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Feasibility Study of Angular Super-Resolution with the Active Surface of a Radio Telescope

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Abstract

The concept of super-resolution refers to various methods for improving the angular resolution of an optical imaging system beyond the classical diffraction limit. A feasible method to design antennas and telescopes with angular resolution better than the diffraction limit consists of using variable transmittance pupils. The simplest transmittance pupils are binary phase shifts masks, also known as Toraldo Pupils, consisting of finite-width concentric coronae which modify the phase of the incident wavefront. In this work we present a preliminary feasibility study to determine if and how the active surface of the 32m Noto radio telescope can be used to modify the wavefront in the same way a Toraldo Pupil would do. Our preliminary analysis suggests that an ideal reflector with fully independent active panels would be able to achieve the super-resolution effect, but the real Noto active surface, where each actuator is connected to four distinct panels, adversely affects the operation of the simulated Toraldo Pupil. We are planning to apply the same analysis to the shaped active surface of the Sardinia Radio Telescope.

1 Introduction

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. In optical microscopy several techniques have already been developed with the aim of narrowing the central lobe of the illumination Point Spread Function (PSF). However, microscopy SR techniques cannot be easily applied to astronomical instrumentation, and thus few efforts have been made to overcome the diffraction limit of filled-aperture telescopes.

Variable transmittance pupils represent one viable approach to achieve SR in Radio Astronomy. Toraldo di Francia suggested in 1952 [1] that the classical limit of optical resolution could be improved interposing a filter consisting of finite-width concentric annuli of different amplitude and phase transmittance at the entrance pupil of an optical system, now also known as Toraldo pupils (TPs, hereafter). The original analytical description of the TP given by Toraldo di Francia assumed an ideal optical system where, for example, the transmittance filters are infinitely thin and an ideal source is assumed that achieves both the required amplitude apodization and uniform phase illumination over the pupil.

However, any practical realization of a TP in the microwave range cannot operate under such ideal constraints, and thus, as part of the "Pupille Toraldo" (PUTO[1]) project, we have experimentally verified that a simple TP can work even under less than ideal conditions. Our measurements demonstrated that the SR effect is achieved with both three- and four-coronae TPs, and also showed a good agreement with previously conducted FEKO[2] EM simulations [2].

2 Implementation of a TP system on a radio telescope

Although diffraction from an isolated TP, illuminated by a plane wave, shows the SR effect, the question arises of as to how combine the pupil together with other optical components, so that an imaging system can also operate in SR mode. More specifically, we have to design a TP optical module that can be inserted at an appropriate location in the optical path of a telescope, in order to achieve an angular resolution better than the diffraction limit.

Ideally, the TP should be placed at the entrance pupil of the telescope (i.e., at the aperture plane of the primary reflector). However, an easier and more accessible location is at the exit pupil of the telescope. Since every modification of the incoming wavefront at the exit pupil is equivalent to the same modification applied at the entrance pupil, we have designed a TP optical module based on a two-lens collimator placed after the Cassegrain focus and before the receiver dewar [3]. 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 TP is placed at the image of the entrance pupil where it can modify the incident wavefront. EM simulations and laboratory measurements of the collimator, showing the SR effect, are described in ref. [3]. EM simulations and preliminary field-tests of the collimator mounted on a test satellite antenna have also shown that SR can be achieved with this optical arrangement (see ref. [4]).

[1] http://www.ifac.cnr.it/PUTO/
[2] http://www.altairhyperworks.com/product/FEKO

A possible alternative method to implement the SR effect on a radio telescope, if an active surface is present, consists of using the active panels of the primary reflector to mimic the behaviour of an ideal TP placed at the aperture plane. Such method presents several advantages compared to the collimator+TP optical configuration described above. First, the required binary phase shifts are introduced using a shaped reflecting surface, rather than a 3D TP in transmission using standard dielectric material, that causes significant losses. A second advantage is that no modification inside the receiver cabin is required, as it would be the case if a TP optical module were to be installed near the secondary focus and in front of the receiver dewar window. The third advantage is that the active surface can be adjusted to work with any available receiver, whereas a separate collimator would have to be fabricated for each receiver. However, depending on the specific active surface, there are also a number of problems which we describe in the next section.

3 Simulating a Toraldo Pupil with the primary reflector

3.1 Test of the method

In order to test the method outlined above, we have projected the 3-coronae TP geometry (TP3, hereafter) described in ref. [5] on the surface of an equivalent paraboloid having a much larger diameter, e.g., a 9m reflector, and we have assigned it a $F = 3$ focal ratio, approximately the same as the Medicina and Noto 32m antennas at their Cassegrain focus. The EM simulations in GRASP[3] have been carried out in reception mode, assuming an incident plane wave, and we have computed separately the complex fields generated at the focus by each of the three coronae projected on the reflector surface, which have been selected in GRASP using the appropriate radial range. Finally, these separate fields have been summed to obtain the total intensity at the focus of the equivalent parabola.

This superposition method has been tested and we show the results in Fig. 1, where the PSF at the focus of the (unmodified) antenna, estimated using the whole antenna aperture, is represented by the red, solid line, while the PSF obtained by summing the individual complex in-phase fields generated by the three coronae is shown by the "+" signs. In this figure we also show the results of the simulation of a TP3-equivalent surface. The triangle represent the ideal case, where the fields generated by the three coronae are summed as before, but assigning a 180° phase shift to the field of the second corona (simulating the phase delay introduced in transmission). The black, solid line shows instead the intensity obtained when the 180° phase shift of the second corona is achieved through an actual displacement of the corresponding surface. The SR effect is clearly visible,

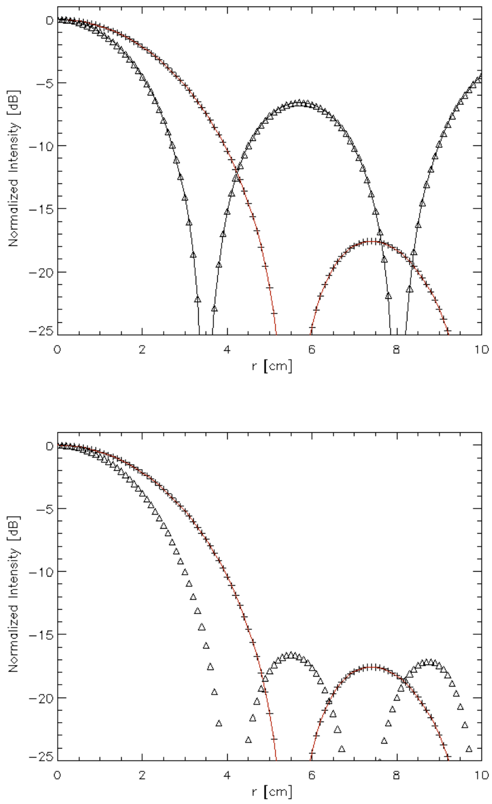

Figure 1. Simulated PSFs at the focus of a 9m diameter, $F = 3$ paraboloid using GRASP. The PSF of the nominal antenna is shown by the red, solid line. The "+" signs shows the intensity corresponding to the in-phase sum of the three individual complex fields. *Top.* The triangles show the result of the sum when the complex field of the second corona in the TP3 is intentionally assigned a 180° phase shift. The black, solid line shows the intensity obtained when the 180° phase shift of the second corona is achieved through an actual displacement of the corresponding surface. *Bottom.* Same as above for a TP4 geometry.

with both a narrower main lobe and higher sidelobes as expected. The bottom panel of Fig. 1 also shows how the PSF is modified when a 4-coronae TP geometry (or TP4) is used instead.

3.2 EM simulations for the Noto antenna

Of the three radio telescopes operated by the Italian National Institute for Astrophysics (INAF), the Noto telescope and the SRT already have an active primary surface. In this preliminary study we have first analyzed the Noto antenna since it has a classical Cassegrain design, whereas the SRT has a more complex shaped design. The Noto active primary surface consists of a total of 248 panels distributed along six separate rings. The two innermost rings of panel are fixed while the four remaining rings are composed of active panels (see top panel of Fig. 2). In order to limit the complexity and extra weight of the actuators network, 244

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

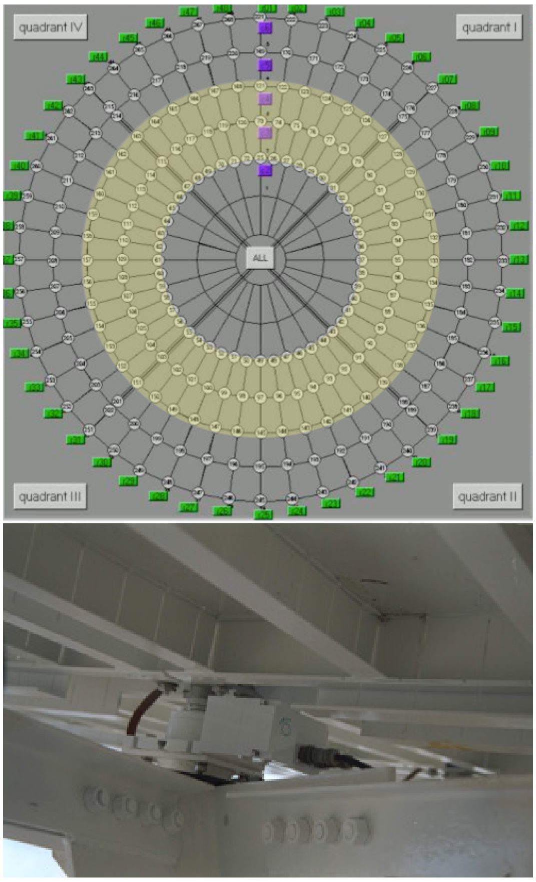

Figure 2. *Top* Distribution of the actuators on the active surface of the Noto 32m antenna. The yellow shaded area corresponds to the panels that need to be shifted to mimic the 3-coronae TP shown later in Fig. 3. *Bottom* Picture showing the corners of four distinct panels connected to a single actuator.

actuators are used with each one positioned at the corners of four panels. Therefore, each actuator operates on four panels simultaneously (see bottom panel of Fig. 2).

The primary active reflector can be shaped to resemble a TP by displacing the appropriate rings of panels. The geometry of the baseline TP that can be implemented with the active surface is limited by the number of panel rings and the size of the individual panels. An additional important limitation is represented by the degrees of freedom allowed to individual panels, as we will discuss later. Therefore, in this preliminary study we discuss the implementation of a simple TP3 which can be implemented using the limited number and geometry of the active rings of panels. One possible choice is shown in Fig. 3 and its projection on the primary reflector is shown in Fig. 2, where it can be seen that the corona inducing the 180° phase delay covers active rings 1 and 2.

In order to perform EM simulations with the modified active surface, we have used the following simplifying assumptions: *(i)* the dual reflector Cassegrain antenna has been replaced with its equivalent parabola; *(ii)* the same geometry of the active primary shown in Fig. 2 has also been used for the surface of the equivalent parabola; and *(ii)* we have temporarily removed the constraint of each actuator moving four panels simultaneously, and we have assumed instead that each panel can move independently from the others. Therefore, in order to reproduce on the primary reflector the geometry of the TP3 shown in figures 2 and 3, the rings of panels 1 and 2 must induce the 180° phase delay on the incoming wavefront. This is achieved by translating all panels in these rings in a direction parallel to the optical axis (or z axis) so that the incoming rays, upon reflection on the shifted panels, are subject to a difference in the optical path equal to $\lambda/2$ as compared to the unaffected rays (see Fig. 4). The panel displacement required is within the maximum allowed stroke of the actuators.

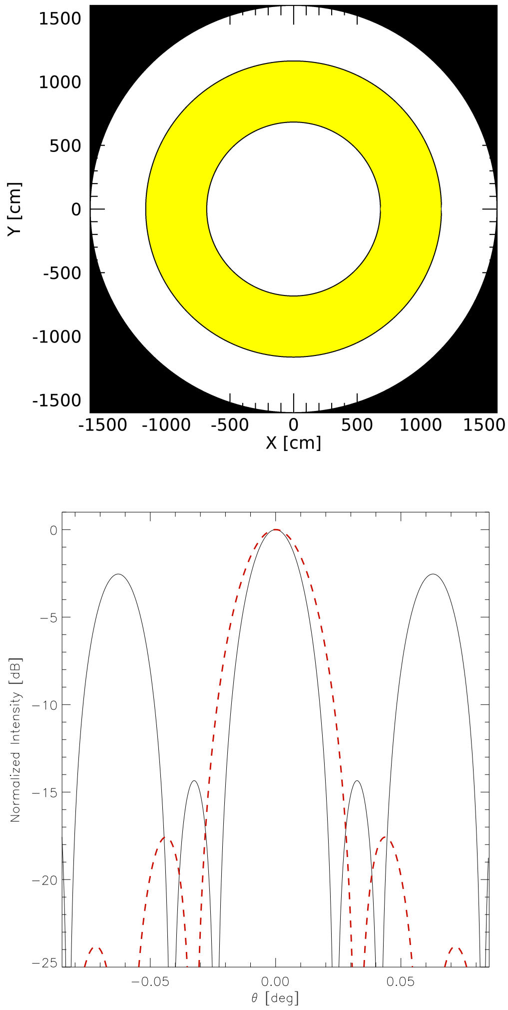

Figure 3. *Top* Geometry of the TP3 selected for the test with the active surface of the Noto antenna. The yellow corona provides a 180° phase delay. *Bottom* Corresponding far-field of the TP3 (black, solid line), with uniform illumination, compared to the pattern of the open pupil (red, dashed line).

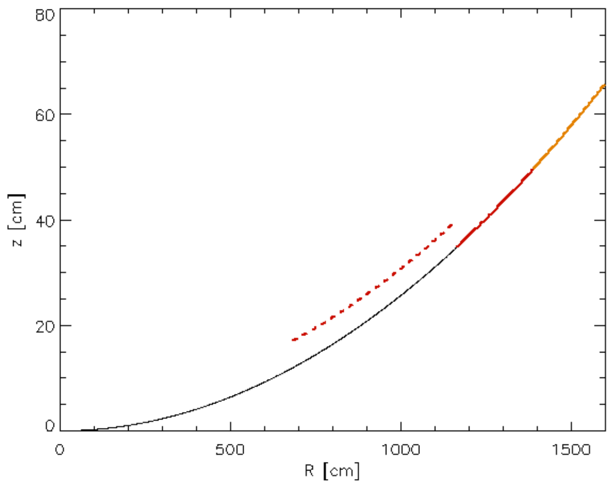

Figure 4. Radial profile of the Noto equivalent parabola with rings 1 and 2 (red, dashed) shifted along the optical axis while rings 3 and 4 are left unchanged (the panels displacement has been exaggerated for better visibility).

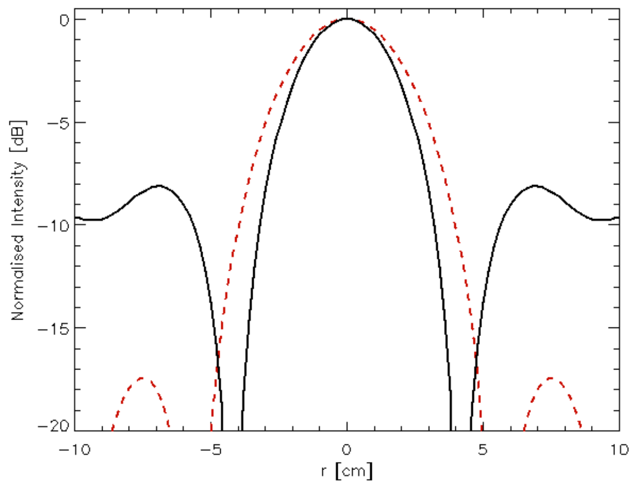

Figure 5. Simulated PSFs at the focus of the Noto equivalent parabola using GRASP. The PSF of the nominal, unmodified equivalent parabola is shown by the red, dashed line. The black, solid line shows the resulting PSF when the active surface is modified according to the TP3 geometry.

With this condition we have calculated the radial profile (r, z) of the modified equivalent parabola and we have imported it in GRASP, and then the EM simulations have been performed using the same method described in Sect. 3.1. Figure 5 shows a radial cut of the PSF of both the unmodified surface and the TP3-equivalent surface, and the SR effect is again visible.

For the next step of this analysis we withdrew the assumption of the ideal active surface, where panels have fully independent movements. As we mentioned earlier, in the real active surface of the Noto antenna each actuator is mounted underneath the convergence point of four panels. Therefore, each actuator (except those at the edges of the active surface) operates on *two* rings of panels simultaneously. As a consequence, while adjusting the surface to mimic the TP3-geometry some of the panels also undergo a partial rotation (around an axis perpendicular to the plane of Fig. 4) instead of a pure translation along the z-axis as in the ideal model. Therefore, the mechanical coupling between adjacent rings of panels prevents the active surface from reshaping exactly as required by, in our case, a TP3-geometry and our EM simulations show that the SR effect is washed-out completely. This failure is due to the limited "spatial resolution" of the active surface of the Noto antenna, where the active panels are organized in a series of 48 radial lines and only four rings.

The situation is quite different for the active surface of the SRT, which consists of 1116 actuators and the active panels are distributed according to 96 radial lines and 14 rings. The major advantage, compared to the Noto antenna, is the much larger number of rings with active panels, providing a much superior spatial resolution as far as the ability of re-shaping the surface is concerned. Therefore, we plan to carry out EM simulations, similar to those described in this work, for the more complex shaped design of the SRT in order to test whether its superior active surface can indeed achieve the SR effect, and also to understand whether the shaped geometry can adversely affect its implementation.

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