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FEKO/GRASP Simulations of Super-Resolution on the 32m Medicina Radio Telescope

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Abstract

Our group at Arcetri is currently carrying out a project devoted to the implementation of *super-resolution* on single-dish radio telescopes, which should result in an angular resolution better than the classical diffraction limit. A feasible method to achieve this goal consists of using variable transmittance pupils. The simplest transmittance pupils are binary phase shift masks, also known as *Toraldo pupils*, consisting of finite-width concentric coronae which modify the phase of the incident wavefront. In this work I show, through EM numerical simulations, that super-resolution can indeed be achieved on a Cassegrain radio telescope. I also discuss the inadequacy of simple analytical models to predict the performance of Toraldo pupils when optically interfaced to a telescope.

1. Introduction

One of the fundamental properties of filled-aperture telescopes is their angular resolution, i.e., their ability to separate points of an astronomical source that are located at a small angular distance. Apart from other effects which can be either cancelled or mitigated (e.g., optical aberrations and atmospheric "seeing"), the diffraction of electromagnetic (EM) waves is generally considered to be a fundamental limit for any imaging device. The concept of *super-resolution* (SR) refers to various methods for improving the angular resolution of an optical imaging system beyond the classical diffraction limit.

Variable transmittance pupils represent one viable approach to achieve SR in Radio Astronomy. The simplest pupils are discrete binary phase masks with finite phase-jump positions (corresponding to a phase change of either 0 or 180 deg), also known as *Toraldo pupils* (TPs) [1,2]. Toraldo di Francia [1] showed that the diffracted beam by a TP is narrower compared to the beam diffracted by a clear aperture with the same outer diameter. In order to achieve SR for astronomical applications it is then necessary to interface the TPs with the telescope and receiver optical system. One possible solution is to place the TP at an exit pupil of the telescope, since any modification of the wavefront at this location is equivalent to modify the wavefront at the entrance pupil of the telescope. If an active surface is available then it is also possible to implement the SR effect on a radio telescope at the entrance pupil [3].

As part of this project our group at Arcetri has simulated and tested an optical module for K-band, based on standard low refractive index materials, able to narrow the point spread function (PSF), thus achieving the SR effect. We have then devised a method to interface this SR module with a test Cassegrain satellite antenna (1.8m diameter) and we have carried out extensive EM numerical simulations to study the performance of the complete optical system. The optical module can be designed using either standard dielectric lenses (see Fig.1) or also a fully reflective optical system using ellipsoidal mirrors. In this summary paper I report on a series of EM simulations at 20 GHz, combining the results obtained through the two commercial software FEKO[1] and GRASP[2], showing that a similar SR optical module can also work with the Medicina 32m radio telescope.

2 Description of the Procedure

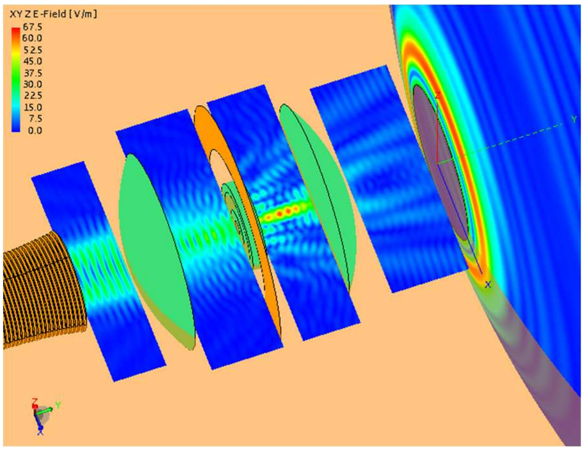
The design concept and performance, as well as the main mechanical and optical requirements of the TP module have already been discussed elsewhere [4]. The current design is based on a two-lens collimator placed after the Cassegrain focus (see Fig.1) and before the receiver dewar. The first lens of the collimator generates an image of the primary which is then brought to a subsequent focus by the second lens. The transmittance filter is placed at the image of the entrance pupil, inside the collimator, where it can modify the incident wavefront.

The baseline optical design of the collimator has been carried out using the original analytical description given by Toraldo di Francia [1], which makes two basic ideal assumptions: (1) the concentric circular coronae forming the TP are infinitely thin; (2) the illumination of the TP has the correct amplitude apodization and uniform phase. At microwave wavelengths it is difficult to obtain an

Figure 1. CAD model of the feed, collimator and satellite antenna (1.8m diameter) K-band system with superimposed the amplitude of the electric field and

[1] https://www.altair.com/feko

[2] https://www.ticra.com/software/grasp/



surface currents, as computed by FEKO. The Toraldo Pupil can be seen in between the two lenses.

arbitrary amplitude apodization of the incident wavefront, and thus only TPs that can achieve SR even with an approximate Gaussian illumination should be selected for the EM simulations. In fact, our tests indicate that the final SR effect strongly depends on the effective illumination of the TP. In addition, the analytical model employed for the design of the geometrical configuration of the TP is often inadequate to predict the effective optical behaviour of the less than ideal TP fabricated using standard refractive material.

Based on these considerations, an initial TP design is selected, which is then modified using the results obtained from the full EM simulations. In this specific work a TP with five coronae (or TP5) has been chosen, and the expected diffracted far-fields by the pupil (computed analytically) are shown in Fig.2 for both the ideal apodization and for a Gaussian illumination. While the SR effect is clearly visible in the top panel of Fig.2, together with the high sidelobes which are typical of TPs, when a realistic Gaussian illumination (but still assuming a uniform phase over the pupil) is applied the SR effect is no longer present. However, in the next section I will show that when the TP is used together with an auxiliary optical system, the results are not necessarily those predicted by this simple analytical model.

3 EM Simulations

In this section I analyze the behavior of the TP when it is used as part of a more complex optical system. In terms of computing time, while a single EM simulation of the TP module & satellite antenna system is feasible with FEKO using the method of moments (MoM; see Fig.1), the corresponding simulation with the 32m Medicina antenna (see Fig.3) must follow a different procedure, due to the much larger diameter involved. I have therefore separated the procedure in two phases: I first run a FEKO simulation that includes only the feed & TP module, using

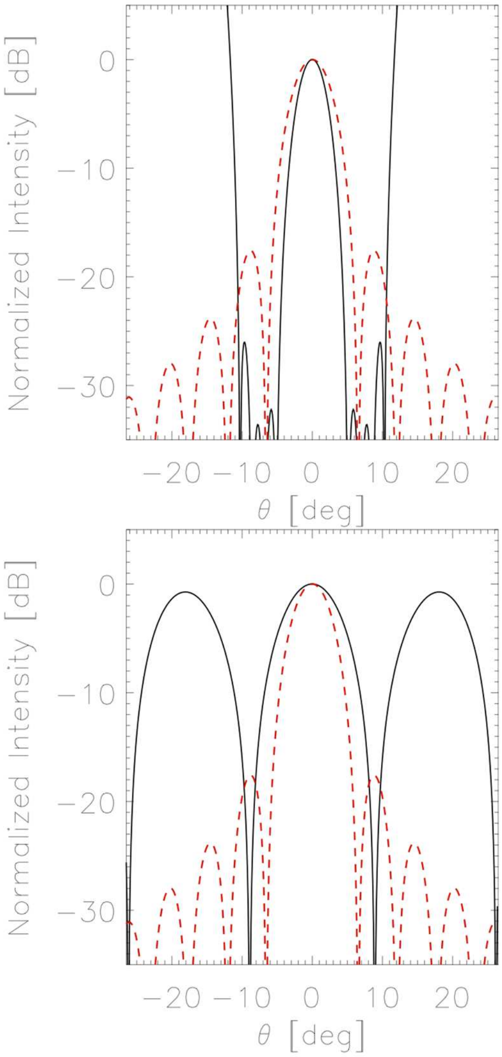


Figure 2. Normalized far-fields at 20 GHz obtained using Toraldo's analytical model for a TP with five coronae and using the correct illumination (top panel) and a realistic Gaussian illumination (bottom panel). The red-dashed and black-solid lines correspond to the diffracted fields by the clear aperture and by the TP5, respectively.

the MoM. The fields at the focus of the second lens, corresponding to the Cassegrain focus of the telescope, are saved in a grid file which is then imported in GRASP, where Physical Optics (PO) is used to propagate the fields at the focus through the telescope and calculate the far-field pattern of the entire optical system.

An example of the results obtained with this procedure is shown in Fig.4, where the amplitudes of the electric fields at the focus of the collimator are shown, for a clear aperture and when the TP is added to the collimator. The fields shown in Fig.4 have then been used as input to GRASP, specifically on a plane located at the Cassegrain focus of the 32m Medicina antenna. PO has then been used to calculate the currents on both primary and secondary reflectors and to finally determine the far-field, shown in

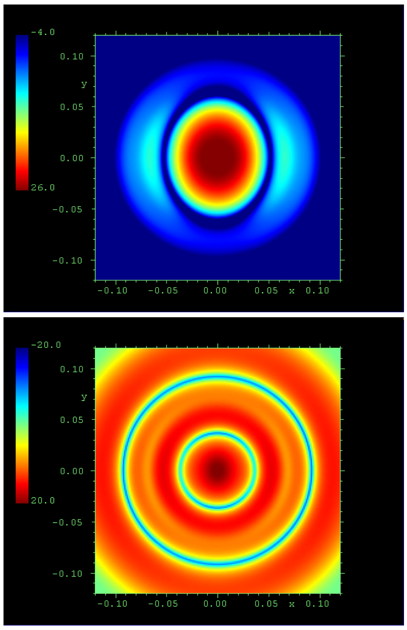
Fig.5. The far-fields have been normalized so that it is easier to compare the width of the main beam.

Figure 3. Picture of the 32m Cassegrain radio telescope located in Medicina near Bologna (Italy).

The two panels in Fig.5 show the results of two designs using the same TP5 as described in Sect.2 and Fig.2, with slightly different collimators. The top panel of Fig.5 corresponds to a collimator where the two lenses are separated by a distance of 160mm, and almost no SR is achieved in this optical configuration (when compared to the nominal antenna beam). On the other hand, when a separation of 180mm is used instead, the main beam shown in the bottom panel of Fig.5 is obtained, which is narrower than the reference beam of the Medicina antenna, thus achieving the SR effect.

It should be noted that the beam obtained with a clear aperture inside the collimator should ideally be the same as that obtained when the feed placed directly at the Cassegrain focus, if beam-truncation effects are negligible. Figure 5 shows that this is not the case, as the beam obtained when the telescope is illuminated through the collimator is slightly wider than the nominal antenna beam. This is likely due to the collimator being in a slightly off-focus position. Despite this, in the configuration shown in the bottom panel of Fig.5 the SR effect is still present even when compared to the nominal beam.

This example shows the sensitivity of the design to the effective complex (amplitude and phase) illumination of the pupil. It also shows that many different effects may contribute to the final result, which are very difficult to predict using a simple analytical model. Only a full EM simulation can reveal whether the selected combination of the geometrical shape of the TP, collimator design and interface with the telescope will lead to an effectively narrower main beam. The modeling and design work become even more complicated when other performance parameters are considered, such as the strength of the sidelobes and the aperture efficiency when the TP optical module is used.



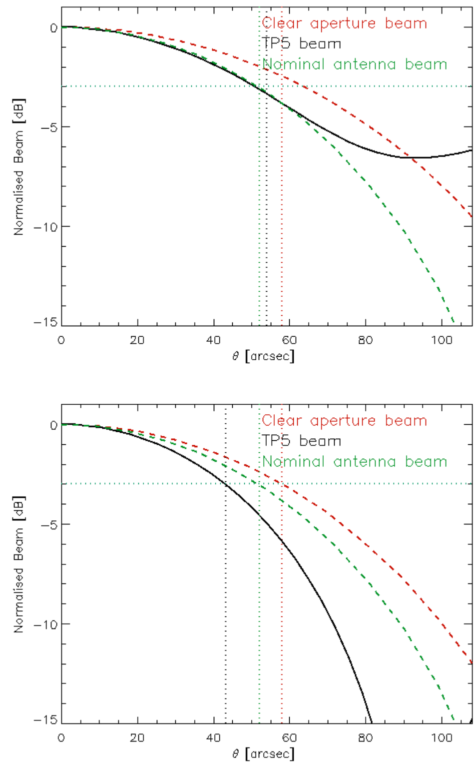


Figure 4. Amplitude at 20 GHz of the near-fields at the focus of the collimator (coincident with the focus of the telescope) for the clear aperture (top panel) and for the TP (bottom panel; axes units are in m).

Figure 5. Normalized far-fields for the Medicina telescope at 20 GHz, obtained with a clear aperture (red-dashed lines) and with the TP5 (black-solid lines). The nominal antenna beam is shown by the green-dashed line. The top and bottom panels show the results obtained with a lens separation in the collimator of 180mm and 160mm, respectively.

4 Conclusions

In this work I have discussed end-to-end EM simulations of a complete antenna system designed to achieve the SR effect on the Medicina 32m radio telescope. The system is based on the use of a TP optical module that is capable to achieve a reduction in the angular width of the main beam, with a simultaneous increase in the strength of the sidelobes and a decrease of the antenna gain. Further analysis is currently being carried out in order to determine an astronomically attractive trade-off between the resolution gain, sidelobes strength and efficiency.

From a design perspective, the current work has shown that a simple approach based on Toraldo's analytical model of the pupil is inadequate to predict the performance of both the TP optical module, based on a simple two-lens collimator, and also of the complete antenna system, including the feed and the Cassegrain telescope. Full EM numerical simulations are required in order to properly take into account the real illumination (amplitude and phase) of the TP.

References

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[3] L. Olmi, P. Bolli and R. Nesti, "Simulations of Angular Super-Resolution with the Active Surface of the Sardinia Radio Telescope," 2022 3rd URSI Atlantic and Asia Pacific Radio Science Meeting (AT-AP-RASC), 2022, pp. 1-3, doi: 10.23919/AT-AP-RASC54737.2022.9814264.

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