First Tests of a Toraldo Pupil Optical Module for the 32m Medicina Antenna

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Abstract

Toraldo Pupils can improve the angular resolving power of an optical instrument beyond the classical diffraction limit (hence the term "super-resolution") using a filter consisting of finite-width concentric coronae with different amplitude and phase transmittance. Toraldo Pupils represent a viable approach to achieve super-resolution on antennas and radio telescopes. In this work we present a summary of the electromagnetic simulations and laboratory tests of a prototype optical module based on a Toraldo Pupil that has been field-tested on the Medicina 32-m radio telescope.

Index Terms – Astronomical Optics, Diffraction, Super-resolution, Telescopes

I. Introduction

One of the fundamental properties of filled-aperture telescopes is their angular resolution, i.e., their ability to separate points of an object that are located at a small angular distance. Apart from other effects which can be either cancelled or mitigated (e.g., aberrations and "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. 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 in the entrance pupil of an optical system, now also known as Toraldo pupils (TPs, hereafter). In this work we present a summary of the most recent results obtained in the context of the "*Pupille Toraldo*" (PUTO[1]) project, which is devoted to a more complete analysis of TPs and how they could be used to implement SR on a radio telescope. During the first part of this project we have performed both EM numerical simulations [2] and laboratory tests [3] at a frequency of 20 GHz that have confirmed and expanded the first measurements carried out in the microwave range [4].

[1] http://www.ifac.cnr.it/PUTO/index.htm

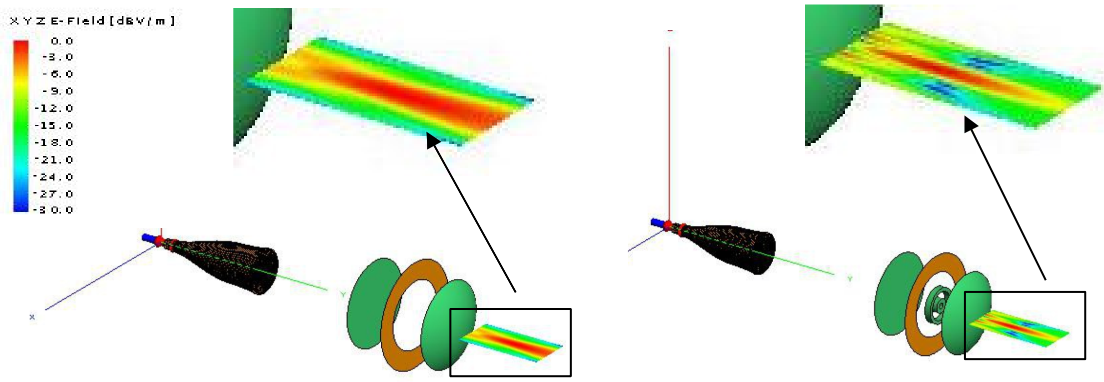

Fig. 1 FEKO simulations at 20 GHz showing the (normalized) field amplitude at the focus of the collimator without (*left panel*) and with (*right panel*) TP. The collimator is illuminated by the same corrugated feed horn of the K-band receiver at Medicina.

II. TP OPTICAL MODULE: EM SIMULATIONS AND TESTS

Following these initial experimental tests we have then designed [5] and tested in the laboratory [6] an optical module based on simple TPs that we planned to mount on the Medicina 32-m radio telescope[2]. The current design is based on a two-lens collimator placed after the Cassegrain focus and before the receiver dewar (see Fig.1). The first lens of the collimator generates an image of the primary reflector 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.

The EM simulations of the optical module were conducted using the commercial software tool FEKO. In the most recent simulations, the 3D model is analyzed in *transmission* rather than in reception. In this model the source was a corrugated feed horn identical to that employed in the K-band receiver operating on the Medicina radio telescope. The results are schematically shown in Fig.1, where the SR effect is visible as the narrower PSF at the focus of the collimator. We then improved the EM model by effectively including the *antenna* optics in the EM simulation. This was performed by using the equivalent parabola to simulate the Medicina Cassegrain telescope (smaller in size but with same focal ratio). Figure 2 shows that while we achieve the correct illumination of the reflector with the basic collimator optics (left panel), we note an anomalous illumination when the TP is applied (right panel). This incorrect illumination is a consequence of the fact that the presence of the TP within the collimator would require a different, optimized feed horn (see Sect. III).

III. LABORATORY AND FIELD TESTS

The two-lens collimator has been extensively tested in the anechoic chamber of the Osservatorio Astrofisico di Arcetri (Firenze) [6]. During these measurements we illuminated the collimator with the same corrugated feed horn as the one employed on

2 http://www.med.ira.inaf.it/

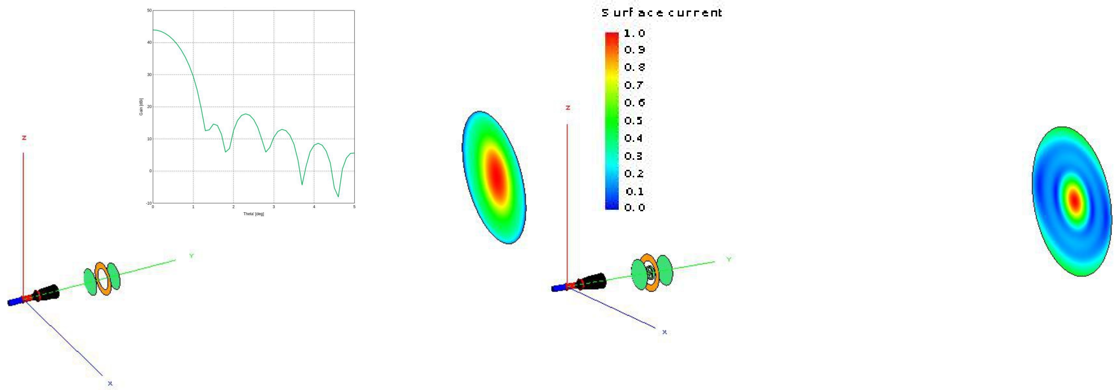

Fig. 2 FEKO simulations at 20 GHz with the equivalent parabola illuminated by the K-band feed-horn through the two-lens collimator, without (*left panel*) and with (*right panel*) the TP applied. The figure shows the (normalized) surface current distribution on the antenna. The inset in the left panel shows the expected far-field antenna pattern.

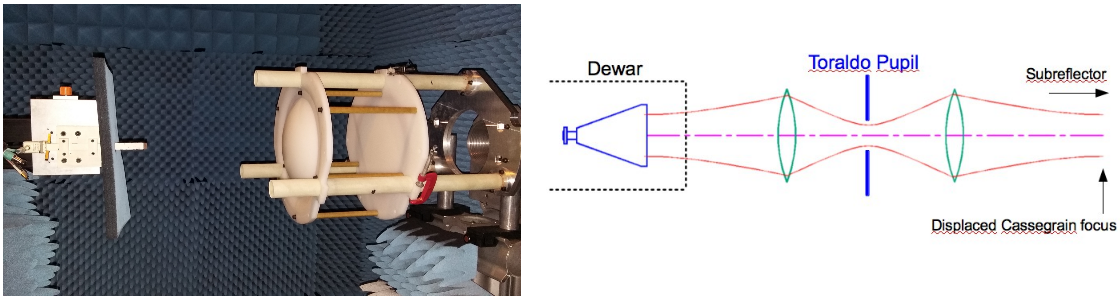

Fig. 3 *Left panel*. Laboratory setup showing the two-lens collimator, illuminated by a K-band corrugated feed horn. The focus fields are sampled with a an open waveguide. *Right panel*. Gaussian-beam propagation in the collimator.

the K-band receiver at Medicina, while the fields at the focus of the collimator were sampled using a waveguide probe (see left panel of Fig. 3). The results from these tests were quite consistent with the FEKO simulations shown in Fig. 1. However, when the open waveguide at the focus is replaced by the corrugated horn (to simulate the real detection process with the K-band receiver, as shown in the right panel of Fig. 3), the significant mismatch between the PSF at the focus of the collimator and the expected fields on the aperture of the horn completely “washes out” the SR effect when the TP is present. This mismatch is the reason of the anomalous illumination of the reflector in the right panel of Fig. 2.

In March 2018 we finally field-tested the two-lens collimator on the Medicina antenna. The collimator was mounted externally on the dewar of the K-band receiver (see Fig. 4) and then we performed two main series of tests: *(i)* after mounting the collimator we had to find the new focal position by executing focus scans on point sources, which allowed to optimize the position of the subreflector (see Fig. 3); *(ii)* then we carried out cross-scans on the point sources, and compared the measured antenna beam with the results obtained without the collimator. During these measurements we used both astronomical point sources and a geostationary satellite (Eutelsat Ka-sat 9a).

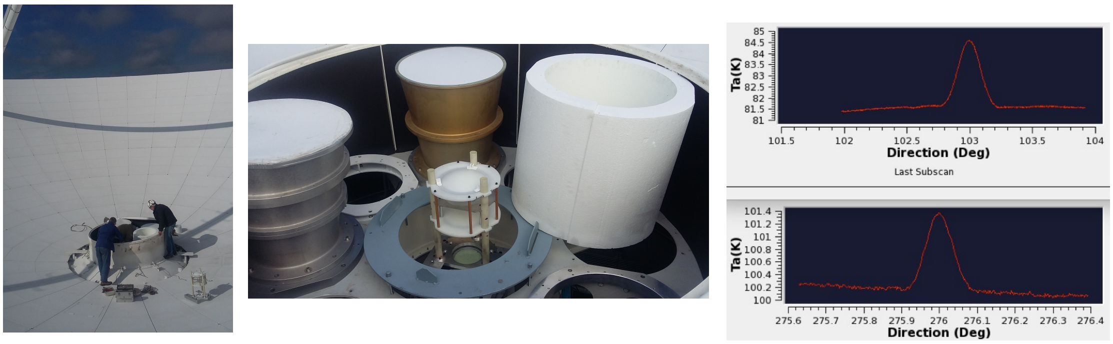

Fig. 4 *Left panel*. Mounting of the collimator at the Cassegrain focus of the Medicina antenna. *Middle panel.* The collimator mounted on the dewar of the K-band receiver. *Right panel*. Example of almost identical antenna beam-patterns obtained during an azimuth scan without (top) and with (bottom) the collimator, but with no TP applied. The raw horizontal scale is not corrected for the different elevations. The vertical scale is raw antenna temperature.

These tests showed that the satellite signal was very difficult to use for focus and pointing scans, especially with a new optical system to be checked. However, the pointing astronomical sources were strong enough to determine the new focus position with the collimator mounted on the receiver and the cross-scans showed that the antenna beam was basically identical with and without the collimator (see the right panel in Fig. 4). When the TP was applied to the collimator it was not possible to make a reliable measurement of the antenna beam, due to the mismatch with the receiver feed-horn, as previously shown during our laboratory tests. An *ad-hoc* receiver and feed horn should be used to fully exploit the SR effect.

Acknowledgement

We gratefully acknowledge the partial support of the Ente Cassa di Risparmio di Firenze (Italy). We also wish to thank all personnel of the Medicina Radio Astronomical Station whose support was fundamental before and during the tests at the antenna.

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