# RECENT DEVELOPMENTS AND CHALLENGES FOR REFLECTOR ANTENNA EM-MODELLING

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## ABSTRACT

This paper concerns the EM-modelling of high-accuracy reflector antenna systems, and in particular of reflectors for space antenna systems. Recent modelling developments are exemplified ranging from general software enhancements to meet customer needs, over specific developments on a particular demanding project, to new research projects. In addition, challenges for the next generation of reflector antenna EM-modelling tools are addressed.

Key words: Reflector Antenna; EM-modelling.

## 1. INTRODUCTION

Electromagnetic (EM) modelling of reflector antenna systems is available through a number of commercial software tools from different vendors. The oldest of the tools were originally developed for a specific part of the reflector antenna system, e.g. the feed chain, the feed horn, or the reflector system, and were based on a dedicated EM-model for the specific part of the system, e.g. mode-matching for the feed horn components and high-frequency techniques for the reflector part. With the increased numerical power, the tools evolved by including a combination of several analysis methods for different parts of the reflector antenna system. In parallel, new tools were developed by adopting a single full-wave analysis method for the entire antenna system.

Today, the space industry demands versatile, flexible, and efficient modelling software with extreme accuracy requirements, and space antenna systems are designed using a combination of these dedicated tools.

During the last 40 years TICRA has been among the leading providers of reflector antenna EM-modelling tools and this paper presents some of the recent developments made at TICRA. Our tools have been developed for the scattering part of the antenna system, and consequently this will also be the focus of the present paper. Hence, feed chain modelling will not be addressed.

We have selected different types of developments, ranging from general software enhancements to meet customer needs, over specific developments on a particular demanding project, to new research projects developing or improving EM-modelling of new reflector technologies.

Despite the fact that significant improvements have been introduced recently for each of the three major areas described above, significant challenges for reflector antenna EM-modelling still remain. This paper addresses two of these future challenges.

The first challenge concerns the problem of including optimisation in the EM-modelling software in a flexible and yet efficient manner. Optimisation has become a mandatory part of the antenna design process and the modelling software must provide the antenna engineer with the necessary toolbox to find the optimal solution. Several optimisation algorithms are available in different tools but the most common approach is based on a brute-force utilization of large computational resources. However, we foresee a large challenge to include optimisation in a much more flexible and efficient way than is currently available. This requires a hierarchical system approach where the antenna engineer zooms in on the solution by gradually refining the model through several levels with increasing details.

The second challenge addresses compact reflector antennas systems for which there is a need for increased accuracy in combination with combined optimisation of feed horn and reflectors. Currently, such systems are designed by a combination of multiple EM-modelling tools with the result that some RF-effects are neglected and the design process becomes relatively slow due to the inherent need for data exchange and lack of compatibility between the tools. The paper presents a planned activity to meet this challenge.

## 2. RECENT DEVELOPMENTS

### 2.1. Feed Horns

Corrugated conical horns play a key role in telecommunications systems, whether on the spacecraft as part of the dedicated telecom payload and the telemetry system, or in a ground terminal as the primary source of the single or dual reflector optics. In addition to the pure telecommunications service, these horns are often also required to carry a tracking function, usually by providing access to the so-called tracking modes at the throat of the horn. Tracking capabilities are thoroughly implemented in ground terminals. With the new broadband telecommunications services, the satellites will generate very narrow, multiple spot beams, with stringent requirements imposed on the pointing accuracy. Therefore it is necessary also to provide tracking capabilities on the telecom antenna itself, which creates a need for efficient telecommunications horns with integrated tracking capabilities. This in turn requires availability of efficient design tools for these kinds of feed systems.

Several analysis tools have been developed which allow the analysis of the corrugated conical horn with single mode excitation (fundamental or tracking). An analysis tool requires the user to provide the geometry of the horn before an analysis is carried out. For many years the analysis tools have been used as design tools either by multiple runs where the horn designer manually changes the geometry in each iteration, or by spawning the analysis tool from a synthesis tool. In both cases, the optimisation is somewhat limited due to the single mode excitation, and typically the horn is optimised with respect to the telecommunication properties only.

In order to be able to design high-efficient multi-mode horns, TICRA's feed-horn tool, CHAMP, was updated to allow simultaneous optimisation of the antenna performances for both the fundamental mode and higher order mode excitation. The development was made as an ARTES-study in a team with Thales Alenia Space (F). A parallel study was carried out by Mician GmbH (D) and MDA Space (CA).

*Figure 1. Multi-mode horn developed by Thales Alenia Space.*

Following the development of a prototype of the tool, an existing multi-mode horn design was further optimized which resulted in significant improvement of the RF-performance. The horn was manufactured, Figure 1, and subsequently RF-tested. Excellent agreement between CHAMP-calculations and measurements was obtained as shown in Figure 2.

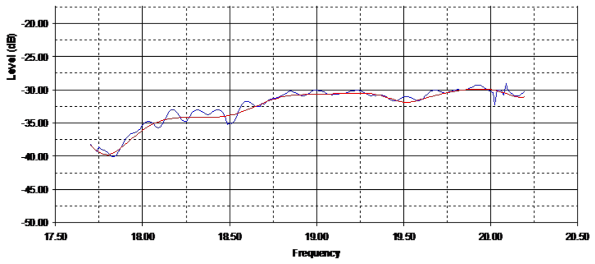


*Figure 2. Comparison of calculated (red) and measured (blue) return loss for the horn in Figure 1. Ref: Thales Alenia Space.*

### 2.2. Reflectors and Supporting Structures

Our reflector modelling tool, GRASP, was originally developed for generic surface and rim shapes. Over the past decades, a variety of more special surface and rim models have been added in order to allow more complex reflector geometries to be defined in an easy way. Still, there is an great demand for modelling very complex shapes with a high level of detail. As an example, it is not uncommon that cutouts are introduced in the main reflector surface due to mechanical constrains. GRASP has traditionally employed a high-level parametric description of reflectors which results in great computational efficiency but at the same time limits the possibility of modelling very complex geometries. To overcome this limitation, we have recently developed a new mesh-representation needed to analyse reflectors having a highly irregular rim shape or holes in the reflector surface.

The most commonly employed mesh elements in commercial EM-modelling tools are flat triangles or second-order curved patches. These low-order mesh elements require a huge number of patches in order to represent the curved reflector surface accurately and this leads to very inefficient modelling algorithms. Instead, the mesh should be kept as coarse as possible while still maintaining an accurate model of the reflector surface. This can be accomplished by using higher-order curved patches, e.g., 4th order quads which typically allow a maximum patch size of up to two wavelengths. A reflector modelling tool based on such patches can maintain a relatively high computational efficiency while still being able to represent fine geometrical details accurately. Commercially available meshing tools have the same limitations as the EM-tools discussed above, i.e., the mesh elements are limited to 1st or 2nd order elements. For this reason TICRA has developed a new mesher which models the curved reflector geometries using 3rd or 4th order quad patches.

An example of the higher-order quad mesh for a reflector with a cutout is illustrated in Figure 3. The largest patches have a side length in the order of 2 wavelengths, and thus much larger than the subwavelength dimensions needed by linear or second-order patches.

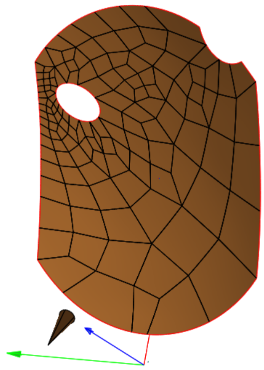

*Figure 3. Mesh using quads used for reflector with cutout.*

In addition to providing fast analysis of complex reflector shapes, the new mesher is an essential component needed for obtaining an efficient computational model of an arbitrary geometry imported from a CAD file. Such an arbitrary meshed model may readily be analysed with the higher-order Method of Moments (MoM) in GRASP whereas the use of high-frequency methods is somewhat more challenging. This latter task will require further developments of GRASP in the coming years.

### 2.3. The Planck Space Telescope

The Planck Space Telescope has pushed the developments of our reflector antenna modelling tools forward. The telescope (shown in Figure 4) is an aplanatic reflector system equipped with 47 microwave detectors operating from 30 GHz to 857 GHz and positioned over the curved focal 'plane' of the antenna.

The objective of the Planck Space Telescope is to observe the Cosmic Microwave Background with an unprecedented accuracy. This objective can only be met if the in-flight measurements can be calibrated to very high accuracy. This in turn requires the radiation pattern for each detector to be known with very high accuracy.

GRASP has been used extensively in the analysis of these radiation patterns. A particularly challenging task has been the determination of the far-out side lobes. Pure Physical Optics calculations are too time consuming and a ray-tracing method must be used. In order to meet the stringent accuracy requirements, it is not sufficient to only consider the scattering by the reflector system. All relevant ray contributions from the complex geometry in

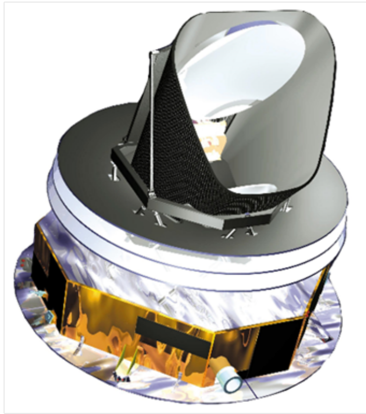

*Figure 4. The Planck satellite with the double reflector antenna surrounded by a baffle to protect against stray radiation. Illustration: ESA.*

the vicinity of the reflectors, e.g. the floor, side panels, and the grooves must be included. The complex geometry results in many quasi-caustic directions, and in these directions, the results obtained by the ray-optical method must be corrected by Physical Optics.

Light from the sky enters the detectors from directions outside the antenna main beam. A detailed straylight analysis based on ray-tracing methods has been performed. It was found that for certain orientations relative to the moon and the planets, up till 8'th-order reflections/diffrations must be included in the straylight analysis. An example of the straylight from a single far-field direction to a single of the detectors is shown in Figure 5. In order to handle the ray-contributions from

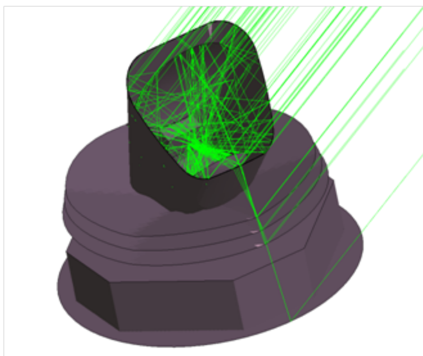

*Figure 5. Example of straylight contributions from a single direction in the sky to a single detector.*

the multiple curved scatterers, a new version of TICRA's ray-optical software tool, Multi-GTD, was developed and subsequently made commercially available.

In orbit, several reflector anomalies are foreseen and also the alignment of the parts of the system must be expected to be influenced at the extreme low operating temperature. The in-flight pattern measurements of a submillimetre space telescope may be improved by determining the actual reflector anomalies and then include these in the final pattern determination. TICRA has developed a special version of our reflector shaping software tool, POS, which performs the retrieval of the in-flight reflector geometry.

The pattern measurements with a celestial object as source often have an insufficient signal-to-noise ratio for a pattern prediction outside the main lobe. Repeated measurements may improve this but even better is the possibility to extract data from different detectors operating at different frequencies. However, much better results are obtained when measurements from several of the detectors are applied to retrieve the surface distortions of the common reflectors.

By simulations it has been demonstrated that the patterns of the antenna on the Planck satellite may be retrieved with high accuracy after the satellite is placed in orbit. Currently, the retrieval of the in-flight reflector geometry is on-going based on the actual in-flight measurements.

### 2.4. Antenna Validation and Processing of Measured Fields - DIATOOL

Despite the ever increasing capabilities of computational tools, antenna validation by measurements is still an inevitable part of the antenna design process. However, it is usually only possible to compare measured and predicted data away from the antenna itself which limits the possibilities for error detection and further processing of the measured fields. TICRA has developed an innovative algorithm that allows reconstruction of the measured fields on a 3D surface conformal to the antenna. The algorithm is based on smooth geometry and current representations and employs a new iterative solution method which is very robust against measurement noise. The possibility of reconstructing currents and fields on a conformal 3D surface opens up a range of applications, including but not limited to:

- Antenna diagnostics by inspection of the reconstructed fields.
- Filtering of undesired contributions by artificial removal of some parts of the structure. Typical examples are cancellation of currents flowing on cables and mounting fixtures.
- Suppression of range reflections or other contributions not originating from the antenna itself. The use of a tight conformal reconstruction surface allows for filtering of rapidly varying field components that are not compatible with the small size of the reconstruction surface.
- Use of the reconstructed currents as a source in further computations. The reconstructed currents can be used to illuminate scatterers that are located very close to the antenna, even deep inside the minimum sphere.

The 3D reconstruction algorithm, as well as a fast planar reconstruction algorithm, have been implemented in an easy-to-use software tool for antenna diagnostics and processing of measured fields. The development has been co-funded by ESA within the ARTES 3/4 program and the new software tool, DIATOOL, will be launched in October 2011.

## 3. NEW REFLECTOR TECHNOLOGIES

### 3.1. Reconfigurable surface

The increased in-orbit lifetime of today's telecommunication satellites combined with the rapid development of the offered services require more flexible payloads for the satellite providers. A special interest was shown in the past years in antennas that can be reconfigured in orbit, in order to change coverages, use the same spacecraft at several orbital locations, and compensate for varying weather conditions. Shaped reflectors lack so far the capability of being reconfigured in orbit, while this can be obtained by an array-fed parabolic reflector.

A number of studies has been performed by different research groups in Europe to quantify the properties, advantages and limitations provided by a shaped reflector equipped with a reconfigurable surface when applied to a realistic mission scenario in Ku-band. Several technologies are being investigated. Among these, Thales Alenia Space (F) in cooperation with the Technical University of Munich (D) investigates a Carbon Fiber Reinforced Silicon (CFRS) surface under an ARTES contract.

TICRA has proposed and investigated a different type of reconfigurable reflector surface in the form of a mesh of interwoven flexible wires, c.f. Figure 6. The reconfigurability is achieved by attaching actuators to a number of control points across the reflector surface. The study has concentrated on Ku-band reflector antennas, where the surface deformations are in the order of a few centimeters. A major advantage is that the forces required at the control points are small, typically in the order of 0.1 N, and that the total energy required to shape the surface is very low, typically less than 10 mJ.

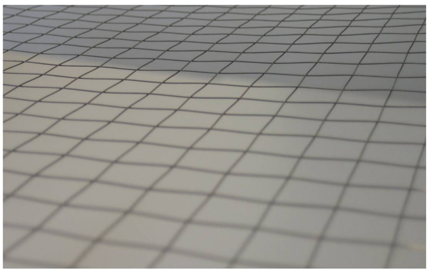

*Figure 6. Close-up photo of a small sample of the interwoven flexible wires surface.*

TICRA has shown that the surface has excellent reconfigurability, as the surface is bending stiff and thus has no loss due to pillowing effects, and as the required surface shapes may be obtained by relatively few light-weight actuators (in the order 50-100 actuators for a 2 m Ku-band antenna).

In the first generation of reconfigurable reflectors the surface is expected to only be reconfigured a few times, e.g. when the spacecraft shifts orbital location. For future generations, TICRA has made a first assessment of the feasibility of this reflector surface for 'real-time' compensation of varying weather conditions. For a solid reflector antenna shaped for uniform coverage gain it is necessary to add a safety factor of 6 dB for bad weather, whereas for the reconfigurable surface the safety factor could be reduced to only 1.5 dB. A typical bad weather situation is depicted in Figure 7. The reshaping for a different scenario is calculated in about 30 seconds and the required shaping range is within $\pm 10$ mm.

*Figure 7. Rain over Copenhagen area, July 13, 2003.*

Preliminary mechanical models of the meshed surface have been investigated in collaboration with the Technical University of Denmark. Many technological issues still need to be solved before the mesh may be ready as a candidate for space antenna systems.

### 3.2. Reflectarrays

Reflectarrays constitute a successful merge of reflector antennas and array antennas. Reflectarrays are similar to a conventional reflector antenna but the focusing effect is achieved by using a planar reflecting surface with a controllable phase delay on different parts of the surface. This controllable phase delay is typically realized by using printed elements. Reflectarrays eliminate the need for the bulky, expensive, and relatively high-loss feeding network required by conventional array antennas. At the same time, reflectarrays are much easier and cheaper to fabricate than traditional smooth or shaped reflectors due to their manufacturing simplicity and low-loss feeding arrangements.

Reflectarrays are becoming viable alternatives to reflector antennas for satellite applications and have been the subject of increasing research interest. The focus of this research is on the design and prototyping of innovative reflectarrays using passive or active array elements, whereas the modeling aspect has received less attention. To obtain high-gain performance for satellite applications, the electrical size of reflectarrays is usually very large, and therefore an efficient and accurate analysis is a challenging task. The commonly adopted analysis method is based on an infinite array solution computed using MoM. However, reflectarrays are aperiodic and the infinite array solution gives rise to discrepancies between simulated and measured radiation patterns. Recently, efficient full-wave simulation techniques have been applied to entire reflectarrays. Even in these cases, discrepancies between simulations and measurements can still be observed, and the increase in computation time makes the methods unaffordable for optimization processes. For space applications, where the accuracy demands are high, an efficient and accurate analysis method is important to precisely determine the radiation properties of reflectarrays, and it is essential for optimization purposes. It is our goal to develop such a simulation tool that satisfies the high accuracy demands required for satellite applications, and at the same time is suitable for optimization. While the focus for other research groups is to accelerate rigorous full-wave techniques, we attempt to improve the accuracy by taking outset in the conventional fast infinite array solution.

To achieve our goal, the sources of error in reflectarray analysis must be identified and investigated, such that efficient solutions to these issues can be found. Under an ESA-contract, TICRA has designed several reflectarray antennas with different sources of error exaggerated. Technical University of Denmark is responsible for the high-precision manufacturing and RF-measurements, c.f. Figure 8. Recent results show that by treating the sources

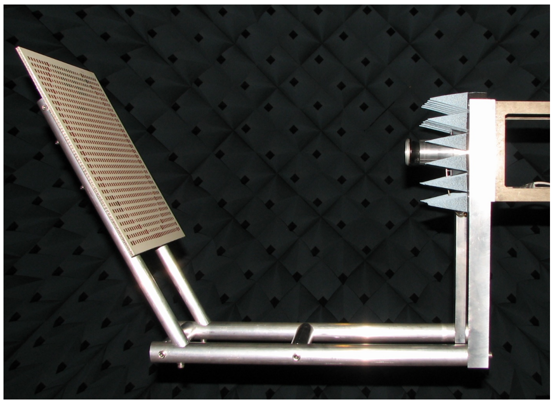

*Figure 8. Benchmark antenna at the DTU-ESA Spherical Near-Field Antenna Test Facility.*

of error correctly, accurate analysis of reflectarrays can be achieved. An example is shown in Figure 9, where different techniques used to calculate the radiation pattern is compared with measurements. However, even though accurate analysis can be achieved, it is at the cost of computation time. This increase in computation time makes the methods unsuitable for optimization purposes. This is a challenging task as the trade off between analysis accuracy and computation time is always a bottleneck. Sev-

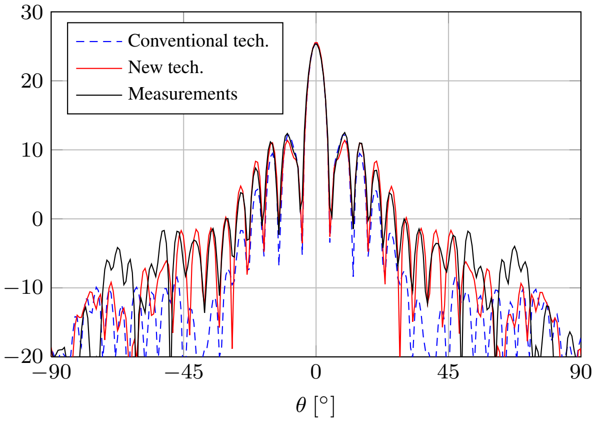


*Figure 9. Comparison of simulations with measurements for the antenna shown in Figure 8.*

eral alternative solutions to improve the efficiency and accuracy of the analysis still remain and are currently being investigated.

## 4. CHALLENGES FOR REFLECTOR ANTENNA EM-MODELLING

### 4.1. Flexible Optimisation

Optimisation has become a mandatory part of the antenna design process and several optimisation algorithms are available in different tools. The most common approach is based on a brute-force utilization of large computational resources which often leads to excessive run-times and sub-optimal solutions. Therefore, we foresee a large challenge to include optimisation in a much more flexible and efficient way than is currently available. This requires a hierarchical system approach where the antenna engineer zooms in on the solution by gradually refining the model through several levels with increasing details.

To obtain an optimum solution within reasonable time, it is necessary to start the optimisation with very few optimisation variables using a high-level description of the configuration. When the initial optimum is found, the model must be refined by adding additional degrees of freedom and re-launching the optimization. This process must be repeated, each time with more degrees of freedom and a greater level of details. This hierarchical optimization approach is able to zoom-in on the optimal solution using much less computational effort than required by a brute-force approach. However, the hierarchical approach requires that the EM-modelling tools offers flexible geometrical modeling capabilities on different levels.

This process has been successfully adopted in our reflector shaping program, POS, for years. The reflector surface is expressed as spline or Zernike mode expansions, in which case the expansion coefficients are the optimisation variables. The shaping starts with a few variables. The user may then add more variables during the optimisation process until no further improvement can be obtained.

A similar approach has recently been adopted in our software package, CHAMP, for feed horn analysis. The corrugated feed horns are restricted to be rotationally symmetric, and thus the geometry considered is relatively simple. Nevertheless, we have made three different models of the horn-profile geometry available. In the high-level model, the entire horn profile is described in terms of only a few parameters. During the optimisation process, the profile may be converted to a spline-profile representation with an arbitrary number of data points. The spline profile may be further converted into spline functions with a higher number of data points or to a detailed description of the horn geometry corrugation-by-corrugation. The last mentioned model is ideal to zoom-in on the sensitive mode-converter part at the end of the optimisation process.

When adding optimisation to other software tools, e.g. GRASP, it would thus be a major advantage to be able to select the optimisation variables from a high-level model of the configuration and subsequently be able to convert the high-level model to more detailed models during the optimisation process. Hence, if efficient optimisation of complex systems shall be realistic in general EM-modelling tools, such tool must include different levels of system modelling with the possibility to zoom-in from the high-level models to the detailed models.

### 4.2. Compact Reflector Antennas

As described previously, the design of compact reflector antennas may currently be performed in different ways: 1) The user may use a combination of several commercial software tools. Each tool has been developed with a specific part of the antenna system in mind, e.g. the feed chain, the feed horn, the reflectors, or the support structures (e.g. struts or dielectric support-cones). The combination of the different tools leads to some RF-effects being neglected or poorly estimated in the analysis, as well as to a relatively slow design process due to the inherent need for data exchange and lack of compatibility between the tools. 2) The user may use a single tool, which uses an approximative but fast EM-model for the entire antenna system. This neglects important effects, but allows optimisation. 3) The user may use a single, accurate tool, e.g. a full-wave solver, and thus include the coupling between the different parts of the system. This solution has the drawback that a change of the geometry in one part require a re-calculation of the entire scene, which for reflector antenna systems typically will make the method too slow for optimisation.

The challenge is to make available a single EM-modelling tool with the following capabilities

- Fast RF-analysis of the combined feed horn, reflector system, and support structures.

- Calculation of the exact coupling between the field inside the feed horn and the scattered field outside the feed horn.
- Fast optimization of the horn geometry while taking into account the general 3D-surroundings, including reflectors.
- Simultaneous optimization of the feed horn geometry and shaping of rotationally symmetric reflectors.
- RF-analysis of general wave-guiding structures with circular or rectangular ports.

This may be obtained by a tool allowing the user to decompose the antenna geometry into several regions, and to use a dedicated, fast EM-model in each of the regions. The tool should use a scattering matrix description of the scattering from each region in order to avoid re-calculation of the entire scene during optimisation.

As an example, consider the circularly symmetric axially-displaced antenna in Figure 10. In the plot to the left, the antenna configuration is shown. Three regions are introduced: 1) A region containing the feed horn interior where mode-matching is used. 2) A region containing the dielectric support cone and the subreflector, and analysed using a higher-order 3D-MoM. 3) A region containing the outer part of the feed horn and the main reflector, and analysed using a higher-order MoM for bodies of revolution (BOR-MoM). The interface between region 2 and 3 could e.g. be a cylindrical interface as shown in the plot to the right. For region 2, the 3D-MoM has been chosen

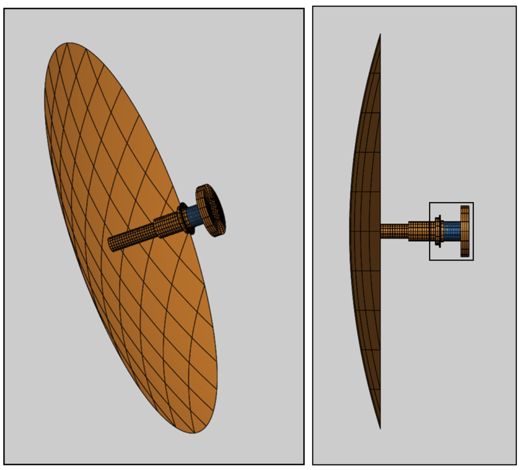

*Figure 10. Axially-displaced antenna with a dielectric-support subreflector.*

instead of the BOR-MoM in order to allow for a non-symmetrical support structure. It is noted, that even with the existence of the non-symmetrical geometry, the main reflector may be analysed by a fast BOR-MOM due to the interface between region 2 and 3. More important, the feed and subreflector geometry may be optimised without the need to recalculate the BOR-MoM solution, due to the scattering matrix representation. Without the decoupling between region 2 and 3, everything outside the horn would need to be analysed using 3D-MoM making the analysis significantly slower.

A new tool developed under an ARTES-contract will be directly applicable to improved synthesis of two-way terminals to meet the stringent sidelobe requirements, and to the design of multi-band compact maritime terminals.

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