Design of an off-set optics with high polarization purity and large Focal-plane Area for CMB polarization observations

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ABSTRACT

This paper describes the study of an optical configuration at 94 GHz for the pre-phase A study of the B-POL program, an ASI study of a next generation space mission devoted to the B-Mode of the CMB polarization. The main requirements of the optical system are:

a) a large Focal-plane Area (FA) with low aberrations with size of 220 mm to host a cluster with 49 feeds;

b) a beam in the sky of about 1 degree for each horn;

c) a high cross-polarization performance better than -30 dB in the entire FA.

The final optics system consists of an off-axis Dragonian antenna employing a paraboloid main reflector illuminated by a concave hyperboloid subreflector. The configuration has relatively flat reflectors and wide FA capabilities and derives from the optical design of the ClOVER experiment. Differing from the ClOVER design, our case has extreme FA size needs. The final optical configuration is a 400 mm diameter primary mirror illuminated from a subreflector with a highly tapered feed. The FA size is 220 mm wide (more than 50% of the primary aperture) and the cross-polarization is better than -30 dB ÷ -35 dB everywhere in the FA. This is achieved by oversizing the optics for a strong underillumination. The electromagnetic analysis was performed with GRASP9, the most powerful commercial tool for the antenna reflector design.

INTRODUCTION

The project "Pre-phase-A study for the B-POL program" is a study for a next generation space mission devoted to the search for the B-Mode of the CMB polarization funded by the Italian Space Agency (ASI: Agenzia Spaziale Italiana). In this framework, the authors, in collaboration with the group of the CNR-IEIIT, are in charge of the study of the Mid Frequency Instrument (MFI also known as SMF) of a sub-orbital precursor experiment meant for technological development and testing in view of the space mission.

The MFI covers the W-band with a central frequency f_0 = 94 GHz and goal bandwidth (BW) of 30%. The central frequency is a trade-off between the position of the minimum foreground emission (expected to be in the range 70 ÷ 90 GHz) and the atmospheric window that sub-orbital experiments can access, constrained by the two Oxygen lines at 60 and 120 GHz. The position of f_0 at about 90 GHz allows a 30% relative bandwidth while keeping far from those two limits.

The space mission will also have a 70 GHz channel, the best for CMB purposes, which cannot be tested with the sub-orbital experiment. However, the technology issues are very similar to those at 90 GHz, whose development and test will thus validate the performances of a 70 GHz system too.

The unusual conditions of weak signal and polarization fraction of the CMB B-Mode require both low noise receivers to achieve the required sensitivity and high polarization purity to minimize leakages from the far stronger unpolarized component and the other polarized term (E–Mode).

The technologies used so far for CMB experiments are essentially two: radiometric and bolometric receivers. Bolometers are the most sensitive detectors at these frequencies, but radiometric front-ends are unsurpassed in terms of polarization purity.

The basic idea for MFI is to take advantage of the best of each of these two technologies, realizing an instrument with the purity of radiometer front-ends along with bolometer sensitivity. This is realized by coupling a radiometric front-end with bolometers used as detectors. In addition, the use of large receiver arrays is also necessary to get the high sensitivity required.

The main aim of the precursor experiment (and of this study) is thus to develop the know-how to realize experiments with large number of feed-horns while preserving an high polarization purity for all of them.

This paper describes the study of the optical design to feed the bolometric array of MFI, study which is in charge of the IRA-OAC group. The electromagnetic analysis of the optical system was performed with a very powerful tool for the study of the reflector antennas: GRASP9 developed by TICRA (http://www.ticra.com).

OPTICS SPECIFICATIONS AND CHALLENGES

MFI is conceived to have a resolution of about 1 deg and host a cluster of 49 feeds in 7 hexagonal tiles of 7 feeds each. Therefore, the challenge here is to design an optics with large FA to locate many horns in a small aperture telescope. This is a typical issue for B-Mode experiments whose aim is to have coarse resolution (the scales of interest are down to 1-2 deg) and, in turn, small apertures.

More specifically, the main optics specifications of the project are as follows:

- Feed spacing: 30 mm (from OMT array design) equivalent to approximately 10 wavelengths;
- Mirror optics to feed a horn array of 7x7 elements (7 tiles, 7 feeds each), requiring a diameter of 220 mm for the FA (see Fig. 1 for the arrangement of the 49 feeds);
- Cross-polarization: 30-35 dB below the co-polar pattern at any feed position;
- Full Width Half Maximum (FWHM) of each feed: ~1 deg @ 94 GHz;
- The size of the primary aperture required to achieve the above specification is around 200 mm. However, it is possible to use an under illuminated larger optics (up to 400 mm for the primary reflector) to enlarge the FA and match the cross-polarization requirements out to the most off-axis feed position. Each tile is arranged so that the apertures of the 7 feeds lay on a plane (flat tile) However, the seven tiles can be individually oriented into different directions for beam optimization;
- All microwave passive components (including possible horns) shall be cooled to 4 K.

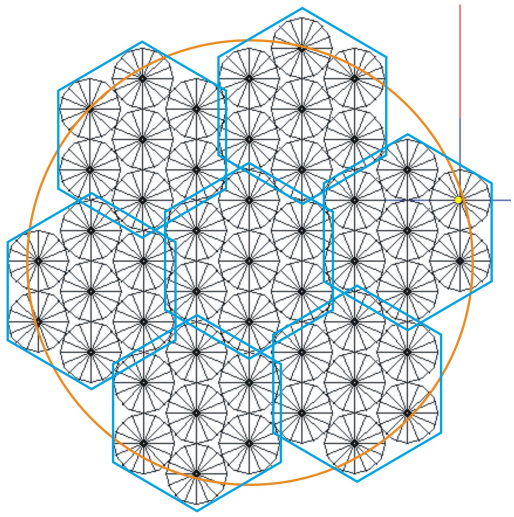


Fig. 1 – Hexagonal arrangement of the feeds in the focal plane. The maximum distance of the outer feeds from the center of the cluster is 108 mm, corresponding to the radius of the external circumference.

Following those requirements, the FA width can be either 100% of the expected aperture (200 mm) or approximately 50% of the larger optics with under-illuminated option (400 mm). Achieving a large FA represents the biggest challenge of the optical design both in terms of blockage of the radiation and of polarization purity for the outermost receivers.

The optical configuration that was selected after a preliminary study consists of horns coupled with reflectors, which is a well established solution. During this preliminary study we also considered the following solutions for the optics/horn system:

1. Horns stand-alone (without mirrors): simple solution but large horns tilted to observe different regions of the sky. This solution would require a more complex and larger dewar to cool down the receiver parts to 4 K.
2. Horns coupled with lens: new and original approach, but the degradation in terms of cross-polarization needs to be accurately studied since the lens system polarization performances are poorly investigated so far .

The adopted solution of horns coupled with reflectors and the above solution #2 require small horns in a quasi-parallel configuration and can therefore fit more easily inside a cool receiver. Solution #1 was discarded because of its large dimensions. Moreover, optical systems based on reflecting mirrors are well known to have excellent polarization performances. Lenses, instead, are less consolidated in optical systems with high polarization performances.

Therefore, we focused the analysis to the horn/reflector's solution by investigating the optical design used in the ClOVER experiment [1] whose performance were optimized for CMB studies to provide a large FA. The ClOVER optical system is a compact range design (also known as a crossed Dragone) with an off-axis unblocked aperture based on a concave hyperboloid secondary coupled to paraboloid primary. Despite being off-axis, this system has a very large focal plane with low aberration and cross-polarization (much larger than the equivalent aperture Gregorian). However, we will show that the crossed Dragone FA is not large enough to satisfy the extreme condition of 100% of the optics aperture.

A convenient step-by-step design procedure to optimize a classical offset Dragonian antenna with circular aperture is given in Chang and Prata [2]; the design provides a zero geometrical-optics cross polarization and minimum spill-over.

NUMERICAL SIMULATION

The main driver of our study was to provide a good illumination for the all feeds located in the FA, and in particular for the outermost ones. This goal is achieved by enlarging the primary mirror aperture and under-illuminating it in order to preserve the desired angular beam resolution.

We initially started aiming at a FWHM = 2 deg system, that means an *ideal* aperture of ~100 mm which afterwards we enlarged up to 250 mm under-illuminating the mirror to get the same FWHM. However, after several attempts with different sets of geometrical parameters, we found that the constraint to assure a FWHM = 2 deg (meaning a small aperture) was in conflict with having a sufficiently large FA (we achieved acceptable conditions of FA up to a diameter of 100 mm instead of 220 mm). We then modified our needs to an optics scaled up by a factor 2, meaning a standard illuminated aperture of 200 mm or an under-illuminated aperture of about 400 mm. This consequently provides a FWHM = 1 deg, that still matches the initial requirements.

In this section we report the analysis of the final configuration that gave the best results.

The input data of the procedure given in reference [2] was set as indicated in Table I (the parameters are defined according to the geometry of Fig. 2).

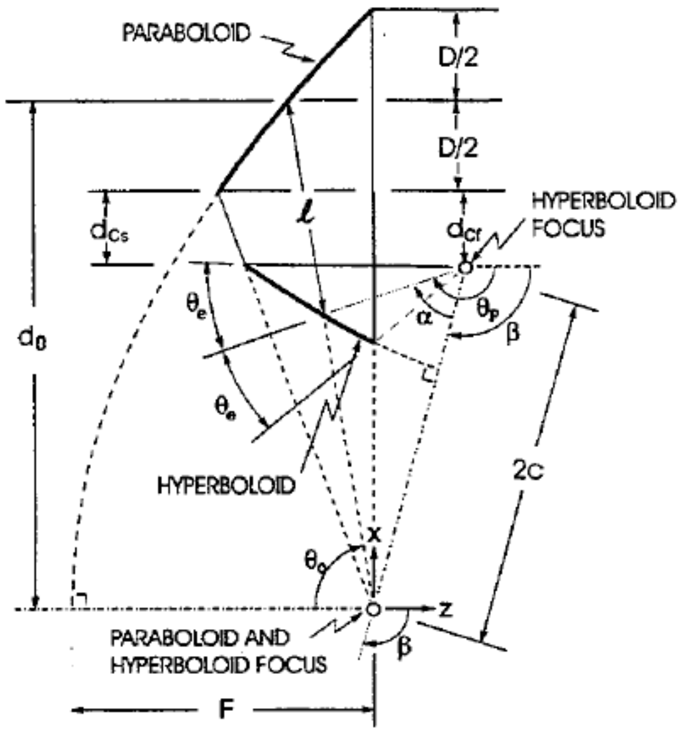


Fig. 2 – Geometry of the Dragonian antenna (from [2]).

D - Projected aperture diameter	*400 mm*
l - Distance between the main and subreflector surfaces -- measured along the principal ray	*400 mm*
θ_e - Angle that the feed sees the subreflector edge	*15 deg*
θ_0 - Offset angle	*-45 deg*
θ_p - Angle between feed boresight and the paraboloid axis	*-90 deg*

Table I – Input parameters for the Dragonian antenna design.

The angle θ_p = -90 deg means that we choose the so-called *side-fed type,* which gives better performance in terms of cross-polarization (the other Dragonian type being called *front-fed.*)

The procedure gave the output parameters reported in Table II.

β - Angle between the hyperboloid main axis and the paraboloid axis	*-59.639 deg*
e - Subreflector eccentricity	*2.798*
F_p - Main reflector focal length	*1296.676 mm*
2c - Subreflector interfocal distance	*1565.654 mm*
d_cf - Feed clearance	*76.733 mm*
d_cs - Subreflector clearance	*22.300 mm*
F_e - Equivalent focal length	*759.575 mm*
F/D - F/D number	*1.899*

Table II – Output parameters for the Dragonian antenna design.

Both d_cf and d_cs > 0 assure a blockage-free configuration, at least for the feed at the center of the FA. Moreover, the rim of the primary mirror is circular, whereas the rim of the secondary mirror is elliptical with the major semi-axis of 165 mm and the minor semi-axis of 153 mm.

The geometrical parameters were entered into the dual reflector wizard of GRASP (see Fig. 3).

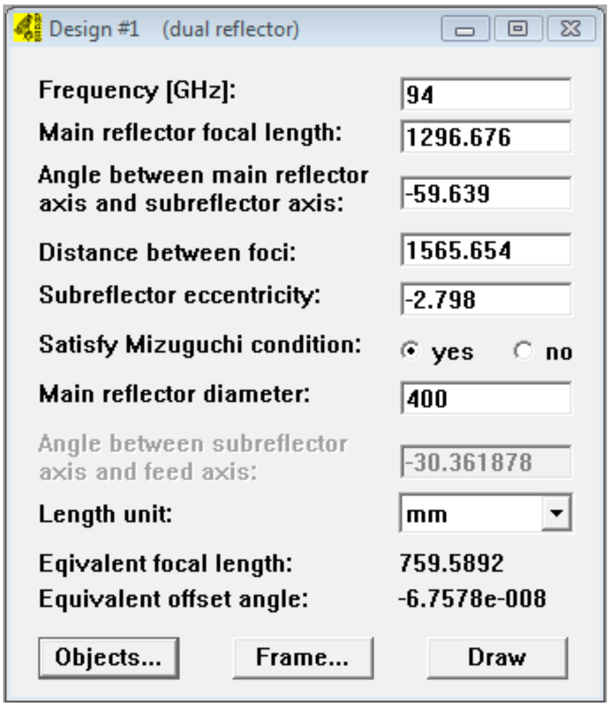
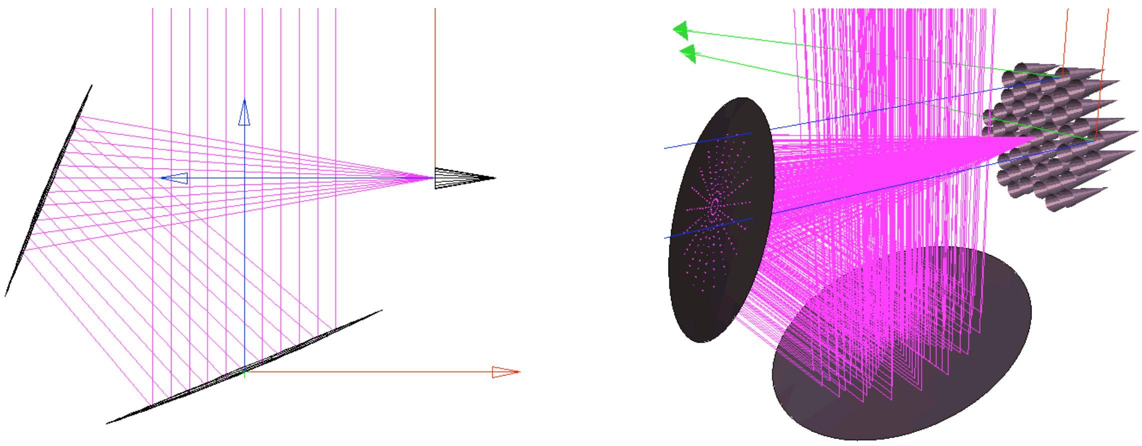


Fig. 3 – GRASP wizard interface.

From those data, GRASP automatically creates all the electrical and geometrical objects to be used in the electromagnetic analysis which is performed using the high frequency technique (Physical Optics). An overview of the optical system can be sketched using the "ray tracing", where optical rays originating in the secondary focus are plotted in the angular range -10 deg < theta < 10 deg, at which the feed illumination drops to -20 dB (Fig. 4a).



(a) (b)

Fig. 4 – (a) Ray tracing of the Dragonian antenna in the xz plane(z-axis in blue); (b) 3D representation of 49 feeds in the FA.

As already discussed, to limit spill-over and to maintain a quite large beam, the mirrors are under-illuminated. The feed pattern is an ideal linearly polarized Gaussian (along x-axis), with -12 dB taper at 7.8° (see Fig. 5 for the feed pattern's behavior). The cross-polarization component of the feed is assumed to be zero in order to investigate the mirror optics effect only. The edge of the subreflector is seen from the feed with an angle 15 deg. The selected Gaussian pattern drops to -20 dB @ 10 deg, i.e. the outer rays traced in Fig. 4a have a power level of the order of 1/100th of the boresight ray. We derived a FWHM = 7.8 deg from Fig. 5. Consequently, the feed aperture diameter is evaluated through the formula 1.2*lambda/D_horn = FWHP, which provides a value of D_horn = 28 mm, compatible with the OMT array spacing (30 mm).

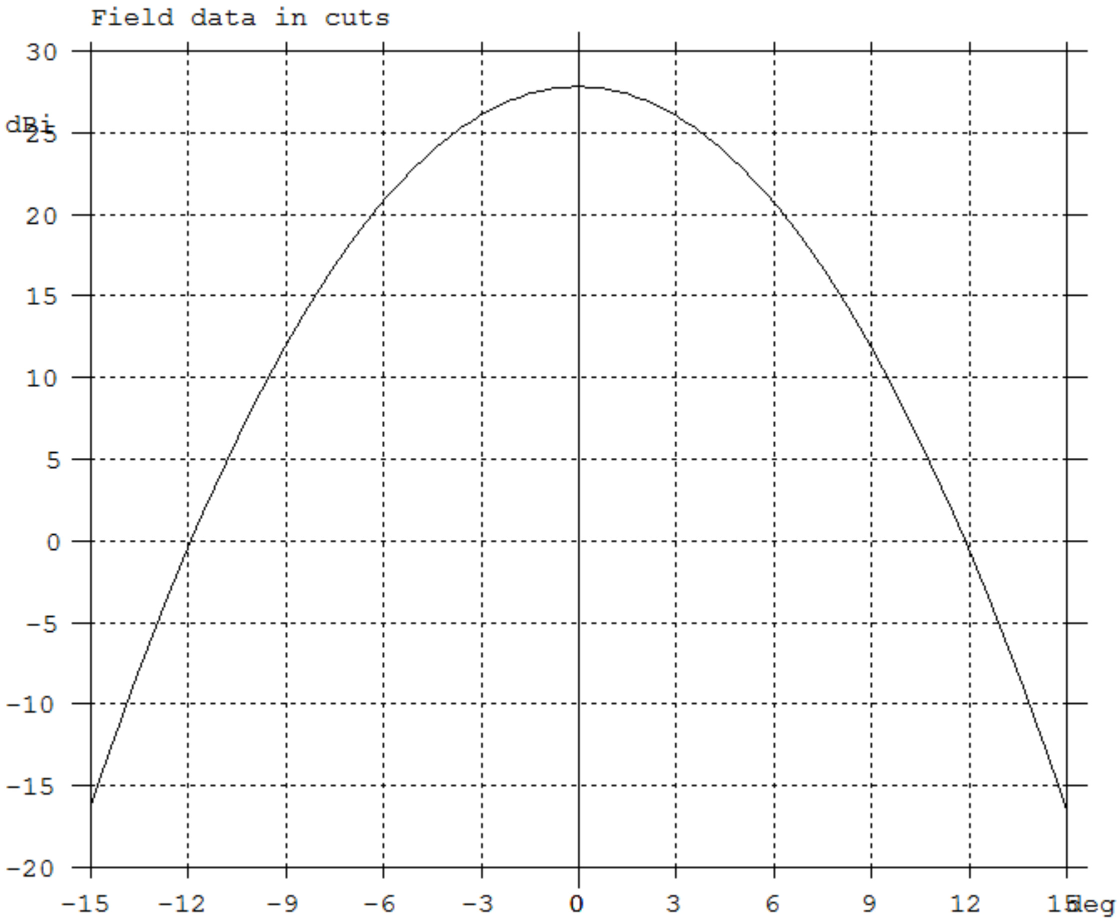


Fig. 5 – Gaussian feed with taper: -12 dB @ 7.8 deg, and -45 dB @ 15 deg.

The beam in the sky is plotted in Fig. 9 (blue curve): the maximum antenna gain is 47.75 dBi, the antenna efficiency is 38.4% (the low efficiency is expected and wanted since the mirror is strongly under-illuminated), and the resolution in the sky is FWHM= 0.78 deg. Another benefit of the under-illumination of the subreflector edge is the low side lobe levels, which are -60 dB below the main lobe (see again blue curve of Fig. 9). Further under-illumination of the mirrors (that would increase the FWHP in the sky and further increase the edge taper) would also require a larger horn aperture, which is incompatible with the OMT array design. In fact, a bigger feed would imply a larger spacing between next receivers and, in turn, a larger FA.

For this configuration, the electric field in the projected primary aperture was plotted in the Fig. 6: the under-illumination of the aperture is evident.

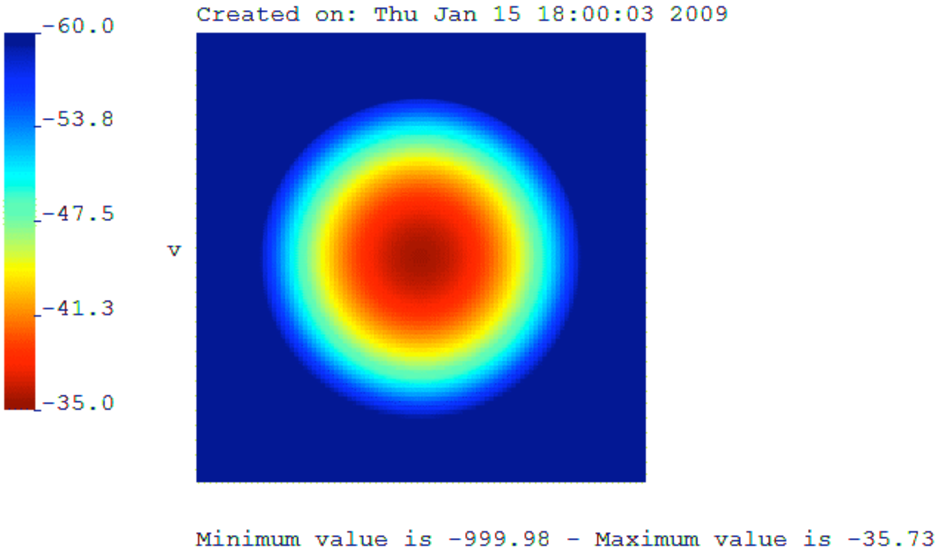


Fig. 6 – Aperture field for the primary mirror.

The most challenging issue is the optimization of the optical configuration for the lateral displacement of the feeds in the FA. Only the maximum shift was considered in this analysis (which represents the worst case). Since the asymmetry of the optical configuration, we consider the displacement in the focal plane along all the four directions from the centre of the FA (negative and positive, both x-axis and y-axis of Fig. 4a). Further analysis, not included in this preliminary study, will face the coupling among the reflectors and each element of the array, looking for an optimization of their arrangement.

We found that orienting the lateral feeds towards the centre of the optics, as usually prescribed, is not an option in our case, since the outermost feeds (+/- 110 mm) are subject to blockage. The key aspect to extend the FA is indeed to limit blockage effects by illuminating appropriately different sectors of the secondary mirror (and consequently of the primary one). This is made possible only by the significant under-illumination. The presence of the blockage effect was considered on the basis of the ray tracing and in particular of the more external ray (those at 10 deg).

The following two cases were analyzed:

- Feed shifted of 110 mm along the positive x-axis (red axis of Fig. 4a) and tilted of 7 deg to avoid blockage (ray tracing plotted in Fig. 7a and sky beam in Fig. 9 in black). The numerical results are: G_{max} = 47.3 dBi, antenna efficiency 34.6%, FWHM = 0.88 deg, and beam direction in the sky at -8.38 deg. The angle that the feed should be tilted to point towards the center of the secondary mirror is 11 deg (see the blockage effects in the ray tracing in Fig. 7b). However, we have verified that the blockage effects for this last case are negligible, being the antenna efficiency equal to 34.3% (corresponding to 99.3% of the previous value).

- Feed shifted of 110 mm along negative x-axis and tilted of 7 deg (ray tracing plotted in Fig. 8a and sky beam in Fig. 9 in green). For this configuration, the numerical results are: G_max = 47.7 dBi, antenna efficiency 38.4%, FWHM = 0.79 deg, and beam direction in the sky at 8.05 deg. In this case, the tilt of the feed to point exactly the center of the mirror is 11 deg (see Fig. 8b). Contrary to what happen for positive shift, the tilt of 11 deg produces now a drop of the antenna efficiency equal to 90% of the case with 7 deg, being equal to 34.6%.

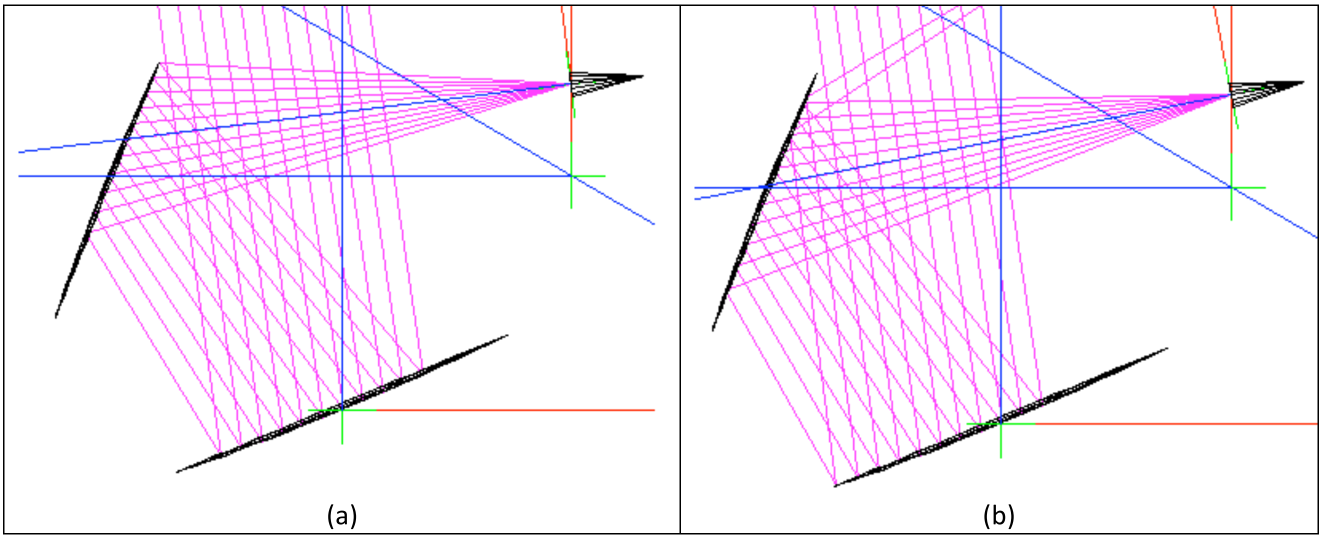


Fig. 7 – Ray tracing in the xz plane for the feed shifted of 110 mm along the positive x-axis and tilt of: (a) 7 deg; (b) 11 deg.

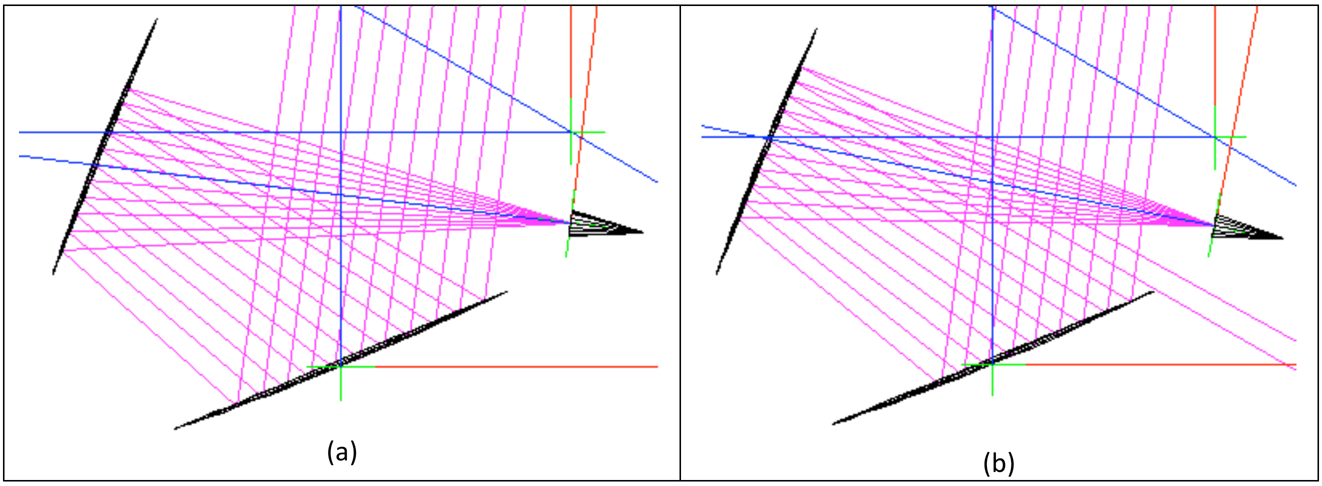


Fig. 8 – Ray tracing in the xz plane for the feed shifted of 110 mm along the negative x-axis and tilt of: (a) 7 deg; (b) 11 deg.

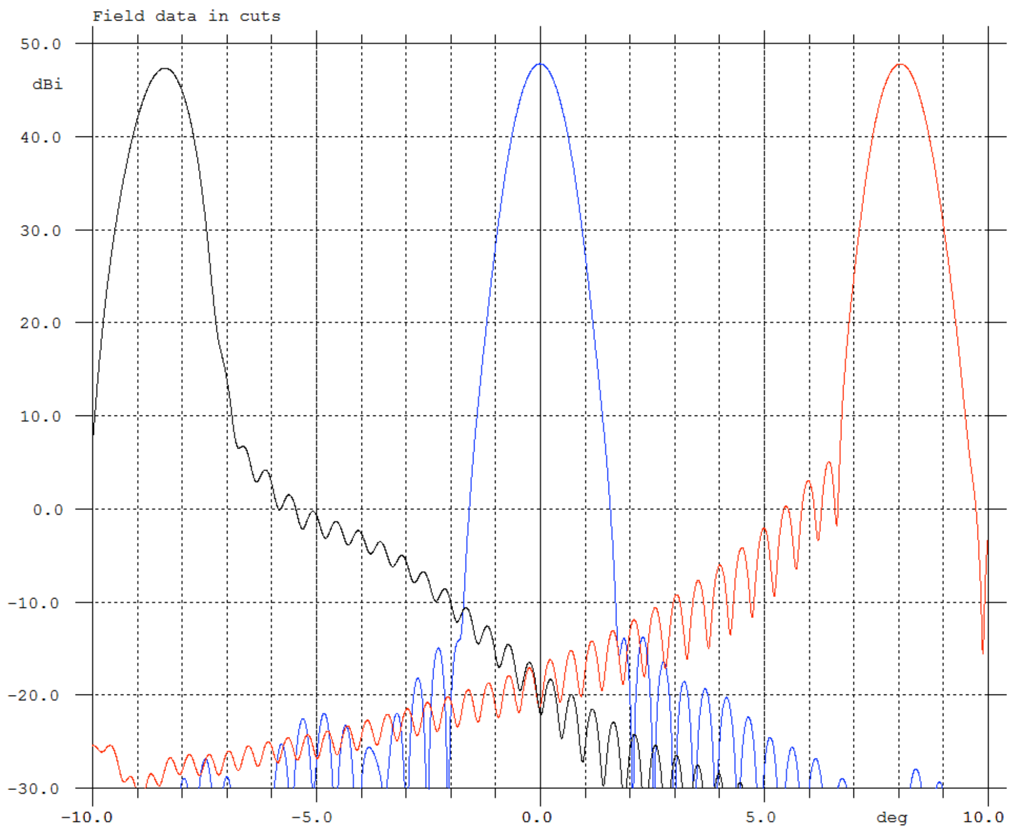


Fig. 9 – Main co-polar antenna beams, in cut phi = 0 deg, for three different configurations: feed at the center of the FA (blue); feed shifted along x of 110 mm (black); feed shifted along x of -110 mm (red).

All those configurations show excellent performance also in terms of spill-over efficiency (and consequently of antenna temperature contribution due to the external environment). The spill-over efficiency is evaluated individually both for the primary mirror and for the secondary one: its value is always higher than 99.8%.

Co-polarized and cross-polarized beams are evaluated in the uv map (u_max=v_max=0.35; u_min=v_min=-0.35) for the three configurations (see Figures 10, 11 and 12).

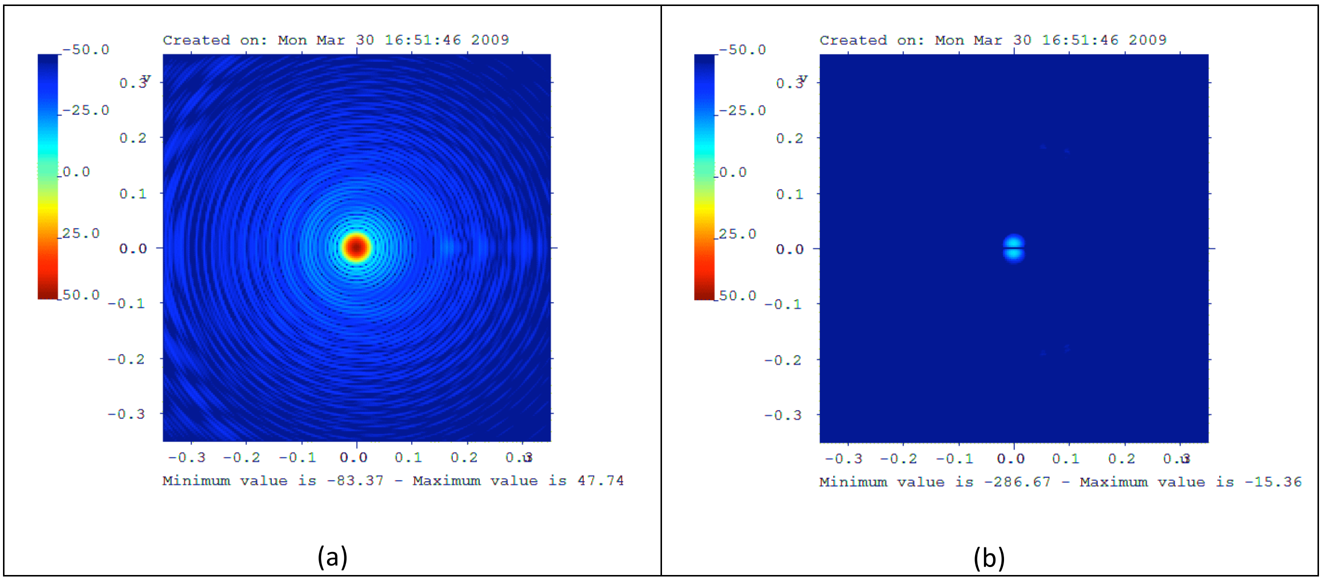


Fig. 10 – Co-polarized and cross-polarized beams with feed at the center of the FA.

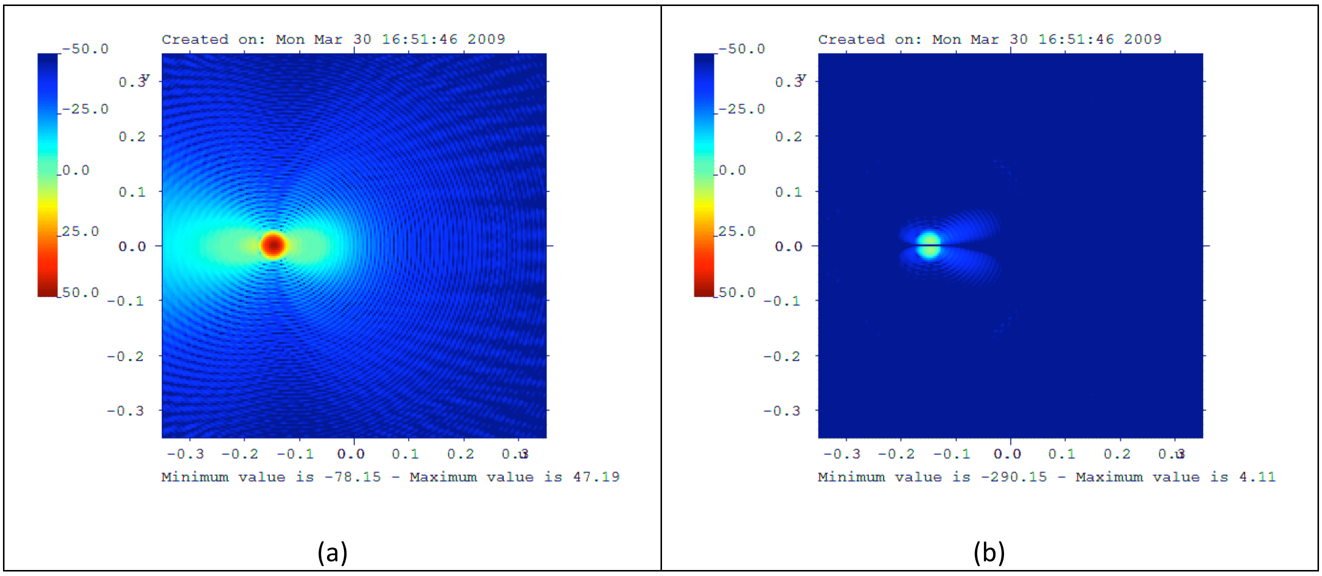


Fig. 11 – Co-polarized and cross-polarized beams with feed shifted 110 mm along x and tilted of 7 deg.

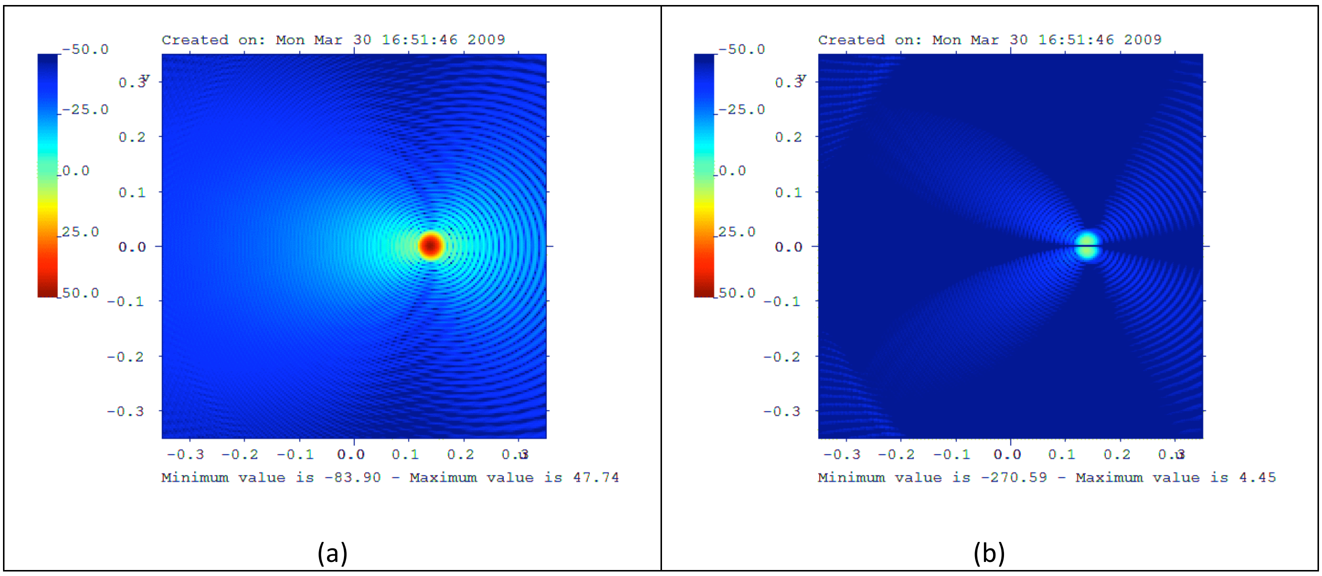


Fig. 12 – Co-polarized and cross-polarized beams with feed shifted -110 mm along x and tilted 7 deg.

The cross-polar performances are excellent for all the three positions. The cross-polar maximum is 43 dB below the co-polar for the two lateral positions (it is 63 dB for the central feed, see Fig. 10) which well matches the specifications (better than 30-35 dB everywhere in the FA). These are excellent results considering that the FA is more than 50% of the mirror aperture.

Then, we analyzed the optical configuration with the feed shifted along the orthogonal direction (y-axis); the ray tracing for this case is plotted in Fig. 13. The maximum shift (110 mm) in positive and negative direction was considered.

- Feed displaced by +110 mm along the FA and tilted by 8 deg (which a series of optimization indicates as the best angle for the receiver tilt) results to be the : G_max = 47.0 dBi, antenna efficiency 32.5%, FWHM = 0.81 deg, and beam direction at -8.19 deg in the phi = 90 deg cut (see Fig. 14 for the co-polar pattern in the main cut).

- Since the system is symmetrical in the y-axis, identical results are achieved moving the feed in the opposite y-direction.

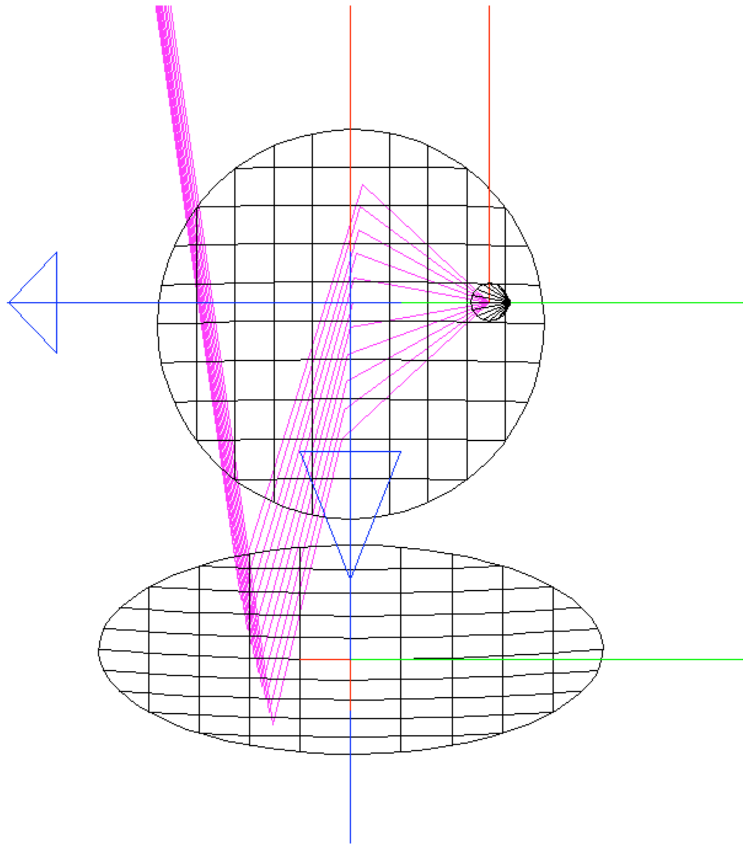


Fig. 13 – Ray tracing in the yz plane for the feed shifted of 110 mm along the positive y-axis and tilt of 11 deg.

The co-polar antenna beams in 1D cut are plotted in Fig. 14, whereas the 2D co-polar and cross-polar maps are in Fig. 15 and 16.

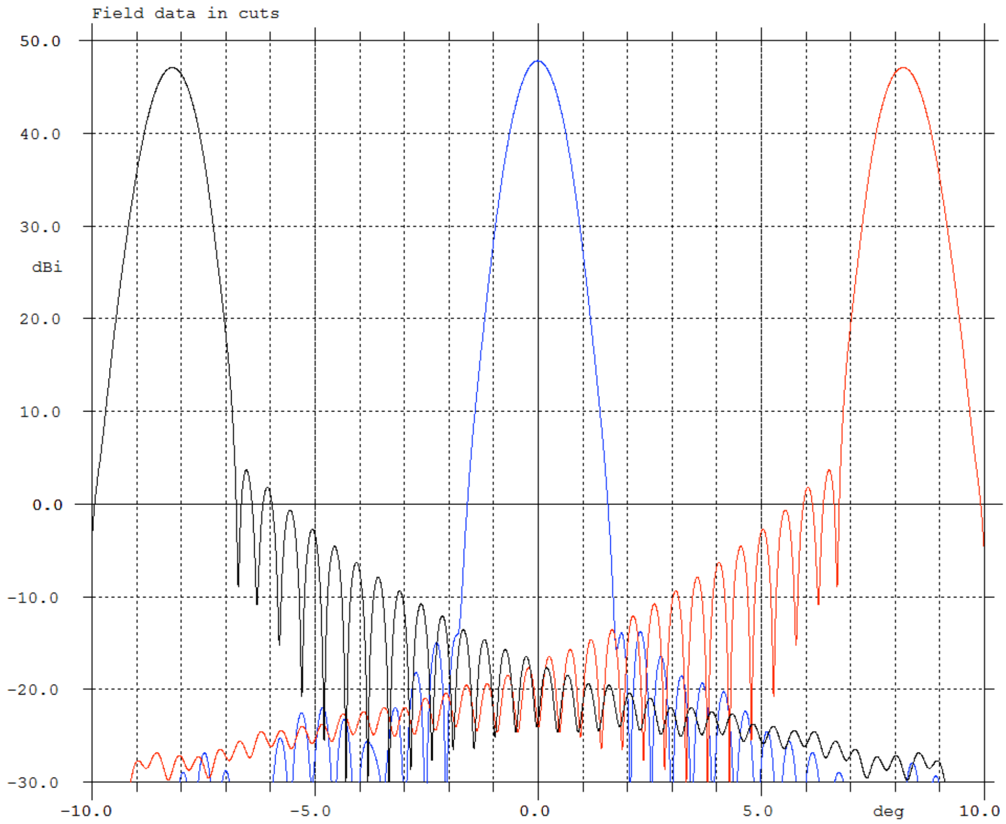


Fig. 14 – Main co-polar antenna beams, in cut phi = 90 deg, for three different configurations: feed at the center of the FA (blue); feed shifted along y of 110 mm (black); feed shifted along y of -110 mm (red).

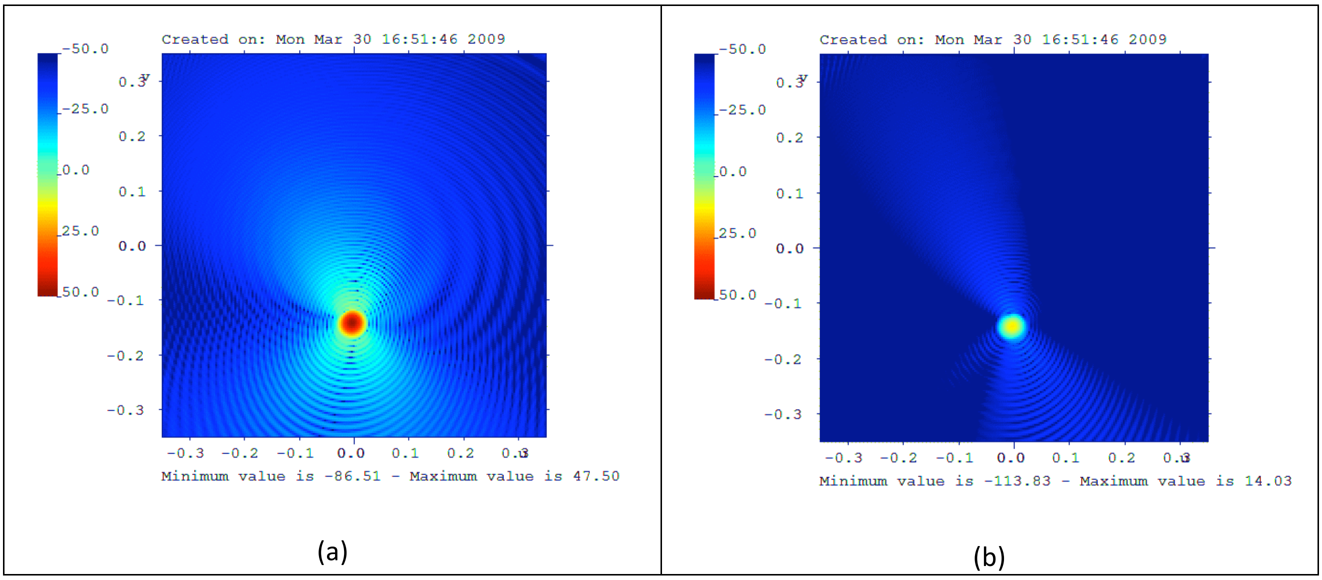


Fig. 15 – Co-polarized and cross-polarized beams with feed shifted 110 mm along y and tilted 8 deg.

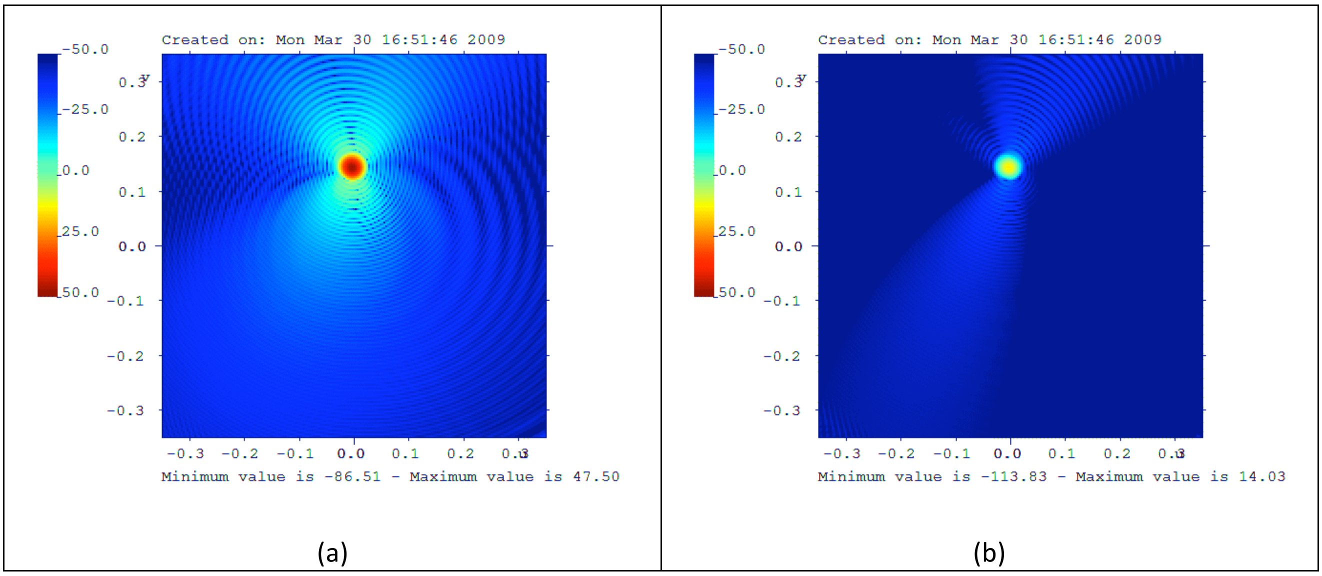


Fig. 16 – Co-polarized and cross-polarized beams with feed shifted -110 mm along y and tilted 8 deg.

Although the cross-polar performance slightly degrades in the y-shifted positions (-33.5 dB), these are still excellent values that match the design specifications.

Finally, the main electromagnetic results obtained for the five configurations analyzed are summarized in Table III. The table includes the antenna gain, the Full Width Half Maximum and the direction of the beam in the sky indicated both in deg and in arcmin, and the cross-polar performance.

Configuration	Gain [dBi]	FWHM [deg & arcmin]	Beam direction [deg & arcmin]	max(cross-pol) - max[co-pol] [dB]
On – focus	47.7	0.78 / 47	0 & 0	-63.1
Δx = 110 mm, θ = -7 deg	47.3	0.88 / 53	-8.4 & -504	-43.1
Δx = -110 mm, θ = 7 deg	47.7	0.79 / 47	8.1 & 486	-43.3
Δy = 110 mm, θ = -8 deg	47.5	0.81 / 49	-8.2 & -492	-33.5
Δy = -110 mm, θ = 8 deg	47.5	0.81 / 49	8.2 & 492	-33.5

Table III – Summary of the main electromagnetic performances for the outermost feed compared to the central feed.

CONCLUSIONS

Starting from a compact range antenna design (a-la ClOVER) we have designed an optics with large FA and high polarization purity. The key points were:

1. a significantly under-illuminated large optics (400 mm instead of the ~200 mm needed by a 1 deg resolution system);
2. the outer feeds tilted to point lateral sections of the secondary mirror to avoid blockage effects (made possible by the strong under-illumination).

With such prescriptions we obtained an extremely large FA (220 mm, which is about 50% of the aperture, and 110% of the "prescribed" aperture of 200 mm) and cross-polarization better than -33.5 dB with respect to the co-polar peak in the entire FA. The angular resolution is about 0.8 deg in the sky.

This is very promising for the possible future space mission that require to host hundreds of feeds in the FA. In fact, scaling up the optics size and accepting finer resolutions (for instance, if the gravitational lensing contribution wants to be measured, a resolution better than 10' is required), we can infer that an optics of 1600 mm can host about 800 feeds at 94 GHz with high polarization purity.

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