in a flight plan (composed of waypoints) that the UAV autonomously tries to follow. Cylindrical, arc cylindrical, and planar grids evaluated in this example are depicted in Figs. 6-8. Dashed lines represent the pre-defined flight paths, whereas the waypoints are represented with thick dots. In the
Table 1  Sizes and FF angular region of validity (ARV) of the measurement domains considered in this contribution (L: horizontal size, V: vertical size)

<table>
<thead>
<tr>
<th>Grid type</th>
<th>R (grid distance)</th>
<th>Grid size</th>
<th>ARV horizontal</th>
<th>ARV vertical</th>
</tr>
</thead>
<tbody>
<tr>
<td>grid #1 (cylindrical)</td>
<td>4 m</td>
<td>V = 3 m</td>
<td>full range</td>
<td>41°</td>
</tr>
<tr>
<td>grid #2 (180°-arc cylindrical)</td>
<td>4.5 m</td>
<td>V = 2.5 m</td>
<td>180°</td>
<td>30°</td>
</tr>
<tr>
<td>grid #3 (planar grid)</td>
<td>4.5 m</td>
<td>H = 7 m</td>
<td>76°</td>
<td>34°</td>
</tr>
<tr>
<td>example 2 (planar grid)</td>
<td>4.5 m</td>
<td>H = 5 m</td>
<td>68°</td>
<td>31°</td>
</tr>
<tr>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

3.3 Antenna diagnostics and FF pattern comparison

An equivalent magnetic currents distribution ($M_i$) is reconstructed on the AUT aperture plane, truncated to a rectangular domain of 60 x 60 cm. This domain is large enough to contain the projected physical AUT aperture, but not too large to avoid increasing the number of unknowns (i.e. points where the equivalent magnetic currents are recovered).

Reconstructed equivalent currents are depicted in Fig. 12 for the following cases: using complex NF measurements at anechoic chamber (Fig. 12a), from simulated NF amplitude at UAV positions for grid #1 (Fig. 12b) (cylindrical), and for NF amplitude measurements with USAM for grids #1 (Fig. 12c), #2 (Fig. 12d) and #3 (Fig. 12e). In all cases, the location and relative power of each element of the horn antenna array can be estimated.

Differences between Figs. 12a and b are mainly due to the use of amplitude-only NF information in the latter case, and the truncation error of the cylindrical domain in elevation (z-axis) of grid #1. In fact, differences are observed along the z-axis rather than along the x-axis. Next, if Figs. 12b and c are compared, the effects of geo-referring errors and probe antenna misalignments in the reconstruction quality can be observed.

When the grid is composed of arc cylindrical surfaces, Fig. 12d, the reconstruction is slightly worse due to the smaller size of the grid along z yielding greater truncation error (see Table 1) even though the AUT is directive. The fact that the UAV stops at each arc endpoint to change direction also implies that the UAV deviations from the ideal path are slightly increased.

The greatest similarity of reconstructed aperture fields between anechoic chamber measurements and UAV measurements is achieved when a planar grid is considered, as observed in Fig. 12e. This might be because the UAV heading does not change (it is always perpendicular to the AUT), whereas in cylindrical grids the UAV heading is continuously changing to point towards the AUT position. However, the use of planar grids requires to accurately determine the NF measurement domain containing most of the radiated power from the AUT, which is typically restricted to the case of quite directive AUTs.

From the recovered equivalent magnetic currents (i.e. aperture fields), the FF pattern can be calculated. FF pattern cut in the H-plane of the AUT is represented in Fig. 13. A good agreement between the reference FF pattern and those measured with USAM can be observed, especially for the main lobes ($\theta \in [\pm 20^\circ, 20^\circ]$). It must be pointed out that the discrepancies are mainly due to the geo-referring errors (which are around 2 cm in the horizontal plane and 1 cm in the vertical direction).

4 Measurement of circularly polarised antennas

The capability of USAM for conducting measurements of circularly polarised antennas is presented in this section. For this goal, there are two possibilities: (i) use of a circularly polarised antenna as probe (or two with reverse handedness if both circular components have to be measured); (ii) use of a linear polarised

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**Fig. 9** Measured NF amplitude for grid #1 at $R_2 = 4$ m radius

**Fig. 10** Measured NF amplitude for grid #2 at $R_2 = 4.5$ m radius

**Fig. 11** Measured NF amplitude for grid #3 at $R_2 = 4.5$ m radius

3.2 NF measurements

For each tested grid, the amplitude of the measured NF is depicted in Figs. 9–11, where the axes are centred at the AUT position (for the sake of simplicity, only the NF on the surface at distance or radius $R_2$ is shown). AUT – probe antenna misalignment is more noticeable in planar measurement grids (grid #3). In addition, these misalignments increase as the acquisition plane gets closer to the AUT.

The size and geometry of the acquisition grid define the truncation error, which determines the region of the FF pattern that can be calculated from NF measurements (angular region of validity) [20]. Table 1 shows the angular region of validity for the measurement domains considered in this contribution. Most of the grids are limited in the vertical direction, as a trade-off between the limited life of UAV batteries and maximising the angular region of validity in this direction. In the case of amplitude-only NF measurements in two or more measurement surfaces, the angular region of validity is defined by the farthest grid. In the case of spherical NF measurements, there is no truncation error.

Measurement grid geometry also has an impact in the UAV flight time, which in this case is directly the NF acquisition time. For this test, UAV flight times were 25 min for grid #1, 20 min for grid #2, and 17 min for grid #3. In the case of grid #1, flight time would have been even longer if the measurements had been taken at a grid with the same radius as grid #2.
antenna as a probe, and measuring the amplitude of the NF with the probe oriented in two orthogonal directions. The latter methodology is simpler in terms of hardware requirements, as linear polarised probes are cheaper and easier to manufacture. An array composed of circularly polarised antennas with reverse handerness placed in a 3-m height mast is selected as AUT, fed with a VCO tuned at 4.65 GHz, as in the example of Section 3. The same monopole antenna of the previous example [31] will be used as a probe. The measurement setup and the elements involved are depicted in Fig. 14.

Based on the conclusions extracted from the results presented in Section 3, as well as the moderate directivity of the helix antenna (13 dB at 4.5 GHz), the planar acquisition was considered for measurements with UASAM. Planar grids were located at 3.2 and 4.5 m away from the AUT, with the height ranging from 2 to 4.5 m in 7 cm steps. The calculated FF angular region of validity is indicated in Table 1.

4.1 NF measurements

Two measurements were conducted on each grid, one with the probe parallel to the ground (a measurement of the \(|E_z|\) component), and the second with the monopole antenna probe perpendicular to the ground (a measurement of the \(|E_y|\) component).
As in Section 3, the AUT was measured at a spherical range in the anechoic chamber, then following the methodology described in Fig. 4 for the comparison of the results.

The amplitude of the NF measured on the planar domain closer to the AUT (R = 3.2) is depicted in Figs. 15 and 16 for horizontal \(|E_x|\) and vertical \(|E_z|\) components. Projection of the circularly polarised field onto two orthogonal linear polarisations results in \(|E_x|\) and \(|E_z|\) having similar amplitude levels. Next, UASAM measurements are compared with the NF simulated using an electromagnetic equivalent model of the AUT obtained from spherical NF measurements at a spherical range in an anechoic chamber [22]. In the case of the horizontal component, there are some discrepancies between simulations and measurements in the lobe centred at \(x = -1\) m, also noticeable in the vertical component (right sidelobe, \(x = -2\) m). These differences can be due to multipath contributions, as the electromagnetic model of the AUT obtained from anechoic chamber measurements cannot take into account reflections on the area where the AUT is placed.

It must be mentioned that the limited battery life of the UAV required two different flights for measuring horizontal and vertical components on each acquisition grid (i.e. four flights overall). Even though the same waypoints were uploaded into the UAV flight controller, UAV positioning errors resulted in small differences between the measurement positions for each component, as it can be noticed if comparing positions depicted in Figs. 15 and 16.

### 4.2 Antenna diagnostics and FF pattern comparison

Amplitude-only NF measurements are introduced in the pSFM to recover an equivalent magnetic currents distribution on the AUT aperture plane. For this measurement setup, the second electromagnetic equivalence principle [21] can be applied, allowing decoupling the integral equations relating the two orthogonal components of the NF \((E_x, E_z)\) with the two orthogonal components of the equivalent magnetic currents on the aperture plane \((M_x, M_z)\). These equivalent magnetic currents can be combined to obtain the right- and left-handed circularly polarised components \((M_{RH} \text{ and } M_{LH})\).

Reconstructed \(M_{RH} \text{ and } M_{LH}\) are depicted in Fig. 17, comparing those reconstructed from UASAM measurements with those reconstructed from the simulated NF on the measurement grid. In both cases, the highest amplitude corresponds to the helix antenna that has reverse handedness. As in the example of Section 3, geo-referencing uncertainties result in worse reconstruction. The displacement in the AUT position comes from the fact that the AUT is centred at different positions in the case of anechoic chamber measurements (Figs. 17a and b: \(0.5\) cm).
offset) and in-situ measurements with UASAM (Figs. 17c and d: −9 cm offset).

Finally, from the reconstructed equivalent magnetic currents, the FF pattern can be calculated. Only the area of the aperture plane within the dashed white line depicted in Fig. 17 has been considered for calculating the FF pattern, for filtering non-desired contributions to the FF.

Comparison of FF patterns calculated from NF measurements at the anechoic chamber, from simulated amplitude-only NF at UAV acquisition grid, and from UASAM measurements, is shown in Figs. 18 and 19. It can be observed an agreement in the main lobe and the sidelobe centred at θ = 30°. However, there are some discrepancies in the left sidelobe (centred at θ = −30°) which are related to those observed in NF measurements. The effects of the


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Dual-probe near-field phaseless antenna measurement system on board a UAV

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Abstract: On-site antenna measurement has been recently attracting an increasing interest in order to assess the antenna performance in real operational environments. The complexity and cost of this kind of measurements have been significantly cut down thanks to recent developments in Unmanned Aerial Vehicles (UAVs) hardware and antenna measurement post-processing techniques. In particular, the introduction of positioning and geo-referring subsystems capable of providing centimeter-level accuracy together with the use of phase retrieval techniques and near-field to far-field transformation algorithms, have enabled near field measurements using UAVs. This contribution presents an improved UAV-based on-site antenna measurement system. On the one hand, the simultaneous acquisition on two measurement surfaces has been introduced and calibrated properly, thus reducing geo-referring uncertainties and flight time. On the other hand, the positioning and geo-referring subsystem has been enhanced by means of a dual-band Real Time Kinematics (RTK) unit. System capabilities have been validated by measuring an offset reflector antenna, comparing the results with measurements at spherical range in anechoic chamber and with measurements collected with a previous version of the implemented system.

Keywords: on-site antenna measurement; dual probes; high directive antennas; dual-band Real Time Kinematics (RTK); phaseless techniques; Unmanned Aerial Vehicles (UAVs); antenna diagnostics.

1. Introduction

In the framework of novel wireless communications systems such as 5G or Internet of Things (IoT), Unmanned Aerial Vehicles (UAVs) are playing an important role for network deployment and monitoring. For example, UAVs are being introduced as network nodes for data gathering in large areas [1,2] and to extend mobile networks coverage by means of drone base stations [3].

Within this framework, on-site calibration [4] and measurement [5-10] of antennas for wireless communications have gained interest thanks to the advances in UAVs technology, which simplify the procedures for on-site measurements. Antenna measurement in anechoic chambers provide accurate characterization of the antenna parameters (e.g., radiation pattern, gain, return losses). However, it must be taken into account that these parameters can be affected by the environment surrounding the place where the antenna is deployed. For example, buildings and obstacles could result in multipath contributions that could modify the coverage. On-site antenna measurements allow assessing the radiation performance of the antenna considering the influence of the surrounding environment.

Improvements in geo-referring and positioning subsystems on board the UAVs, capable of providing centimeter-level accuracy, have also enabled on-site antenna measurement at higher frequency bands. Current state-of-the-art on on-site antenna measurement has shown the feasibility of these systems up to C-band [5,6].
The most common geo-referring and positioning subsystems that can be mounted on UAVs are Global Navigation Satellite Systems (GNSS) – Real Time Kinematics (RTK), Inertial Measurement Units (IMUs), laser rangefinders, photogrammetry systems, and barometers. Combination of these systems can lead to geo-referring accuracies within few centimeters. Ground-based laser trackers can also be used to increase accuracy one order of magnitude [6].

Most of the prototypes and systems for on-site antenna measurement using UAVs are intended to operate in the far field (FF) region of the antenna-under-test (AUT) which, in the case of electrically large antennas (e.g. reflector antennas, mobile networks base station antennas) can be hundreds of meters away from the AUT [7,8]. As explained in [9], there are some restrictions for direct measurement of the FF pattern using UAVs, namely safety restrictions (forbidden flight areas) and UAV flight autonomy. These issues can be overcome if measurements are carried out in the near field (NF) region of the AUT, so that the furthest distance from the AUT to the UAV is not greater than 10-20 m. The feasibility of NF measurements using UAV-based systems has been proved in [9-12].

In order to recover the FF pattern of the AUT from NF measurements, near-field-to-far field (NF-FF) transformation techniques must be applied [13]. For this reason, complex (i.e. amplitude and phase) NF measurements are required. However, complex NF measurements require more expense (and weighty) hardware to be placed on board the UAV. Besides, phase measurements are more sensitive to geo-referring uncertainties. An alternative to the use of complex receivers is provided by phase retrieval techniques, capable of recovering phase information from amplitude-only measurements [14-19]. Once the phase of the field is retrieved, NF-FF transformation techniques can be applied to calculate the AUT radiation pattern. Besides, NF measurements can be post-processed for antenna diagnostics (e.g. detection of malfunctioning elements).

There are two main groups of phase retrieval methods. On the one hand, holographic techniques have been proved to be very accurate and efficient in terms of measurement time, as just one measurement surface has to be scanned. However, these techniques require additional hardware component (e.g. a reference antenna or an injected reference signal) [14]. On the other hand, iterative techniques do not need additional hardware elements, but the NF radiated by the AUT must be measured on two or more acquisition surfaces [15-18]. Thus, for on-site NF antenna measurements using UAVs, the latter group of methods is more suitable, allowing a faster and easier deployment of the system. Nevertheless, recent developments in phaseless antenna measurement techniques using a single acquisition surface [19] are a promising solution aiming to avoid the need of two acquisition surfaces.

In [9,11,20] an UAV-based system for on-site antenna measurement has been presented, assessing the performance of the implemented system for antenna diagnostics and characterization. This contribution presents several novelties to improve the measurement accuracy of the system, thus enabling the characterization of high directive antennas such as reflectors. These improvements are: i) use of a dual-channel receiver, that allows placing two receiving antennas (probe antennas) at two different distances onboard the UAV, thus collecting NF measurements at two different distances simultaneously; ii) introduction of a GNSS dual-band RTK receiver, which increases positioning and geo-referring accuracy and reliability. The former also helps to reduce the flight time, since only one flight is required to gather measurements at two different surfaces. The later contributes to reduce the deployment time, since the convergence time (i.e. the time until a corrected position is obtained) improves compared to a single-band RTK receiver. Besides, several technical flaws found in the previous version of the prototype for on-site measurements that had an impact in the accuracy of the measurements have been assessed and solved.

Experimental validation has been conducted measuring a C-band reflector antenna which, up to the authors’ knowledge, has not been carried out before using other state-of-the-art UAV-based antenna measurement systems.

2. System Description
2.1. Hardware Architecture

A picture of the implemented UAV-based system for on-site antenna measurement is shown in Figure 1. The main subsystems onboard the UAV are:

- **Communications subsystem:** consisting of a Wireless Local Area Network (WLAN) operating in the 2.4-2.5 GHz and 5.7-5.8 GHz frequency bands. The radio transmitter and receiver for radiofrequency control (R/C) of the UAV operate at 433 MHz.

![Diagram of UAV system components](image)

**Figure 1.** Picture of the implemented prototype, highlighting the placement of the two probe antenna, the mounting frames for the probe antennas, and the distance between them.

- **Control subsystem:** composed by the UAV controller, which gathers positioning data and radiofrequency measurements, and forwards them to the ground control station that processes geo-referred NF measurements.

- **Radiofrequency subsystem:** composed by two commercial monopole antennas working in the 4 to 7 GHz frequency band [21] acting as probe antennas for NF measurements, connected to a dual-channel radiofrequency power detector based on the ADL5519 chip [22]. To maximize the distance between the two measurement acquisition surfaces, these probe antennas are placed 80 cm away, as shown in Figure 1. The output of these channels is converted into a digital sequence and sent to the ground station (a laptop) using the WLAN.

- **Positioning and geo-referring subsystem:** composed by the GNSS-RTK unit onboard the UAV [23]. A laser rangefinder is also integrated to improve height positioning, although the GNSS-RTK unit is accurate enough to avoid the need for a laser rangefinder (it was mandatory for accurate height information in previous versions of the prototype [9,12]). The positioning system is completed by the
default positioning components typically included on board UAVs, namely: conventional GNSS receiver, barometer, and Inertial Measurement Unit (IMU).

2.2. Dual-channel receiver calibration and mounting

The feasibility of the dual-channel receiver has been presented as a proof of concept in [12], where the receiver was placed on board the first version of the developed prototype for on-site antenna measurement. However, it was found that the two input channels were unbalanced, resulting in a 3-4 dB difference in the measured radiofrequency (RF) power, which can be due to small differences in the monopole antenna radiation patterns and the RF cables connecting the antennas and the inputs of the receiver. This unbalance in the dual-channel receiver required the implementation of a calibration stage, conducted as follows:

1) The UAV is manually placed at a known distance (e.g. 1 m) from an omni-directional transmitting antenna (e.g. a monopole antenna), so that the two monopole antennas onboard the UAV are at the same distance from the transmitting antenna, having the same orientation.

2) The signal level measured at each channel is recorded, and the unbalance between both channels ($\Delta RF_z(r_1)$) is obtained.

3) Steps 1) and 2) can be applied for different distances between the UAV and the omni-directional transmitting antenna, yielding $\Delta RF_z(r_2)$, $\Delta RF_z(r_3)$, ..., $\Delta RF_z(r_n)$.  

4) Dual-channel unbalance correction factor is estimated as mean$[\Delta RF_z(r_i)]$, n=1,2, ..., N. After this calibration stage, the unbalance between the two input channels was reduced to less than 0.5 dB.

To maximize the distance between the two monopoles placed on board the UAV, different solutions were considered. In [12], two plastic tubes were attached to the UAV frame (Figure 1, [12]). However, it was found that they were not robust enough to avoid vibrations induced by the UAV propellers, which have an impact in the measurements geo-referencing accuracy. After several in-flight tests, ad-hoc mounting frames were designed to mitigate vibrations on the monopole antennas. The mounting frames for the monopole antennas, manufactured using 3D printing, are depicted in Figure 1.

The fact that both the mounting frames for the monopole antennas and the UAV frame are made or plastic reduces scattering and interferences from the UAV itself. Placing the monopole antennas away from the UAV also contributes to mitigate this issue.

2.3. GNSS-RTK unit: features and integration in the system

The GNSS-RTK unit on board the UAV [23] is a dual-band multiconstellation GNSS receiver, which is more robust to multipath and can keep centimeter accuracy even in challenging environments (e.g. with limited sky). Besides, the convergence time (time required by the GNSS-RTK module to resolve carrier phase ambiguities to integer number, i.e. to achieve a “fix” status) is smaller, and it can recover faster from temporary loss of accuracy than single-band GNSS-RTK modules. Therefore, the proposed positioning system provides better accuracy and overall performance compared to the single-band GNSS-RTK unit used in the previous versions of the system [9,12]. Quantitatively, it has been found that the average time to reach a “fix” status (i.e. to obtain cm-level accuracy coordinates) was reduced from more than 2-3 minutes to less than 10 s. Assessment of the GNSS-RTK systems was done in the same scenario in all the cases (airfield of the University of Oviedo, https://goo.gl/maps/sMx3pN1jmTjEELpCi).

Concerning the integration of the GNSS-RTK unit [23], a customized dual-band RTK receiver was integrated into the UAV. An ad-hoc driver for the RTK system that runs on a Single Board Computer (SBC) on board the UAV was developed. This driver is in charge of: i) receiving RTCM (Radio Technical Commission for Maritime Services) corrections via internet using a Transmission Control Protocol (TCP) from an RTK base station (at a fixed position on the ground); ii) forwarding the RTCM corrections to the RTK rover beacon (on board the UAV); iii) receiving binary positioning information from the RTK rover beacon and transforming it into human-readable data (obtaining the
enhanced coordinates); iv) forwarding the enhanced coordinates to the flight control software and to the RF measurement software using a User Datagram Protocol (UDP) connection. A scheme of how these hardware devices and software modules are interconnected is depicted in Figure 2.

Furthermore, the accuracy was also improved by a factor of around 3 in all directions of space, with the current dual-band system having an accuracy of 0.5 cm in the horizontal plane and 1 cm in the vertical direction. It must also be noticed that its ambiguity resolution is more robust so it is less likely to lose the fix status.

![Diagram](image)

**Figure 2.** Scheme of the hardware devices associated to the dual-band GNSS-RTK unit, highlighting the software modules that were developed for its integration into the UAV controller (single board computer).

As a result, these improvements enable a better UAV navigation and measurement geo-referring accuracies. The former helps to reduce the deviation of the UAV flight path from the desired path defined with waypoints. The latter contributes to improve the accuracy of the antenna diagnostics information and the radiation pattern.

In the configuration presented in this contribution, GNSS corrections are taken from a fixed based station of the Spanish "Instituto Geodésico Nacional" [24]. This allow to avoid the deployment of a fixed RTK beacon in the ground (to act as base station for the RTK system), which results in less hardware complexity and faster deployment of the system. Connection to the fixed base station is done by providing 3G/4G connectivity to the WLAN.

2.4. Near Field Measurements Processing

As explained in Section 1, the system proposed in [9,11,20] makes use of the NF measurement data collected on two or more surfaces surrounding the AUT. These measurements are post-processed by means of phase retrieval techniques to recover phase information.

Iterative phase retrieval methods, such as the ones presented in [15-18], require the NF measured on the two acquisition surfaces to have different spatial distribution, taking advantage of the fact that the field distribution in the NF region depends on the distance to the AUT [13].

UAV-based systems for on-site antenna measurements are limited by the life of the batteries that feed the systems on board the UAV. The use of a dual-channel radiofrequency power detector connected to two probes mounted on different positions on the UAV enables the simultaneous acquisition of the NF on two different surfaces. Furthermore, geo-referring uncertainties have the same impact in both acquisition surfaces, avoiding cumulative errors if measurements on each acquisition surface were conducted in two different flights. The latter would increase measurement time and thus, the operational cost.

As shown in Figure 1, the two 3D-printed plastic structures designed and manufactured to mount the two probe antennas on the UAV frame allow achieving a maximum separation between
probes of 80 cm. The probes and the two channels of the power detector have been tested on ground to ensure that they exhibit the same performance in terms of dynamic range and sensitivity. Besides, the calibration procedure explained in Section 2.1 has been conducted to correct the unbalance between the channels of the power detector.

![Figure 3. Flowchart of the phaseless Sources Reconstruction Method, based on the minimization of a non-linear cost function [12,18].](image)

NF measurements acquired on the two measurement surfaces are post-processed using the phaseless Sources Reconstruction Method (pSRM) [16]. This method is based on minimizing a cost function (F) relating the measured NF samples on each acquisition surface \( (E_{NF,p1}, E_{NF,p2}) \) to the NF radiated by an equivalent currents distribution \( (M_{eq}) \) that characterizes the AUT. The pSRM iterates until finding an equivalent currents distribution that radiates the same NF as the measured one.

Concerning the cost function to be minimized, there are two main approaches. On the one hand, the forward-backward implementation of the pSRM is based on the minimization of a linear cost function, which requires working with complex representation of the NF. Thus, an initial guess of the phase distribution on the measurement surfaces is required. A description of the forward-backward implementation technique is presented in [16] and revisited in [18] in order to assess its performance for on-site antenna measurement. On the other hand, a non-linear cost function relating the amplitude of the measured NF \((|E_{NF,p1}|, |E_{NF,p2}|)\) and the amplitude of the NF radiated by the equivalent currents can be set, as illustrated in Figure 3. In this case, the initial guess is done on the equivalent currents, which is simpler than estimating an initial guess for the phase of the NF in the measurement surfaces. The better performance of the pSRM based on non-linear cost function minimization over the forward-backward technique has been analyzed and discussed in [18].

Once convergence is achieved, or the maximum number of cost function minimization iterations has been reached, the output is an equivalent currents distribution that is used to compute the phase
of the NF on the measurement surfaces. Then, the complex NF can be used for antenna diagnostics (NF-NF transformation) or for the calculation of the radiation pattern of the AUT (NF-FF transformation).

The reason why pSRM [16,18] has been chosen over other iterative phase retrieval techniques [15,17] is due to its capacity to work with non-canonical, non-uniformly sampled acquisition surfaces, which is likely to occur in the case of airborne-based measurement systems. As explained in [16], either the SRM or its phaseless version, pSRM, are based on the electromagnetic integral equations relating an equivalent currents distribution defined on a surface enclosing the AUT with the field radiated by these equivalent currents. These integral equations are discretized using piecewise basis functions. Other phaseless techniques for antenna measurement are based on wave mode expansion (e.g. planar [17], cylindrical [25], and spherical [26]), which are computationally much more efficient than the SRM/pSRM, but they require the NF to be uniformly sampled. Compressed sensing techniques can deal with sparse measurements as well [27], even in the case of phaseless measurements [28], resulting in measurement time reduction. However, sparse sampling patterns can be complex to be translated into a UAV pre-defined flight path.

![Figure 4. Pictures of the reflector antenna chosen as AUT. (a) Measurement at spherical range in anechoic chamber of the University of Oviedo; (b) Placed outdoors for on-site measurement.](image)

3. Experimental validation

The aforementioned improvements in the proposed UAV-based system for on-site antenna measurements have been assessed experimentally. For this purpose, an offset reflector antenna working at 4.65 GHz, and fed with a circularly-polarized helix antenna, has been selected as AUT (Figure 4). This AUT has a directivity of ~30 dB, being the main beam (which has a -10 dB beamwidth of BW_{0.5} ~12°) tilted $\theta = 20^\circ$ with respect to the vertical axis for this scenario. For this AUT, the FF distance is around 8 m ($124 \lambda$) at the frequency of 4.65 GHz. One of the reasons that led to the choice of this antenna was to prove the capabilities of the system for testing high directive antennas, widely used in applications such as radioastronomy or satellite communications. For reference purposes, the AUT was also measured at the spherical range in anechoic chamber of the University of Oviedo (Figure 4 (a)). As this AUT was chosen for the on-site measurements conducted with the previous version of the prototype presented in [12], results shown in this contribution will be compared with the ones in [12] to highlight how the proposed improvements have an impact in the measurement results.
Figure 5. Picture of the UAV and the reflector antenna placed on top of a 1.5 m high metallic mast, and scheme of the distances of the measurement domain.

Figure 6. Amplitude (normalized, in dB) of the NF measured at the geo-referred UAV flight path positions. Notice the offset in the vertical axis (y-axis) of the acquisition surfaces in order to capture the tilted main beam of the reflector antenna. The origin of the coordinates system is at the antenna.

As shown in Figure 4 (b) and Figure 5, the AUT was mounted on top of a 1.5 m height metallic mast, and then placed in the airfield of the University of Oviedo. The transmitted signal was a tone at 4.65 GHz generated using an oscillator, and later amplified up to 15 dBm.
First, a preliminary flight along a vertical axis 4.5 m (70 \( \lambda \)) away from the AUT was conducted to determine the placement of the maximum of the AUT main beam. Once its position was found, the flight path and, consequently, the acquisition surfaces, were defined as shown in Figure 5.

The implemented system allows defining different kind of measurement domains, e.g. planar, cylindrical, spherical [29]. In the case of high directive antennas, such as the AUT selected for validation purposes, a planar measurement domain is sufficient for proper characterization of the AUT, since most of the power radiated will be within the acquisition domain. An acquisition domain of \((x, y) = (4, 2.4)\) m size was defined, later truncated to \((x, y) = (3, 2)\) m to reduce the amount of NF data, as shown in Figure 6.

![Flowchart of the validation methodology followed in the example presented in Section 3.](image)

The convergence of iterative phase retrieval methods such as the pSRM is influenced by the distance between the acquisition surfaces and the AUT, as well as the spacing between the acquisition surfaces. A quantitative assessment of the influence of these parameters is provided for this AUT, taking advantage of the fact that this antenna has been characterized at spherical range in anechoic chamber. In particular, an analysis based on simulated flight path positions using the NF calculated on these positions from an electromagnetic model of the AUT, has been conducted. This model has
been obtained from NF measurements at spherical range in anechoic chamber (Figure 7) following the methodology presented in [18].

Figure 8. Analysis of the pSRM convergence (cost function error) for different spacing between acquisition surfaces and several distances to the AUT. Simulated geo-referred flight path acquisition points has been considered, evaluating the NF radiated by an electromagnetic model of the AUT at these positions.

Results depicted in Figure 8 show that best cases correspond to a spacing between acquisition surfaces within 60 cm – 120 cm (9.3 \( \lambda \) - 18.6 \( \lambda \)) and an AUT-acquisition surface distance not greater than 5 m (77.5 \( \lambda \)). Besides, it must be taken into account minimum and maximum UAV flight distances from the AUT (depicted in Figure 8): too close increases the risk of accidental collision (e.g. due to a sudden wind gust) and too far increases the size of the acquisition grid. Based on the results of Figure 8, it was decided to set the AUT-UAV distance around 4.5 m away from the AUT (1.5 m further than in [12]). Acquisitions distances were 4.5 (70 \( \lambda \)) for the first measurement grid, and 5.3 (82 \( \lambda \)) for the second one (see Figure 5 and Figure 6).
A grid spacing in height (y-axis) of 5 cm (0.77 λ) was chosen as a trade-off between sampling rate and number of scans that can be performed taking into account the capacity of UAV batteries. If grid spacing were set to 0.5 λ (3.2 cm) to ensure Nyquist sampling rate [13], this would result in 75 scans along x-axis, which would require replacing the battery before the acquisition can be completed. With a grid spacing of 5 cm, the number of scans is reduced to 48, avoiding UAV battery replacement in the middle of the measurement process. Nevertheless, in the case of planar NF measurements of directive antennas, relaxation of the sampling rate above Nyquist can be admitted provided the grating lobes do not fall within the FF angular margin of validity.

For validation purposes only the horizontal (x-axis) component of the field has been measured, as it can be deduced from the position of the monopole probe antennas in Figure 1. Nevertheless, the vertical (y-axis) component of the NF could be acquired as well by rotating the two probes 90° and repeating the flight using the same flight waypoints defined for the measurement of the horizontal component.

Once the flight path was defined, the AUT was measured using the UAV-based system described in Section II. NF measurements were simultaneously acquired in both acquisition surfaces after a 12 minutes flight. The overall number of samples collected was 6016, in agreement with the number of samples that would result from uniform half-a-wavelength (λ/2) sampling of a 3 m x 2 m plane, which would be 5766. A video of the UAV-based system in operation can be watched at: https://youtu.be/k3CleGTkHxE.

![Image](image_url)

**Figure 9.** NF on the measurement surface #1 depicted in Figure 6. Comparison between (a) the NF estimated from an equivalent currents model of the AUT using anechoic chamber measurements and (b) on-site NF measurements.

Regarding validation purposes, on-site NF measurements were compared with the NF estimated from an equivalent currents model of the AUT obtained from complex measurements at spherical range in anechoic chamber. The NF radiated by the equivalent currents model was
evaluated at the positions shown in Figure 6, as outlined in the flowchart depicted in Figure 7. The comparison of the NF measured and evaluated at the two acquisition surfaces is depicted in Figure 9. Despite the main lobe of the reflector antenna being properly characterized, positioning and georeferring uncertainties as well as the limited dynamic range of the dual-channel receiver introduce some distortion in NF measurements acquired with the UAV-based system (Figure 9 (b)).

![Diagram](image)

Figure 10. Amplitude (a) and phase (b) of the reconstructed aperture fields from complex NF measurements at spherical range in anechoic chamber. Amplitude (c) and phase (d) of the reconstructed aperture fields from on-site NF measurements, current prototype. Amplitude (e) and phase (f) of the reconstructed aperture fields from on-site NF measurements, previous prototype [12]. Solid black line represents the projected profile of the reflector antenna.

Next, the amplitude-only information of the NF acquired at the two measurement surfaces shown in Figure 6 is introduced in the pSRM to recover an equivalent currents model of the AUT, as outlined in the flowchart of Figure 3. The recovered equivalent currents model of the AUT is used to calculate the NF on the AUT aperture plane as well as the radiation pattern. For validation purposes, the same procedure followed with on-site NF measurements will be conducted with the NF on the measurement surfaces estimated from NF measurements at spherical range in anechoic chamber (flowchart of Figure 7). Concerning pSRM convergence, it was achieved after 33 iterations when the
NF inputs were on-site measurements, and after 25 iterations when the NF was estimated from anechoic chamber measurements. Calculation time was 55 s in a conventional laptop, that is, ~8% of the measurement time using the UAV.

NF on the AUT aperture plane is depicted in Figure 10. Figure 10 (a) and (b) correspond to the amplitude and phase distribution of the NF when anechoic chamber measurements are considered, whereas Figure 10 (c) and (d) are the estimated aperture fields calculated from on-site NF measurements. In both cases the amplitude distribution fits the shape and size of the reflector antenna. In the case of the phase distribution, the typical phase-shift of off-centered reflector antennas can be noticed along the vertical direction (y-axis). For comparison purposes, aperture fields distribution from the proof-of-concept shown in [12] are depicted in Figure 10 (e) and (f): in this case AUT diagnostics is not as accurate as in the improved prototype, as some artifacts appear outside the projected aperture of the reflector antenna (upper left side). Differences in the phase distribution are mainly due to the different tilt of the reflector antenna in this validation example and in [12].

![Figure 11](image1.png)

**Figure 11.** Filtered aperture fields on the AUT aperture plane. Amplitude (a) and phase (b) of the reconstructed aperture fields from complex NF measurements at spherical range in anechoic chamber. Amplitude (c) and phase (d) of the reconstructed aperture fields from on-site NF measurements using amplitude-only information. Solid black line represents the projected profile of the reflector antenna.

From the aperture fields, the AUT radiation pattern can be calculated by means of NF-FF transformation. To get rid of the noise and artifacts observed in Figure 10 which are outside the area corresponding to the AUT physical aperture size (solid black line in Figure 10), filtering can be applied: aperture fields outside the AUT physical aperture size are discarded. Thus, the radiation pattern is calculated from the aperture fields of Figure 11. Far field pattern is depicted in Figure 12, where it can be observed that the reflector antenna was slightly tilted when measured at spherical range in anechoic chamber. For a better comparison, the main beam vertical cut is shown in Figure 12 (c). It can be observed the agreement between the far field calculated from on-site NF-
measurements using the UAV-based antenna measurement system, and the one calculated from NF measurements at spherical range in anechoic chamber.

Figure 12. Far field pattern. (a) From complex NF measurements at spherical range in anechoic chamber; (b) From amplitude-only information from on-site NF measurements, current prototype; (c) From amplitude-only information from on-site NF measurements, previous prototype [12]; (d) Comparison between NF-FF transformation from measurements at spherical range in anechoic chamber and on-site measurements.

4. Discussion

From the results shown in Figure 12 it can be noticed that the main beam is wider in the case of on-site NF measurements. The most likely reason is that reflections on the ground (see Figure 5), due to the realistic environment where the AUT is placed, make the measured NF data different from that of the ideal case of anechoic environment in chamber measurements, thus resulting in the filling of the sidelobes adjacent to the main beam. It must be remarked that, in particular, the filling of the sidelobe at \( \theta = 25^\circ \) can be observed using measurements taken both with the previous and current
prototype. This result justifies the importance of on-site measurements, as they allow assessing the influence of the environment surrounding the AUT.

Concerning quantitative assessment of the AUT radiation pattern, Table 1 shows a comparison of the radiation pattern parameters, namely -3 dB beamwidth and directivity. In the case of using NF amplitude-only data, the UAV-based system for antenna measurement presented in this contribution provides similar results as NF measurements at spherical range in anechoic chamber. Furthermore, the improvements in positioning and geo-referring, as well as better characterization of the dual-channel receiver, result in better estimation of the radiation pattern with respect to the proof-of-concept shown in [12], as it can be concluded from Table 1 and Figure 12.

Another important result from this contribution is the capability of the pSRM for measuring off-centered high-directive antennas, providing diagnostics and radiation characterization. In previous works, such as [30], validations for this kind of antennas were based on simulations.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Directivity</th>
<th>-3 dB beamwidth</th>
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</thead>
<tbody>
<tr>
<td>Anechoic chamber measurements. NF-FF, complex NF.</td>
<td>29.8 dB</td>
<td>6.6°</td>
</tr>
<tr>
<td>Anechoic chamber measurements. NF-FF, amplitude-only data.</td>
<td>29.5 dB</td>
<td>6.8°</td>
</tr>
<tr>
<td>On-site measurements. Previous prototype [12]. Amplitude-only.</td>
<td>29.4 dB</td>
<td>6.9°</td>
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<tr>
<td>On-site measurements. Current prototype. Amplitude-only.</td>
<td>29.6 dB</td>
<td>6.7°</td>
</tr>
</tbody>
</table>

5. Conclusions

Several improvements of a UAV-based system for on-site antenna measurements have been presented in this contribution. The use of a dual-channel radiofrequency power detector allows the simultaneous acquisition of NF measurements on two measurement surfaces, thus reducing positioning and geo-referring uncertainties with respect to the case in which two independent flights were needed for acquisition on each surface. Besides, the introduction of a dual-band multiconstellation RTK unit improves GNSS-RTK reliability. Both advances also yield smaller flight and deployment times, as well as more accurate measurements compared to previous prototypes of the implemented system. These features would make measurements at higher frequency bands feasible.

Results prove the capability of the improved system for characterization of high directive antennas, thus broadening the field of application where UAV-based antenna measurement systems can be introduced.

6. Patents


Supplementary Materials: The following are available online at https://youtu.be/k3CleG7kJxE. Video: video showing the UAV-based system for on-site antenna measurement under operation.


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References


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