RF DESIGN TOOL FOR END-TO-END OPTIMISATION OF HIGH-PERFORMANCE MULTIBEAM ANTENNA SYSTEMS

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***Abstract*—This paper describes a new integrated RF design tool for analysis and optimisation of reflector-based multibeam antenna systems. The new tool combines several powerful algorithms into a flexible software framework that allows end-to-end optimisation of antenna systems comprising of passive microwave components, feed horns, reflectors, and advanced surfaces such as reflectarrays, transmitarrays, or frequency and polarisation selective surfaces. The term *end-to-end* is used to indicate that the entire multibeam system can be optimised as one model where only the final performance parameters of the complete antenna system are included, e.g., the return loss at the input ports of the first feed chain components and the resulting beam shapes after the last reflecting surface. We illustrate the new capabilities with design examples, e.g., a single-feed-per-beam feed cluster that is directly optimised for improved C/I ratio of the beams radiated by the main reflector.**

I. INTRODUCTION

High-Performance multibeam antennas for space applications are often realized using a reflector system in which a large number of feeds are illuminating a reflecting surface that generates a multitude of focused beams. The feed system may use a single feed per beam configuration or a multiple feed per beam configuration and in both cases each feed is typically realized as a smooth-walled or corrugated horn in conjunction with several passive microwave components, e.g., polarizers, orthomode junctions, or filters. Significant research efforts have recently been devoted to further enhance multibeam antenna performance by utilizing advanced concepts in which one or more reflectors are replaced with a periodic or quasi-periodic surface, e.g., frequency or polarization selective surfaces, reflectarrays, or transmitarrays. In all the aforementioned cases, the RF design of the microwave components, the feed, the reflector, or the periodic surface, is typically performed using separate high-end optimisation tools dedicated to a specific purpose. Consequently, each antenna subsystem is optimised separately which implies that subsystem requirements must be derived and expressed in terms of intermediate performance parameters that are not performance parameters of the overall antenna system. This approach where optimisation is applied at the subsystem level is known as an indirect optimisation, because there is no direct relation between the variables being optimised, e.g., the feed geometry, and the actual performance parameters of interest, e.g., the beam shape produced by the reflector. Efficient RF design tools are available at the subsystem level while tool limitations imply that an end-to-end RF model encompassing all antenna subsystems is often not feasible or the analysis time is far too time-consuming to allow optimisation.

The present paper describes two recently completed RF design tool developments performed within ESA's ARTES framework [1], [2]. The combination of these two developments and the industry's standard tool for reflector analysis, GRASP, provides a single powerful RF design tool that allows an end-to-end model to be defined, analyzed, and optimised. The model may include passive microwave components, feed horns, and any number of reflecting surfaces, including solid reflectors, frequency- or polarization-selective surfaces, reflectarrays, or transmitarrays. All geometrical parameters included in the model may be optimised, e.g., the dimensions of arbitrarily shaped waveguide components, horn profiles, reflectors shapes, or the geometrical parameters of the individual periodic element in a reflectarray. In addition to the traditional indirect optimisation at the subsystem level, the new tool also supports a direct optimisation approach where the performance is only evaluated on the final antenna parameters of interest, e.g., the reflection level at the first waveguide component in the feed chain and the directivity of the beams radiated by the last reflecting surface. Intermediate parameters, such as the feed taper, are left unspecified because these are not performance parameters of the overall antenna system. Furthermore, the tool allows all beams in a multibeam system to be optimised simultaneously which implies that important performance parameters involving multiple beams, e.g., the C/I ratio, can be directly optimised.

The paper is organised as follows. Section II describes the new integrated software tool for feed chains and Section III describes the new integrated software tool for periodic and quasi-periodic surfaces. Finally, multibeam design examples will be presented in Section IV.

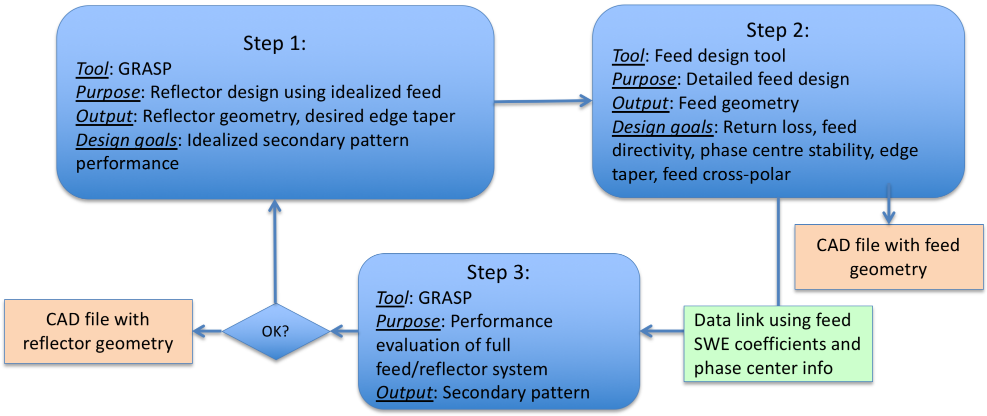

Fig. 1. The present reflector antenna design process that involves multiple dedicated tools.

II. Analysis and Optimisation of Feed Chains

GRASP was recently supplemented by an integrated feed chain design tool [1] that simplifies the reflector/feed design process significantly. The new design process is discussed in Section II-A below, whereas Section II-B outlines the capabilities of the new tool.

A. *Improved Reflector/Feed Design Process*

Reflector antennas are by far the most used antenna technology for telecommunications satellite antennas, ground station antennas, and high-gain user terminals. Strong requirements have always been posed to the antenna performance and the reflector antennas are therefore typically designed using the well-established and validated antenna design tool, GRASP, which provides an accurate analysis of the isolated reflector antenna performance. However, GRASP does not allow the reflector feed and other feed chain components to be analysed. As a consequence, the antenna designer must design the feed chain in a separate feed design tool. The requirements for the feed chain must be derived from the overall system specifications and appropriate design goals must be formulated at the subsystem level, e.g., feed directivity, beam width, phase centre, and cross-polar level. This complex multi-tool design process is illustrated in Figure 1. The process must often be repeated iteratively to achieve the desired performance. By using the new integrated feed design tool, the design process is significantly simplified as illustrated in Figure 2. Three distinct improvements have been realised:

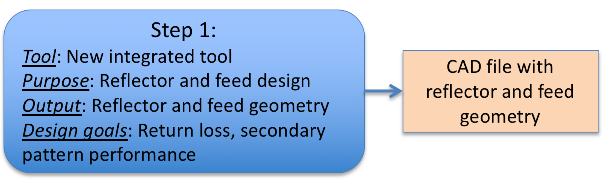

Fig. 2. An improved reflector antenna design process involving only a single fast tool.

- The error-prone data exchange between two separate tools is avoided. In addition, the optimised geometry is available in a single CAD file, thereby eliminating the risk of misplacing the parts.
- The accuracy of the RF analysis is improved because a full-wave analysis of both the reflector and the feed chain is available within a single tool. If two separate tools are used, important field interactions may be missed.
- The use of a separate feed design tool implies that intermediate design goals must be introduced when optimising the feed, e.g., the feed phase centre and beam width. These intermediate performance metrics are not relevant parameters for the final antenna system and this optimisation approach is therefore an indirect approach. The single-tool solution provides a direct feed optimisation approach where the optimisation goals are defined on the actual performance parameters of interest, i.e., the secondary pattern. The direct optimisation technique enables better antenna designs by avoiding intermediate feed design goals.

B. *Capabilities of the Integrated Tool for Feed Chains*

The new tool is built upon a Generalized Scattering Matrix (GSM) framework that is used to decompose the problem into smaller regions, each solvable with an efficient method suitable for the specific subproblem. The individual subproblems are connected via waveguide ports of circular, coaxial, rectangular, og arbitrary shapes. The GSM of each subproblem is then computed by one of the methods mentioned below and the overall GSM of the assembly can be obtained through a rigorous elimination of all internal ports. This hybridized approach allows a component-based definition of even complex feed assemblies that can be analyzed in a very short time and with very high accuracy. The available analysis methods all provides full-wave accuracy and include the following:

- Closed-form analytic expressions are used for simple waveguide components.

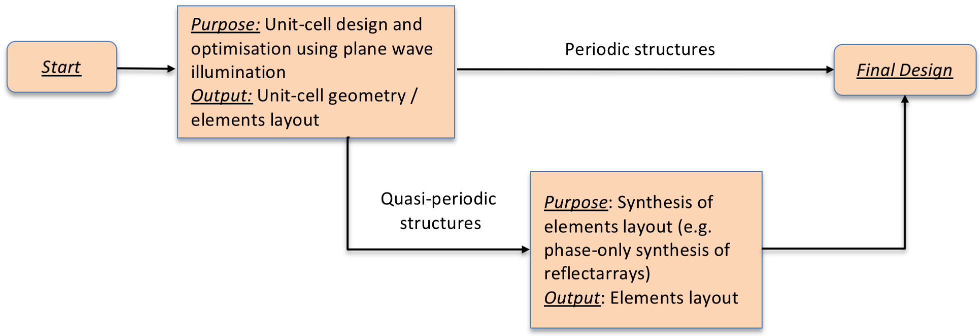

Fig. 3. Illustration of the conventional design process for periodic and quasi-periodic surfaces.

- Classical mode-matching algorithms are used for horn analysis [3], [4], [5].
- Modal analysis is also available for more complex waveguide components by means of the generalized admittance matrix method [6], [7].
- Body-of-Revolution Method of Moments (BoR-MoM) is available for rotationally symmetric waveguide geometries and apertures.
- Arbitrarily shaped waveguide components and apertures are analysed with a higher-order 3D Method of Moments (3D-MoM) [8].
- A FEM-based analysis [9] which has been extended with higher-order basis function for improved accuracy is available for waveguides with arbitrary cross sections.

The component-based approach has several advantages, in particular when complex feed assemblies are defined. For instance, the same component may be reused several times in the same model, providing huge savings for typical feed chains. Furthermore, during the optimisation process the software automatically determines the subset of components that are influenced by a particular change of the optimisation variables, thus requiring an update of the GSM. For the remaining components the previously computed GSM can be directly reused. The component-based definition also simplifies the setup since a large number of commonly encountered components has been implemented in a library of predefined components.

III. Analysis and Optimisation Periodic and Quasi-periodic Surfaces

The main application area of the new tool is the design of periodic or quasi-periodic surfaces that can reflect or transmit electromagnetic fields to fulfil certain radiation characteristics when illuminated by an external source, e.g., a feed horn. Such surfaces can often be categorized in two groups:

1) Periodic surfaces which consist of identical array elements, e.g., traditional frequency selective surfaces (FSS) and polarization selective surfaces (PSS).
2) Quasi-periodic surfaces which consist of non-identical array elements, e.g., reflectarrays, transmitarrays, advanced FSS/PSS surfaces with non-identical elements, modulated impedance surfaces, etc.

Such surfaces are currently used in many types of antenna systems and will find an even wider range of applications in the next generation of high performance antenna systems.

For the design of periodic and quasi-periodic surfaces, some software tools allow the entire structure to be defined in one model, but the computation time for a single-frequency analysis is in terms of hours and hence, such tools generally do not permit numerical optimisation. As a consequence, the design process used today is always based on tools with dedicated features for periodic surfaces, as explained in Section III-A below. Section III-B outlines the capabilities of the new tool.

A. Design Process for Periodic and Quasi-Periodic Surfaces

The RF-design of periodic surfaces is currently done at the unit-cell level where an infinite array consisting of identical unit-cells illuminated by a plane wave is assumed. The unit-cell is then optimised to fulfil a set of reflection and transmission specifications from which the final design is obtained. This conventional design process is illustrated in Figure 3. There are significant drawbacks associated with this approach:

1) The finite size of the surface is not accounted for during the optimisation.
2) A plane wave illumination is assumed and the near-field properties of the feed are neglected.
3) The approach does not allow the optimisation of the periodic surface together with the entire antenna system. For instance for a dual-reflector system consisting of a FSS sub-reflector and a solid main-reflector, it is not possible to optimise the FSS and the reflectors simultaneously.

For quasi-periodic surfaces, the design process involves an additional step (also indicated in Figure 3) after the unit-cell and the type of array elements have been

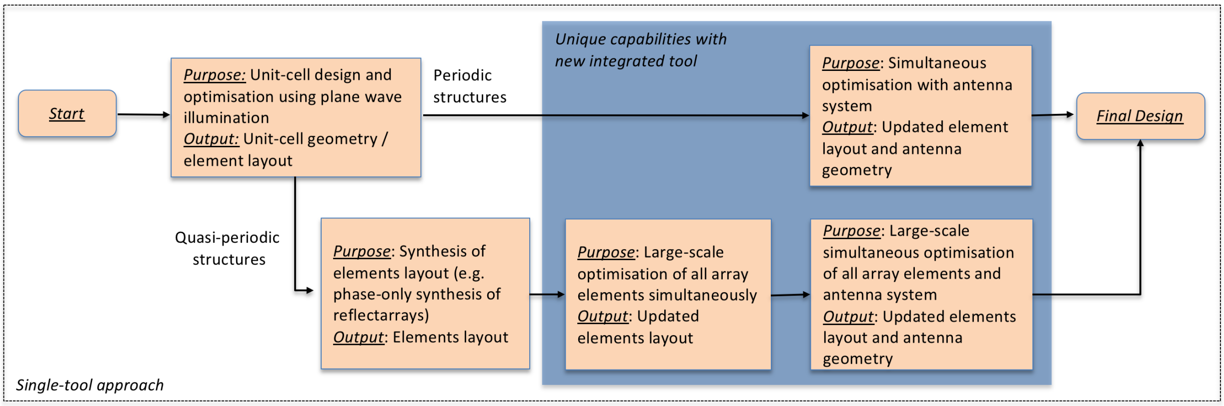

Fig. 4. Illustration of the design process using the new integrated tool. The initial steps in the design process are identical to the existing design methods. However, additional analysis and optimisation capabilities are included (within the blue box) which allow the simultaneous optimisation of the periodic/quasi-periodic surfaces together with the entire antenna system.

selected. In this step, each element on the surface is optimised, a single element at the time, to arrive at the final design. Each optimisation step typically involves 1-6 variables in the element considered. This step corresponds to the so-called phase-only approach where the required phase distribution on the surface is obtained first, and subsequently, the array elements are adjusted, element-by-element, to provide the required phase distribution. This approach inherits the three drawbacks mentioned above for periodic surfaces. Furthermore, the phase-only approach optimises each element individually by considering the local phase response, which is an intermediate quantity. The actual antenna requirements are instead formulated in terms of the secondary pattern performance. As a consequence, the phase-only approach breaks the direct relation between the optimisation variables and the optimisation goals, leading to suboptimal designs.

The improved antenna design process illustrated in Figure 4 circumvents all the aforementioned limitations for both periodic and quasi-periodic surfaces. The initial steps in the process are identical to the conventional design approach. However, once the initial steps are completed, the new tool will allow additional optimisation steps to further enhance the performance (shown in the blue box in Figure 4):

- For periodic surfaces, the geometrical parameters of the (identical) elements and the remaining part of the antenna system are optimised simultaneously, while also taking into account the finite size of the surface as well as possible near-field characteristics of the source.
- For quasi-periodic surfaces, the new tool is able to perform a full-scale and simultaneous optimisation of all geometrical parameters, typically between 10,000-60,000 variables, including again the finite size and near-field characteristics of the source. As a final step, all the geometrical parameters of the non-identical elements on the quasi-periodical surface and the remaining part of the antenna system can be optimised simultaneously.

It should be emphasized that the additional optimisation steps outlined above represent a major technological challenge. The conventional phase-only approach employs a sequence of small optimisation problems, typically with 1-6 variables at the time. The new direct approach employs one large optimisation problem where all optimisation variables, typically between 10,000 and 60,000, are optimised simultaneously. The challenges associated with such a large optimisation problem are enormous and the problem has remained unsolved until recently. The fact that all parameters are optimised simultaneously implies that a local mismatch between the desired and actual element performance can be compensated by all the other elements. This compensation is not possible when the elements are optimised one-by-one.

B. Capabilities of the new Integrated Tool for Periodic and Quasi-Periodic Surfaces

The new integrated tool for periodic and quasi-periodic surfaces contains three algorithms, all based on surface integral equation (IE) methods, that have been developed for the analysis of various type of elements arranged in a 2D lattice. Two of these methods are dedicated to commonly encountered special cases, i.e., printed elements on multilayered substrates and thick metallic screens with perforations. The dedicated methods are very fast but limited in terms of the geometry they can handle. A third method has therefore been developed; this method can handle arbitrary periodic elements but is somewhat slower than the dedicated methods. The multi-solver approach has been chosen to keep the software tool as fast as possible while supporting all possible periodic elements. The three solvers are:

1) Spectral-domain higher-order MoM for printed structures. This algorithm can easily handle

many dielectric layers, it is efficient and well-validated, however, the metallization layers must be confined to the interfaces between the dielectric layers.
2) Periodic MoM for thick perforated metallic screens which are often used in dichroic plate filters. For such structures, a fast IE solution hybridized with mode-matching has been developed which results in an algorithm simillar to that of [10].
3) Higher-order Periodic MoM for arbitrary 3D objects arranged in a 2D lattice. This algorithm can handle any unit cell geometry and can be applied where the two algorithms discussed above cannot. The formulation is derived from the work in [11] which we have extended to handle higher-order basis functions, composite metallic/dielectric structures, as well as both finite and infinite dielectric regions.

In addition to the periodic solvers outlined above, the new tool also includes two accurate methods for computing the radiation patterns of finite-sized periodic or quasi-periodic surfaces. In the first method, each array element is analyzed assuming local periodicity, i.e., the individual element is assumed to be located in an infinite array of identical elements [12]. The reflection/transmission characteristics of the each element are determined by any of the three solvers listed above and are subsequently used to form equivalent currents from which the far-field is calculated. The equivalent magnetic and electric currents are constructed on a surface that encloses the finite sized surface. An alternative method has been derived by considering the surface as a continuous modulated surface impedance. By doing so, we remove any references to the individual array elements. By applying the equivalence principle, equivalent currents enclosing the finite sized surface is again defined. Both methods have also been extended to handle curved surfaces accurately.

The analysis methods described above have been implemented in the flexible GRASP framework that allows any number of periodic or quasi-periodic surfaces to be defined, as well as being combined with other methods available in GRASP or the feed chain design tool described in the previous chapter. Powerful optimisation capabilities are also included, as well as a library of commonly encountered unit cell geometries or even arbitrarily shaped user-defined elements.

IV. Application Examples

The capabilities of the new software tools are now illustrated with two design examples involving multibeam antennas. In both cases, we consider a single-feed-per-beam (SFPB) multi-beam reflector setup which are commonly used on High Throughput Satellites (HTS). In the most classical implementation, four reflector apertures are needed to provide a large number of highly directive beams using frequency and polarisation discrimination between adjacent beams. This configuration is also referred to as a 4-colour frequency/polarization reuse scheme. In the first example, we optimise the feed cluster directly to minimise the interference between beams while in the second example, we show that a reflectarray with polarisation-selective beam steering can be used to reduce the number of required reflectors from four to two.

A. Design of single-feed-per-beam multibeam antenna

In this example, we consider the design of a reflector and a feed cluster intended for a classical 4-colour SFPB setup using four apertures in total. The selected configuration is shown in Figure 5 where a feed cluster of 19 feeds are illuminating a 1.2 m reflector corresponding to 80λ at 20 GHz. The feed cluster uses three different kinds of feeds, one feed at the centre, 6 feeds in the ring around the centre feed, and 12 feed in the outer ring. The geometrical parameters of the feed horns are optimised and optimisation goals are defined on the secondary patterns of the 19 beams and on the return loss of the feed chain. The software allows for optimising the patterns of the individual beams, as well as the C/I quantity, i.e., the interference of a beam from all other beams.

A detailed view of the feed cluster is shown in Figure 6. In addition to the 3 different horn geometries, the feeds include a fairly complex feed network. This feed network is identical for all feeds meaning that it needs only to be analysed once. Each feed network consists of the following components from the built-in Waveguide Library:

- 10 straight pieces of rectangular waveguide
- 4 180° smooth bends of rectangular waveguide
- 4 90° smooth bends of rectangular waveguide
- 2 Stepped rectangular waveguides
- 2 Junctions between 3 rectangular waveguides
- 2 Linearly tapered rectangular waveguides
- 1 custom 5-port waveguide turnstile defined using a CAD file

The fact that some of the components are identical, further reduces the computation time since they need only be analysed once. The 3 different horn geometries each consist of a sequence of 5 linear profiles in combination with an exterior aperture, again being defined using the built-in Waveguide Library.

The initial design assumes that all 19 feed horns share the same geometrical design. This design is optimised with goals on the secondary pattern of the 19 individual beams. For each beam goals are set to the beam's Centre Directivity, the Edge-of-Coverage Directivity, and the C/I. From the resulting design the feed geometries are optimised a second time. This time the 3 different feeds are allowed to diverge resulting in a total of 28 optimisation variables. The same goals are applied again, however, due to the different positions

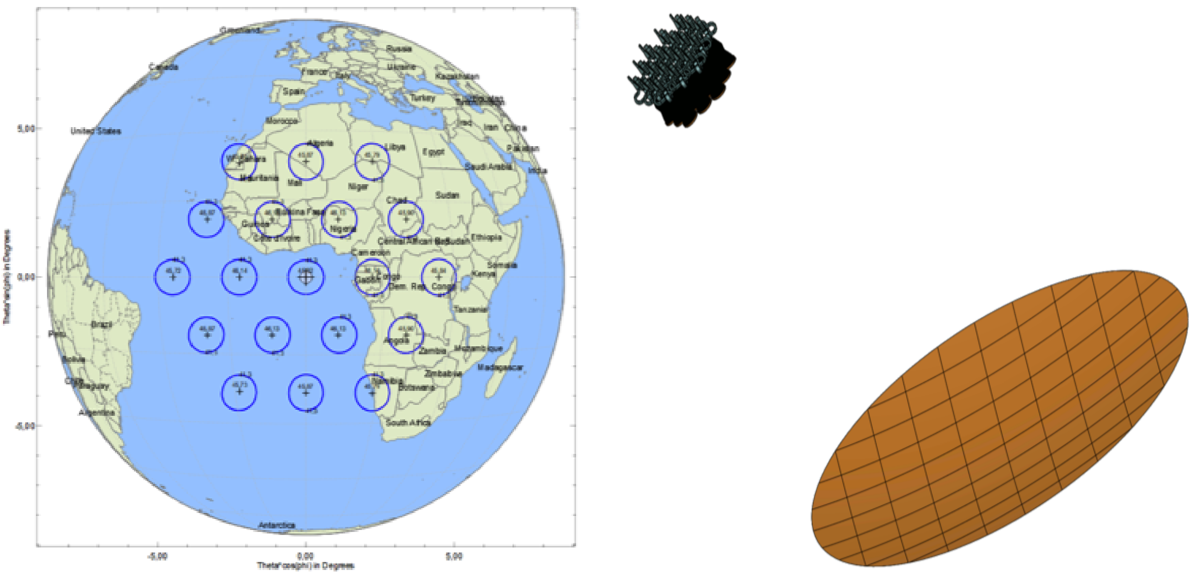

Fig. 5. Left: 19 beams produced by a single reflector in a 4-colour SFPB multi beam setup. right: Reflector system with the 19-beam feed cluster. Each feed includes a turnstile OMT, power combiners, and multiple waveguide bends. A close-up of the feed cluster that includes three different feed geometries are shown in Figure 6.

TABLE I
OPTIMISED PERFORMANCE OF MULTI-BEAM ANTENNA. THE TABLE SHOWS THE WORST CASE AMONG THE 19 BEAMS.

	Before (1 feed design)	After (3 feed designs)	Improvement
Centre Directivity	45.52 dBi	45.65 dBi	0.13 dB
Edge-of-Coverage Directivity	40.00 dBi	40.42 dBi	0.42 dB
C/I	22.46 dB	24.11 dB	1.65 dB

TABLE II
LAPTOP COMPUTATION TIME PER FREQUENCY FOR A 80λ MULTI-BEAM REFLECTOR WITH COMPLEX FEED CHAIN.

	All beams	Per beam
Initial computation time	26 s	1.4 s
Average computation time during optimisation	4.7 s	0.2 s

Fig. 6. Feed cluster with 19 feeds in three different configurations. Each feed includes a turnstile OMT, power combiners, and multiple waveguide bends.

of the feeds in the feed cluster, the optimisation results in different horn geometries.

In Table I the obtained values of the beam performances are summarised. The use of 3 different feed designs for the central position and two rings is seen to improve the performance significantly compared to using the same design for all feeds. The initial analysis of the antenna system can be performed in 26 seconds on a laptop computer, including the full-wave analysis of all feeds and the waveguide components in the feed chain, as well as the radiation pattern evaluation of all 19 beams. The average time needed for repeated evaluations during the horn optimisation is significantly shorter, as can be observed in Table II. It can be observed, that the average computation time per frequency and beam is well below one second. Finally, it is worth mentioning that C/I optimisation is only possible in an integrated tool offering both feed and reflector design at the same time.

B. Design of a Multi-beam Ka-band Reflectarray for HTS Applications

As mentioned previously, the classical SFPB 4-colour setup requires four main reflector apertures. However, by replacing the reflectors with reflectarrays, the same number of beams can be produced by only two apertures instead of four. This reduction is obtained by generating adjacent beams in orthogonal polarization from a single reflectarray. In particular, two circularly polarized beams with the appropriate beam separation on the ground can be generated by a single dual-polarized feed, provided that the reflectarray can generate a polarization-selective beam tilt. Furthermore, the beam tilt should be the same in both Tx (19 GHz) and Rx (28.8 GHz) such the beams covers the same area on the ground at both frequencies.

The array elements selected for this application is shown in Figure 7, it is a dual-band split hexagonal-loop dipole element which offers several degrees of freedom. Furthermore, the geometry of the feed/reflectarray configuration is shown to the right: 15 separate feeds are used to generate 28 independent beams in both Tx and Rx. The reflectarray was optimised at 19 GHz (Tx) and 28.8 GHz (Rx) and the total number of optimisation variables is 54,032. The total optimisation time was less than 12 hours on a laptop computer, which illustrates the efficiency of the new tool for an advanced case.

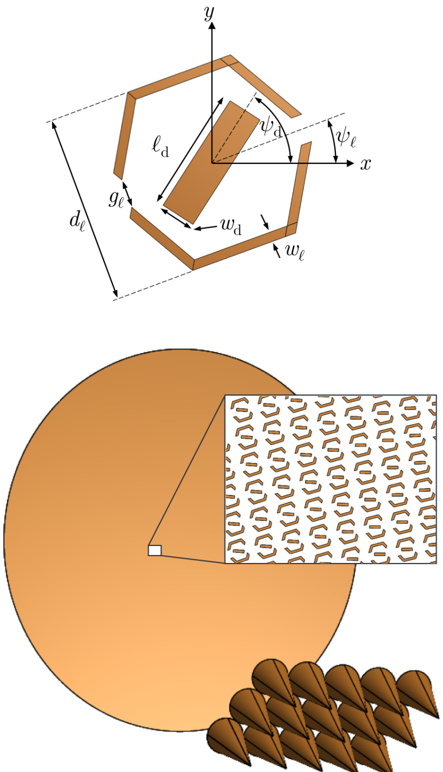

Fig. 7. Geometry of a curved reflectarray providing polarization-selective beam tilt. Top: Periodic element with several degrees of freedom. Bottom: Geometry of the HTS reflectarray antenna with 15 feeds, providing 29 circularly polarized beams for a global coverage HTS mission.

The radiation pattern of the optimised reflectarray is shown in Figure 8. It is seen that 28 circularly polarized beams are generated in RHCP and LHCP in both Tx and Rx. Note that only two of these reflectarrays are needed to provide global coverage in both Tx/Rx. Additional details on this concept can be found in [13].

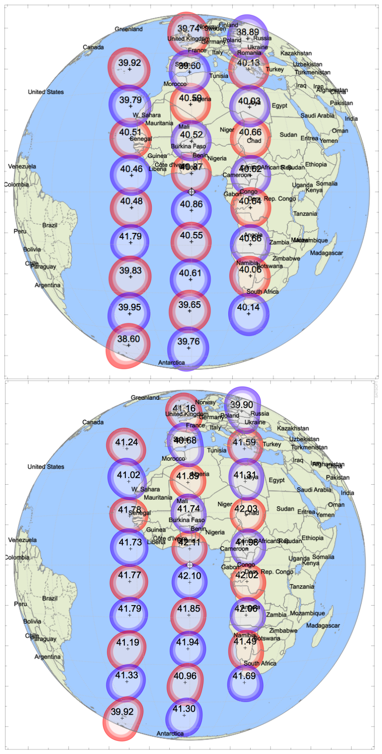

Fig. 8. Spot beam coverage obtained with curved reflectarray offering polarization-selective beam tilt. 28 circularly polarized beams are generated in RHCP and LHCP in both Tx (top) and Rx (bottom).

V. Conclusion

This paper presented two new software developments that are both integrated with the reflector modeling tool GRASP. The resulting RF design tool enables end-to-end optimisation of complex reflector-based multibeam antennas. The optimisation goals are only the actual performance metrics of the overall antenna system, e.g., the return loss of the first waveguide component in the feed chain and the beam shape produced by the last reflector. All beams are optimised simultaneously which implies that important parameters like the C/I can be directly included as an optimisation goal. The tool provides a unique combination of analysis methods for passive microwave components and feeds, reflectors, and surfaces with periodic or quasi-periodic array elements. This class of surfaces includes reflectarrays, transmitarrays, polarizers, and frequency or polarization-selective surfaces. The new tool provides direct optimisation capabilities for such surfaces, even in cases where several thousand array elements are optimised simultaneously and in conjunction with passive microwave components.

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