A Doubly Curved Modulated Frequency Selective Surface Sub-Reflector in a Dual-Band (Tx/Rx) Multiple-Beam Reflector Antenna

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***Abstract*—A dual-band (Tx/Rx) multiple spot beam reflector system for high throughput satellites in Ka-band is presented. The configuration is a multiple-feed-per-beam dual reflector Cassegrain antenna with a frequency selective surface (FSS) sub-reflector that separates the response between Tx and Rx frequency bands. Using this configuration, a full multiple-beam coverage employing the four-colour frequency/polarisation reuse scheme can be produced using only a single main reflector. By utilising a modulated FSS sub-reflector, the performance of the antenna system is significantly improved compared to using a periodic element distribution on the sub-reflector.**

***Index Terms*—frequency selective surface, reflector antenna, frequency reuse.**

I. Introduction

Multiple-beam reflector antennas are becoming more and more popular for telecommunication applications due to their capability of delivering high capacity for high-throughput satellites (HTS). This kind of technology commonly utilises multiple-beam reflector antenna farms, requiring four dual-band (Tx/Rx) single-feed-per-beam (SFB) reflector apertures on the satellite platform [1]. A key challenge in the development of improved HTS antenna systems is to find solutions enabling a full dual-band (transmit and receive) multiple-beam coverage with a reduced number of main reflectors, as those are the most limiting in terms of platform accommodation and stowage volume.

With the in-flight demonstration of the multiple-feed-per-beam (MFB) MEDUSA focal array [4], a full dual-band transmit/receive (Tx/Rx) multiple-beam coverage can be covered using two main apertures. The same can also be achieved by SFB operation by considering polarising selective surfaces, e.g., polarisers [6] or reflectarrays [7].

One way to produce a full multiple-beam coverage using only one main reflector antenna is to combine two MFB feed systems through a frequency selective surface (FSS) sub-reflector. A first discussion and a preliminary investigation of this concept was presented in [2], [3]. The concept is currently being investigated further in an on-going ESA activity, and a detailed analysis of such an antenna system that achieves a full dual-band coverage using only a single main reflector is presented in this paper. The proposed solution consists of a multiple-beam dual reflector Cassegrain antenna system with a doubly curved FSS sub-reflector operating in Ka-band. A key feature of this design is that it provides congruent Tx and Rx multiple-beam coverage through an adequate design of the optics. The FSS sub-reflector is designed to be reflective in Tx band and transparent in the Rx band. By introducing a modulated layout (varying size) of the FSS elements on the sub-reflector, the performance of the antenna system is improved compared to using a periodic element distribution on the sub-reflector.

II. Mission Specifications and Antenna Geometry

A 40 beam Ka-band antenna with a four-colour frequency reuse coverage of Europe in both Tx and Rx is proposed. The frequency band distribution and polarisation distribution between the four beam colours are presented in Table I. The feed arrangement in Tx and Rx each consist of a hexagonal lattice MFB cluster, where seven feeds are used in an overlapping configuration to generate each beam [4].

An illustration of the antenna geometry is presented in Fig. 1, and the values of the geometrical parameters of the antenna system are presented in Table II. Here f is the focal length of the main reflector, $2c$ is the focal distance of the sub-reflector and α is the angle from the main reflector axis to the sub-reflector. A parabolic main reflector with a focal length of 3.6 m and a diameter of 2.7 m is used. A doubly-curved hyperboloid surface is used for the FSS sub-reflector which consists of approximately 35 500 elements. The sub-reflector rim is slightly elliptic with a diameter of 68 cm in the offset direction and 60 cm in the orthogonal direction. The curvature of the sub-reflector is relatively small with an eccentricity e of 4.1.

TABLE I
Colour specification of the proposed four-colour frequency and polarisation reuse scheme.

Colour	Red	Yellow	Green	Blue
Polarisation	RHCP	LHCP	RHCP	LHCP
Frequency sub-band	1*	1*	2†	2†

* 20.2–20.7 GHz in Tx, 30.0–30.5 GHz in Rx.
† 20.7–21.2 GHz in Tx, 30.5–31.0 GHz in Rx.

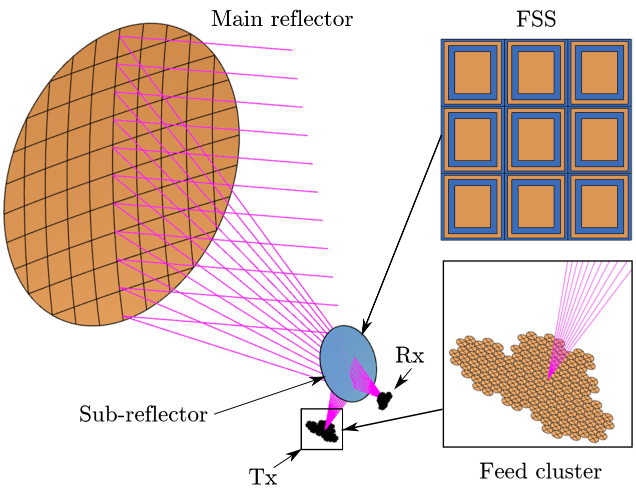

Fig. 1. Dual reflector Cassegrain antenna including FSS sub-reflector marked in blue and MFB clusters in Tx (left feed cluster) and Rx (right feed cluster).

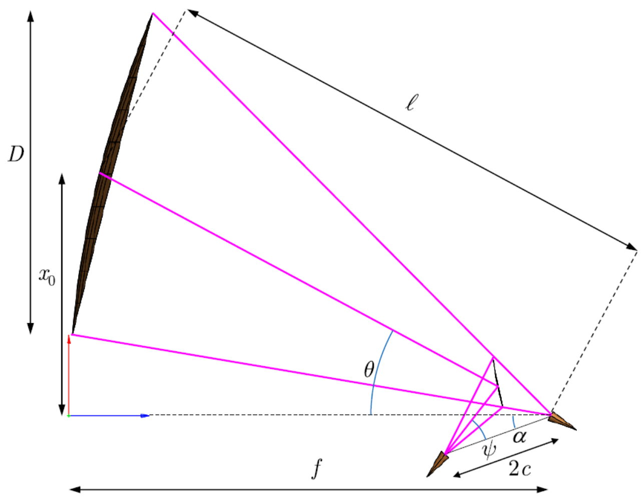

Fig. 2. Definition of the design parameters of the proposed dual reflector Cassegrain antenna system.

The antenna system was designed in a number of steps. First, the optics of the Cassegrain antenna system and the FSS were designed individually. Then, all components of the antenna system were assembled and optimised together to improve the overall performance in terms of the main beam characteristics of the antenna.

A great number of FSS designs were considered when trying to find a suitable element for the dichroic sub-reflector.

TABLE II
DESIGN PARAMETERS OF THE PROPOSED DUAL REFLECTOR CASSEGRAIN ANTENNA SYSTEM.

e	$2c$ [m]	D [m]	α [°]	ψ [°]	z_p [m]	θ_i [°]
4.1	1.0	2.7	18.6909	30.2987	17.41	39.16

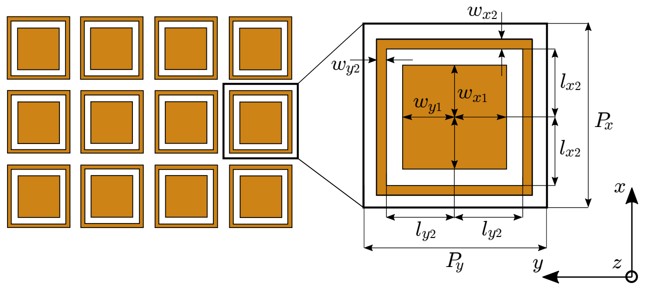

Fig. 3. Rectangular patch and loop band stop FSS design (left) and its design parameters (right).

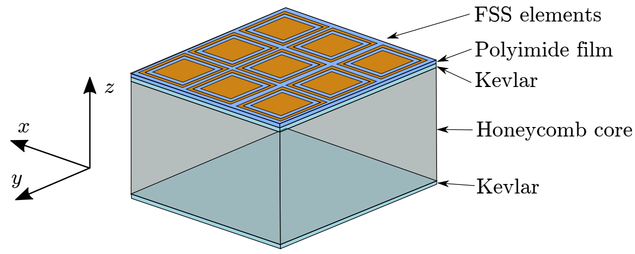

Fig. 4. Baseline FSS design with the sub-reflector material stack-up.

Different element unit cell models were implemented in the QUPES software product in the TICRA Tools framework [8], where the spectral domain periodic method of moments (PMoM) solver was used to analyse and optimise the element parameters based on the filtering performance of the FSS. A trade-off was then carried out between the performance of the FSS and the mechanical complexity of the design. It was concluded that a single resonant layer of the element in Fig. 1, consisting of a concentric rectangular patch and a rectangular loop, could provide the desired scattering properties in the Tx and Rx bands. The selected FSS element was inspired by the design in [5], and the design parameters of the element are presented in Fig. 3. The main parameters of the element are the cell width P_y, the cell height P_x, the patch size parameters in the two directions w_{x1} and w_{y1}, the loop size parameters l_{x2} and l_{y2} and finally the loop width in the two directions w_{y2} and w_{x2}.

The dichroic sub-reflector consists of a stack-up of two thin Kevlar facesheets separated by a 25 mm thick low permittivity Kevlar honeycomb core. The FSS elements are etched on a copper clad flexible polyimide film bonded to the facesheet at the side of the sub-reflector facing the Tx feed array. An illustration of the sub-reflector material stack-up is presented in Fig. 4. For applications requiring wider bandwidth additional resonant layers could be added to the FSS and alternative FSS element designs could also be considered.

III. SIMULATION RESULTS

The antenna system was optimised and analysed using the TICRA Tools software framework [9]. The spectral domain PMoM solver in QUPES was used to analyse the scattering from the FSS at unit cell level, in the case of plane wave illumination, at scan angles in the range $\theta = [15°, 55°]$. The

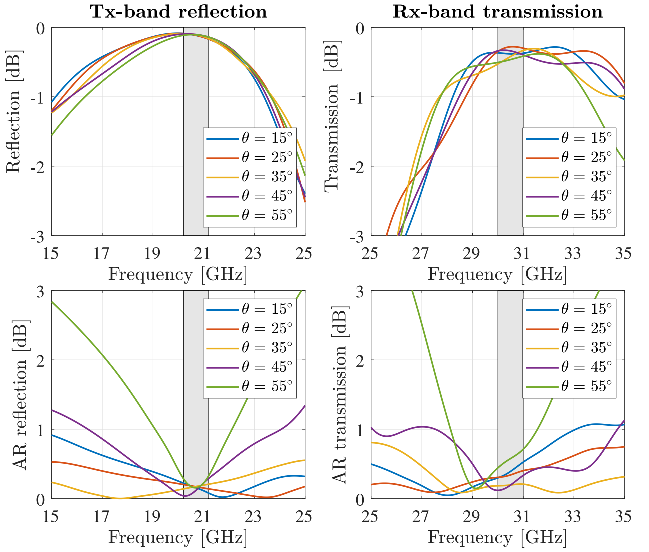

Fig. 5. Simulation results of the optimised FSS design at unit cell level.

TABLE III
WORST CASE BEAM PERFORMANCE VALUES OF THE ANTENNA SYSTEM USING THREE DIFFERENT SUB-REFLECTOR CONFIGURATIONS.

Sub-reflector	Frequency band	EoC directivity [dBi]	C/I [dB]	XPD [dB]
Ideal FSS	Tx	47.08	15.04	39.11
	Rx	47.76	15.51	36.58
Periodic FSS	Tx	46.88	15.14	30.15
	Rx	46.45	16.52	23.72
Modulated FSS	Tx	46.81	16.89	29.70
	Rx	47.52	16.98	28.89

results in Fig. 5 indicate that the FSS reflection loss is lower than 0.2 dB in the full Tx band and the transmission loss is on the order of 0.4–0.6 dB in the full Rx band. The circular polarisation purity, expressed as axial ratio (AR), is better than 0.3 dB in reflection in the full Tx band and the AR in transmission is below 0.7 dB in the full Rx band.

The spectral PMoM solver in QUPES was also used to analyse the scattering of the FSS sub-reflector at antenna level, and the physical optics/physical theory of diffraction (PO/PTD) solver in GRASP [10] was used to analyse the scattering from the main reflector. The performance of each individual beam in Tx and Rx was evaluated based on fixed beam locations with a spacing of 0.33°. The main performance quantities of interest of each beam are the edge of coverage (EoC) directivity, the carrier over interference (C/I), and the cross-polarisation discrimination (XPD).

Simulation results from three iterations of the antenna design are presented in Table III. First, an ideal FSS sub-reflector was used, represented by a PEC sub-reflector in Tx and a transparent sub-reflector in Rx. Then, a periodic FSS sub-reflector was used, and finally a modulated FSS sub-reflector with FSS elements of varying size was introduced.

The results in Table III represent the worst-case performance

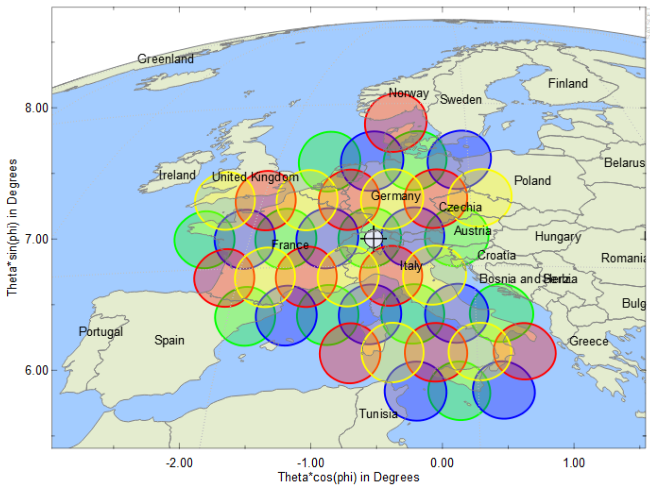

Fig. 6. Tx beams of the antenna system with a modulated FSS sub-reflector. Co-polarisation contour curves are plotted at 46.0 dBi at the centre frequency of operation in each beam.

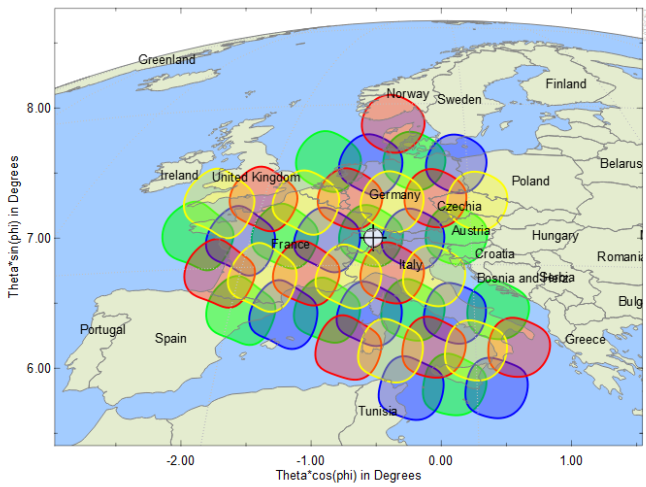

Fig. 7. Rx beams of the antenna system with a modulated FSS sub-reflector. Co-polarisation contour curves are plotted at 46.0 dBi at the centre frequency of operation in each beam.

values throughout all the beams in the entire Tx and Rx frequency bands, respectively. When comparing the results of the ideal FSS sub-reflector and the results of the periodic FSS sub-reflector in Table III it is observed that introducing the non-ideal periodic FSS sub-reflector implies a performance degradation of the antenna system in terms of EoC directivity and XPD. By optimising the sub-reflector FSS element parameters in a modulated (quasi-periodic) fashion, some of the lost performance can be recovered, and in terms of C/I the performance is improved even in relation to the ideal FSS by more than 1 dB. The Tx band co-polarisation main beams of the antenna system with the modulated FSS are shown in Fig. 6 and the Rx band co-polarisation main beams are presented in Fig. 7.

IV. CONCLUSION

An antenna system consisting of a high throughput dual-reflector antenna has been presented. A full dual-band (Tx/Rx) multiple-beam coverage over Europe has been achieved using a single main reflector aperture in combination with two MFB feed systems and a modulated FSS sub-reflector. The FSS sub-reflector consists of an array of concentric copper patches and loops and achieves reflection in Tx band, and transmission in Rx band, for dual circular polarisations. Significant antenna level performance improvements have been achieved by designing a modulated FSS sub-reflector in TICRA Tools QUPES compared to using a periodic FSS sub-reflector.

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