Improvement of the Bandwith in Spaceborne Reflectarrays Based on a Optimization Procedure

Daniel R. Prado*, Manuel Arrebola†, Marcos R. Pino† and George Goussetis*
*Institute of Sensors, Signals and Systems, Heriot-Watt University, Edinburgh, U.K. Email: {dr38, g.goussetis}@hw.ac.uk
†Group of Signal Theory and Communications, Universidad de Oviedo, Spain. Email: {arrebola, mpino}@uniovi.es

***Abstract*—Direct-to-home (DTH) applications usually require a radiation pattern with a given footprint on the surface of the Earth. They also impose stringent cross-polarization requirements in the form of crosspolar discrimination (XPD) or isolation (XPI) in a given bandwidth. This paper describes a wideband optimization procedure and performance results of a very large spaceborne reflectarray for DTH application in a 10% bandwidth. The procedure is divided into three stages to facilitate convergence towards a wideband performance. First, a initial narrowband design is obtained. Then, a broadband optimization including XPD requirements is carried out with a limited number of DoF. Finally, more DoF are included in the last stage to obtain a wideband reflectarray with improved cross-polarization performance. An improvement of 4.8 dB is achieved in the cross-polarization performance for both XPD and XPI in a 10% bandwidth, while ensuring that the copolar pattern complies with the specifications in the whole band.**

***Index Terms*—reflectarrays, optimization, space communications, shaped-beam, generalized intersection approach**

I. Introduction

A drawback of planar reflectarrays is their narrow bandwidth due to the use of resonant elements and the differential spatial delay [1]. The use of sub-wavelength elements may improve the bandwidth of reflectarrays [2] at the expense of reducing the total range of phase-shift provided [3], which limits the design of advanced reflectarrays with shaped beams. In addition, sub-wavelength elements do not solve the differential spatial delay, which is critical in very large reflectarrays. The latter issue may be solved with the use of true time delay elements [4], although their topology may be complex when dealing with two polarizations. Another solution is to employ faceted [5] or curved [6] reflectarrays, at the expense of complicating the geometry and overall cost of the antenna.

In this work, an alternative method for planar reflectarrays employing a multi-resonant element and performing an optimization at several frequencies is proposed for dual-polarized, contoured-beam reflectarrays with improved cross-polarization performance. In this way, both bandwidth limitations are overcome, since the multi-resonant elements provide more bandwidth [1] and the optimization at several frequencies minimizes the differential spatial delay produced by the planar nature of the reflectarray antenna. A very large reflectarray with southern Asia coverage is employed to demonstrate this design strategy, using the generalized intersection approach [7] as the optimization algorithm. The procedure is divided into three stages to facilitate convergence towards a wideband performance. First, a narrowband design at central frequency is carried out. Then, using a limited number of degrees of freedom (DoF), a multi-frequency optimization is carried out. Finally, the number of DoF is increased to further improve the wideband performance of the reflectarray. Requirements in the form of crosspolar discrimination (XPD) are also considered. The optimized reflectarray complies with the copolar specifications in a 10% bandwidth (11.80 GHz—13.20 GHz) while the XPD is better than 33 dB in the whole band.

II. Design Methodology

A. Reflectarray analysis

A single-offset configuration is considered, in which a feed (horn antenna) illuminates the surface of the reflectarray. The incident tangential field $\vec{E}_{\text{inc}}(f)$ will vary with frequency, and the reflected tangential field is then calculated as:

$$\vec{E}_{\text{ref}}(f) = \boldsymbol{R}(f)\vec{E}_{\text{inc}}(f), \tag{1}$$

where

$$\boldsymbol{R}(f) = \begin{pmatrix} \rho_{xx}(f) & \rho_{xy}(f) \\ \rho_{yx}(f) & \rho_{yy}(f) \end{pmatrix} \tag{2}$$

is the matrix of reflection coefficients, which also depends on frequency, as well as on other factors such as the substrate of the unit cell, its geometry, etc. These coefficients are computed with a full-wave analysis tool assuming local periodicity. For the case at hand, the unit cell shown in Fig. 1 is considered, which is analysed by the method of moments based on local periodicity (MoM-LP) described in [8].

After the reflected tangential field in (1) has been obtained, the far field is computed using Love's equivalent principle, obtaining the E_θ and E_φ components. The copolar and crosspolar components are then readily obtained using Ludwig's third definition of cross-polarization. For its use in a broadband optimization procedure, this analysis is carried out independently at several frequencies within a specified band.

B. Broadband Design Methodology

The design methodology is divided into three stages to facilitate convergence towards a broadband performance and it is based on the multi-resonant cell shown in Fig. 1. This unit cell is composed of two sets of four parallel dipoles each in two layers of metallization. Each set of four dipoles controls the phase-shift for each linear polarization. In addition, the dipoles introduce different resonances, providing broadband performance [1]. Since the dipole lengths are responsible for

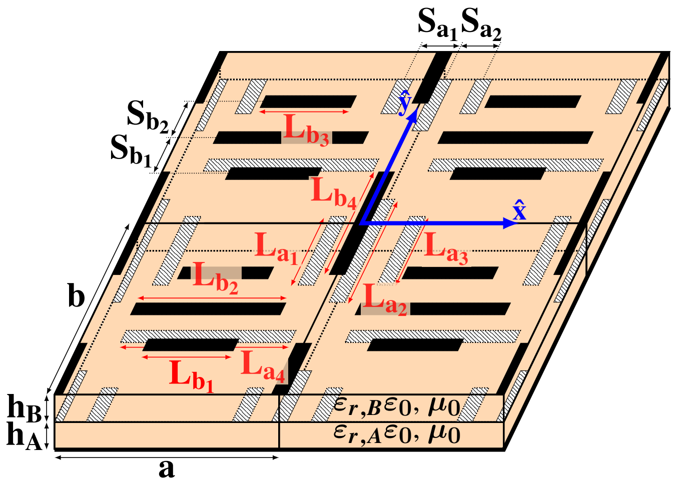

Fig. 1. Multi-resonant unit cell based on two sets of coplanar dipoles in two layers of metallization.

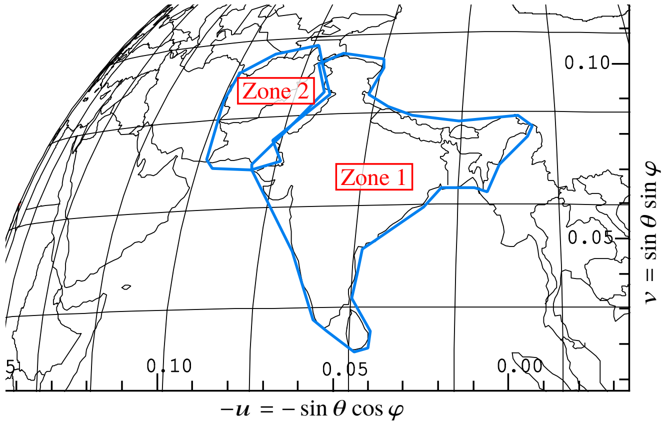

Fig. 2. Footprint of the southern Asian coverage, with (u, v) coordinates in the satellite coordinate system.

providing the phase-shift, they will be used as optimizing variables (in red in Fig. 1) while the rest of the parameters will remain fixed.

The first stage consists of a phase-only synthesis (POS) and a layout design at central frequency. For the POS, a focused beam in a direction (θ_0, φ_0) is employed as starting point. Since the POS can only impose requirements on the copolar pattern, the resulting reflectarray will meet the copolar specifications, but in general it will not comply with cross-polarization requirements. In addition, it will have narrowband performance.

Thus, in the second stage, a broadband optimization will be carried out, imposing both copolar and cross-polarization requirements. This is an intermediate step in which a limited number of DoF are optimized. Based on the unit cell shown in Fig. 1, two DoF per element will be considered, T_x and T_y, defined as follows:

$$\begin{aligned} L_{a_4} &= T_x; \quad L_{b_1} = L_{b_3} = 0.63T_x; \quad L_{b_2} = 0.93T_x \\ L_{b_4} &= 0.95T_y; \quad L_{a_1} = L_{a_3} = 0.58T_y; \quad L_{a_2} = T_y. \end{aligned} \tag{3}$$

The optimization will be carried out at three frequencies, central (12.50 GHz) and extremes (11.80 GHz, 13.20 GHz), which approximately corresponds to a 10% bandwidth. This is done by modifying the cost function of the generalized intersection approach [7], which now takes the form:

$$\begin{aligned} F = \sum_{f=1}^{N_f}\sum_{m=1}^{M} \Big\{ & W_{f,1}(\vec{r}_m)\left[\mathrm{CP}'_{\min,f}(\vec{r}_m) - \mathrm{CP}_{\min,f}(\vec{r}_m;\bar{\xi})\right] + \\ & W_{f,2}(\vec{r}_m)\left[\mathrm{XPD}'_{\min,f}(\vec{r}_m) - \mathrm{XPD}_{\min,f}(\vec{r}_m;\bar{\xi})\right]\Big\}^2, \end{aligned} \tag{4}$$

where N_f is the number of frequencies at which the optimization is carried out, $N_f = 3$ in the present case; M is the number of coverage zones; $\vec{r}_k = (u, v)_m$, with $u = \sin\theta\cos\varphi$ and $v = \sin\theta\sin\varphi$, is an observation point in the coverage zone; W_f is a weighting function which depends on the frequency and observation point; $\mathrm{CP}'_{\min,f}(\vec{r}_m)$ and $\mathrm{XPD}'_{\min,f}(\vec{r}_m)$ are the reference parameters being optimized ($\mathrm{CP}_{\min}$ is the minimum gain in a coverage area); $\mathrm{CP}_{\min,f}(\vec{r}_m;\bar{\xi})$ and $\mathrm{XPD}_{\min,f}(\vec{r}_m;\bar{\xi})$ are the current parameters generated by the reflectarray, which depends on the vector of optimizing variables $\bar{\xi}$. In this case, the vector $\bar{\xi}$ includes the values of T_x and T_y for all reflectarray elements that are optimized.

Finally, in the third stage the number of DoF is increased to six per unit cell. The length of all dipoles is free to vary with the exception of the lateral dipoles for each linear polarization, which will be the same to maintain the cell symmetry ($L_{a_1} = L_{a_3}$ and $L_{b_1} = L_{b_3}$, see Fig. 1).

III. Results for a Reflectarray with Southern Asian Coverage

A. Antenna Definition and Requirements

The considered reflectarray is elliptical in a single offset configuration. It is comprised of 6640 elements in a regular grid of periodicity 12 mm in both dimensions. The feed is placed at (−352.9, 0.0, 1061.7) mm from the reflectarray center and it is modelled as a $\cos^q\theta$ function, in which the parameter q defines the directivity of the feed and varies with frequency. Specifically, the values for q are 16, 18 and 20 at 11.80 GHz, 12.50 GHz and 13.20 GHz, generating an illumination taper of −16.1 dB, −17.9 dB and −19.7 dB, respectively. The width of the dipoles is set to 0.5 mm while the separation center to center between them is 2.5 mm. Commercial substrates were chosen, the Arlon AD255C for layer A, and the Diclad 880 for layer B.

Fig. 2 shows the footprint of the southern Asia coverage considered in this work. This footprint corresponds to the coverage of the SES-12 satellite, placed in geostationary orbit at 95° E. The official specifications [9] stipulate an EIRP of 52 dBW for zone 1 and 48 dBW for zone 2, which can be converted into gain with:

$$G(\mathrm{dBi}) = \mathrm{EIRP}(\mathrm{dBW}) - P_t(\mathrm{dBW}), \tag{5}$$

where P_t is the power of the transponder. Considering $P_t = 150$ W, it gives a gain requirement of 30 dBi and 26 dBi for

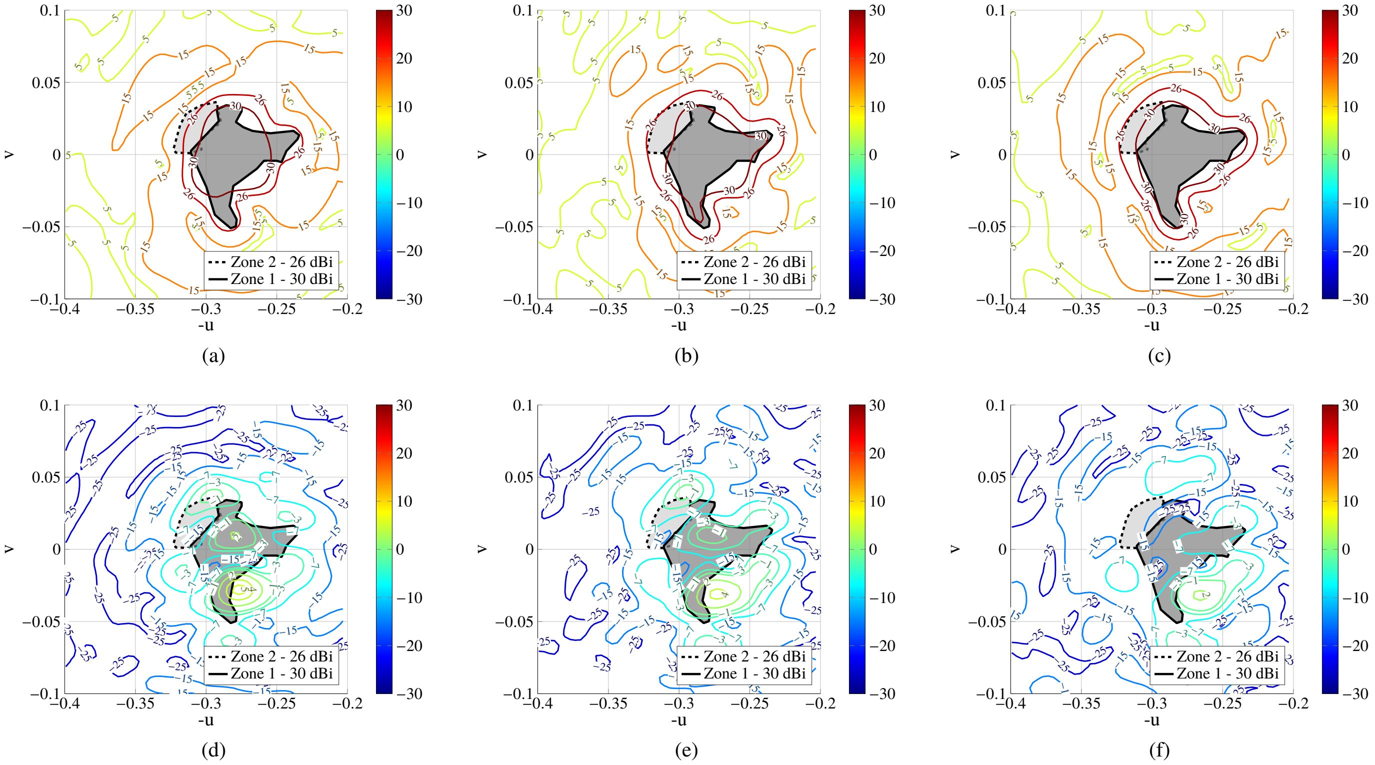

Fig. 3. Copolar (top) and crosspolar (bottom) radiation patterns for Y polarization (all of them in dBi) at 13.20 GHz for (a), (d) stage 1; (b), (e) stage 2; and (c), (f) stage 3 of the broadband design procedure.

zones 1 and 2, respectively. The design process will take into account typical pointing errors (0.1° in pitch and roll, and 0.5° in yaw) and it will be carried out in dual-linear polarization, with the same specifications in both polarizations. The cross-polarization goal is to achieve a minimum of 33 dB for the XPD.

B. Central Frequency Design

First, a phase-only synthesis (POS) is carried out whose result is two phase distributions, one for each linear polarization, such that the generated copolar pattern complies with the specifications. Then, a layout is obtained by adjusting T_x and T_y for each unit cell. Although this layout complies with the copolar specifications at central frequency, it is narrowband. For instance, the minimum copolar gain for zone 1 at 11.80 GHz is 25.26 dBi. Moreover, this reflectarray does not even comply with the cross-polarization requirements at central frequency. Thus, a direct layout optimization employing the MoM-LP tool will be carried out next.

C. Broadband Optimization Results

The broadband optimization is carried out with the algorithm presented in [7] using the cost function defined in (4). It employs the MoM-LP directly in the optimization loop. First, only two DoF per element are considered. The goal is to improve the copolar performance of the antenna in a 10% bandwidth with a limited number of DoF while also imposing cross-polarization requirements.

The worst case for the minimum copolar gain after stage 1 was zone 1 at 11.80 GHz for polarization Y with a value of 24.19 dBi, and zone 2 at 13.20 GHz for polarization Y with a value of 22.56 dBi. After the optimization carried out in stage 2, those values improved to 28.80 dBi and 26.45 dBi, respectively. The XPD_{min} (minimum value of the XPD in a given zone) also improves. Now, the copolar pattern is close to fulfil requirements in the whole band. On the other hand, the lowest value of XPD_{min} in stage 1 is 24.40 dB which improves to 27.12 dB after the optimization. However, it is almost 6 dB below the specification of 33 dB.

In the final stage, 39 291 variables are optimized at the same time. The final optimized layout complies with both, copolar and cross-polarization requirements at the three frequencies. Fig. 3 shows the evolution of the copolar and crosspolar components for Y polarization at 13.20 GHz for the three stages. This polarization and frequency represent the worst case. In addition, Table I gathers the results for the three stages of optimization. For the final layout, the minimum value of XPD_{min} in the 10% bandwidth is 33 dB in zone 1 for polarization Y at 13.20 GHz. Compared to the worst case of the initial design in stage 1, the XPD_{min} has improved 8.6 dB.

Finally, Tables II and III show the variation in minimum copolar gain, minimum XPD and XPI for each zone at the three frequencies between the initial and final designs. The improvement in both, copolar and cross-polarization performance is noticeable. The negative values correspond to zones of the

Table I
RESULTS OF THE DIRECT LAYOUT OPTIMIZATION FOR THE REFLECTARRAY WITH SOUTHERN ASIAN FOOTPRINT WITH TWO DIFFERENT COVERAGE AREAS IN DUAL-LINEAR POLARIZATION. THE RESULTS ARE SHOWN FOR THE INITIAL AND OPTIMIZED DESIGN AT THREE DIFFERENT FREQUENCIES IN AN 10% BANDWIDTH. CP_{MIN} IS THE MINIMUM COPOLAR GAIN IN A COVERAGE ZONE AND IS IN DBI. XPD_{MIN} AND XPI ARE IN DB.

		Zone 1						**Zone 2**					
		Polarization X			**Polarization Y**			**Polarization X**			**Polarization Y**		
Design	**Frequency**	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**
	11.80 GHz	25.26	30.14	26.75	24.19	28.60	24.94	28.65	36.15	36.03	28.79	35.25	34.69
Stage 1	12.50 GHz	31.52	32.50	32.08	31.36	30.51	29.56	28.63	32.99	31.13	28.91	31.76	29.87
	13.20 GHz	27.57	28.93	26.34	27.18	24.40	22.83	25.16	29.46	26.92	22.56	25.27	23.29
	11.80 GHz	29.96	32.52	31.65	28.80	31.14	29.50	27.86	41.72	39.93	27.58	39.27	38.29
Stage 2	12.50 GHz	30.88	33.77	32.45	30.61	31.12	30.09	28.59	35.77	34.06	28.89	34.17	32.88
	13.20 GHz	29.77	30.42	30.40	29.45	27.12	26.60	26.70	31.38	29.12	26.45	28.99	27.56
	11.80 GHz	30.65	37.69	37.25	30.12	34.37	33.78	27.73	42.08	41.10	26.92	38.88	38.68
Stage 3	12.50 GHz	30.92	37.28	36.92	30.95	34.39	33.77	28.21	38.92	38.68	28.29	39.09	38.80
	13.20 GHz	30.68	36.77	36.31	30.46	33.00	32.68	27.24	38.82	35.91	26.94	37.11	35.98

Table II
VARIATION BETWEEN THE INITIAL DESIGN (STAGE 1) AND THE FINAL OPTIMIZED LAYOUT (STAGE 3) FOR POLARIZATION X. VALUES IN DB.

	Zone 1			**Zone 2**		
Frequency	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**
11.80 GHz	+5.39	+7.55	+10.50	–0.92	+5.93	+5.07
12.50 GHz	–0.60	+4.78	+4.84	–0.42	+5.93	+7.55
13.20 GHz	+3.11	+7.84	+9.97	+2.08	+9.36	+8.99

Table III
VARIATION BETWEEN THE INITIAL DESIGN (STAGE 1) AND THE FINAL OPTIMIZED LAYOUT (STAGE 3) FOR POLARIZATION Y. VALUES IN DB.

	Zone 1			**Zone 2**		
Frequency	**CP_{min}**	**XPD_{min}**	**XPI**	**CP_{min}**	**XPD_{min}**	**XPI**
11.80 GHz	+5.93	+5.77	+8.84	–1.87	+3.63	+3.99
12.50 GHz	–0.41	+3.88	+4.21	–0.62	+7.33	+8.93
13.20 GHz	+3.28	+8.60	+9.85	+4.38	+11.84	+12.69

initial design that complied with the copolar specifications and whose gain decreased to compensate for the improvement at other frequencies. However, the copolar pattern complies with specifications in the whole band for both linear polarizations.

IV. CONCLUSION

In this work, a multi-frequency optimization procedure based on the generalized intersection approach and a multi-resonant unit cell has been presented. The design process is divided into three stages. First, an initial narrowband design at central frequency is carried out. Then, a broadband optimization using two degrees of freedom (DoF) per element is carried out, imposing requirements in the minimum copolar gain and minimum crosspolar discrimination. The result of this second stage is a reflectarray that is close to fulfil specifications in the copolar pattern in the whole band. Finally, for the third stage the number of DoF per element is increased to six and the final optimized layout complies with both, copolar and cross-polarization requirements. This procedure was applied to a very large reflectarray for direct-to-home application with southern Asian coverage to work in a 10% bandwidth with improved cross-polarization performance, obtaining excellent results.

ACKNOWLEDGMENT

This work was supported in part by the Ministerio de Ciencia, Innovación y Universidades under the project TEC2017-86619-R (ARTEINE); by the Ministerio de Economía, Industria y Competitividad under the project TEC2016-75103-C2-1-R (MYRADA); by the Gobierno del Principado de Asturias/FEDER under the project GRUPIN-IDI/2018/000191; and by Ministerio de Educación, Cultura y Deporte/Programa de Movilidad "Salvador de Madariaga" (Ref. PRX18/00424).

REFERENCES

[1] J. Huang and J. A. Encinar, *Reflectarray Antennas*. Hoboken, NJ, USA: John Wiley & Sons, 2008.

[2] D. M. Pozar, "Wideband reflectarrays using artificial impedance surfaces," *Electron. Lett.*, vol. 43, no. 3, pp. 148–149, Feb. 2007.

[3] L. Guo, P.-K. Tan, and T.-H. Chio, "On the use of single-layered subwavelength rectangular patch elements for broadband folded reflectarrays," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 424–427, 2017.

[4] E. Carrasco, J. A. Encinar, and M. Barba, "Bandwidth improvement in large reflectarrays by using true-time delay," *IEEE Trans. Antennas Propag.*, vol. 56, no. 8, pp. 2496–2503, Aug. 2008.

[5] C. T. Tong, C. E. F. Raelene, and K. C. Tian, "Comparison of simulated performance of faceted & flat reflectarray antennas," in *International Symposium on Antennas and Propagation (ISAP)*, Busan, South Korea, Oct. 23–26, 2018, pp. 1–2.

[6] J. A. Encinar, M. Arrebola, and G. Toso, "A parabolic reflectarray for a bandwidth improved contoured beam coverage," in *The Second European Conference on Antennas and Propagation (EuCAP)*, Edinburgh, Scotland, United Kingdom, Nov. 11–16 2007, pp. 1–5.

[7] D. R. Prado, M. Arrebola, M. R. Pino, R. Florencio, R. R. Boix, J. A. Encinar, and F. Las-Heras, "Efficient crosspolar optimization of shaped-beam dual-polarized reflectarrays using full-wave analysis for the antenna element characterization," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 623–635, Feb. 2017.

[8] R. Florencio, R. R. Boix, and J. A. Encinar, "Enhanced MoM analysis of the scattering by periodic strip gratings in multilayered substrates," *IEEE Trans. Antennas Propag.*, vol. 61, no. 10, pp. 5088–5099, Oct. 2013.

[9] "SES-12's mission," https://www.ses.com/our-coverage/satellites/365 [Accessed: 27 April 2020].