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B-POL Test Telescope
First Design

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1 The Telescope

The CASE1 configuration is an off axis Gregorian telescope, with a parabolic main reflector and an ellipsoidal sub reflector. The telescope satisfy the *Dragone-Mizuguchi* condition that minimize the cross-polarisation induced by the off axis configuration: the three angles α, β, and γ shown in Fig. 1 are related by the two equations [1]:

$$\tan\alpha = M \cdot \tan\beta$$

$$\tan(\gamma + \beta) = M^2 \cdot \tan\beta$$

where M is the magnitude of the secondary mirror and e is its eccentricity,

$$M = \left|\frac{e+1}{e-1}\right|.$$

1.1 Coordinate Systems

Four coordinate systems have been defined for representing the optics in GRASP8 (see Fig. 1):

- **system_main** is the global coordinate system in which the main reflector is defined. Its origin is at the vertex of the parabola, the Z– axis coincides with the parabola axis of revolution, the X– axis points toward the primary mirror, and the Y– axis complements the coordinate system,
- **system_sub** is the coordinate system in which the sub reflector is defined. Its origin is at the focus of the secondary mirror, the Z– axis is at about 60 degrees from the major axis of the parent ellipsoid of the secondary mirror, with positive direction on the concave side of the primary mirror, the X– axis is parallel to the sub reflector rim and points toward the higher part of the sub reflector, and the Y– axis complements the coordinate system,
- **system_feed** is the coordinate system in which the feed horn is located. Its origin is at the other focal point of the sub reflector ellipsoid and the Z– axis points toward the centre of the sub reflector forming an angle of about 22 degrees from the sub reflector axis,
- **system_LOS** is the line of sight coordinate system. Its origin is in the center of the main reflector, the Z– axis is parallel to the parabola axis of revolution with the positive direction on the concave side of the primary mirror.

These frames are listed in Table 1. The origin of each coordinate system and three orientation angles have been written according to the GRASP8 definition [2].

1.2 Telescope parameters

The telescope is designed in Gregorian off axis configuration. The main reflector is parabolic with the focal length equal to 360 mm and the diameter of the projected circular rim is 600 mm. The sub reflector is ellipsoidal with eccentricity equal to 0.35. Its axis is tilted of about 22 degrees from the main reflector axis. The sub reflector rim is elliptical with half-axis equal to 240 and 230 mm. The equivalent $f_\#$ is about 1.1, according to

$$f_e = f \cdot M \cdot \frac{1 + \tan^2(\beta)}{1 + M^2 \cdot \tan^2(\beta)}.$$

Table 1: Definition of the coordinate systems used in GRASP8.

Axis System	Base	Location (X_{base},Y_{base},Z_{base}) [mm,mm,mm]			Orientation (θ,φ,ψ) [$^\circ$,$^\circ$,$^\circ$]		
system_main	–	0.00	0.00	0.00	0.00	0.00	0.00
system_sub	system_main	0.00	0.00	360.00	142.28	0.00	180.00
system_feed	system_sub	–276.34	0.00	161.36	164.25	0.00	180.00
system_feed	system_main	398.76	0.00	110.42	0.00	0.00	0.00

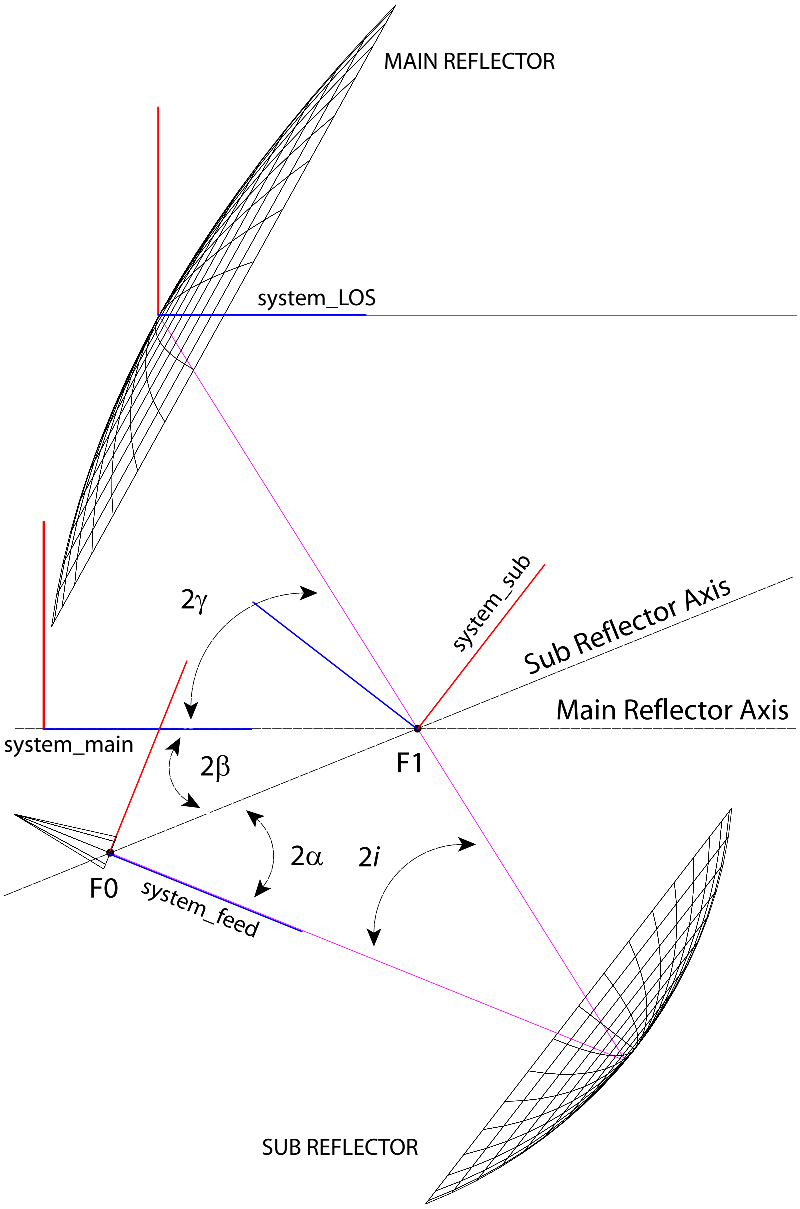

Figure 1: Telescope geometry.

Table 2: GRASP8 telescope parameters

Primary Mirror	Rim	Class Elliptical Rim: rim_main centre (x: 398.76 mm; y: 0.00 mm) half axis (x: 300.00 mm; y: 300.00 mm) rotation 0°
	Surface	Class Parabolid: surface_main focal length 360.00 mm vertex (x: 0.00 mm; y: 0.00 mm; z: 0.00 mm)
	Scatterer	Class Reflector: reflector_main coordinate system system_main surface surface_main rim rim_main centre hole radius 0.00 mm
Secondary Mirror	Rim	Class Elliptical Rim: rim_sub centre (x: -116.60 mm; y: 0.00 mm) half axis (x: 241.59 mm; y: 230.29 mm) rotation 0°
	Surface	Class Ellipsoid: surface_sub vertex distance 914.29 mm foci distance 320.00 mm axis angle 59.72°
	Scatterer	Class Reflector: reflector_sub coordinate system system_sub surface surface_sub rim rim_sub centre hole radius 0.00 mm

2 The Structure

The shielding structure has been defined in GRASP8 using plane reflectors with rectangular and triangular rims. The final structure is shown in Fig. 2.

Table 3: Definition of the coordinate systems used in GRASP8.

Axis System	Base	Location $(X_{base},Y_{base},Z_{base})$ [mm,mm,mm]			Orientation (θ,φ,ψ) [°,°,°]		
system_g	system_main	–150.00	0.00	–280.00	30.00	180.00	0.00
system_b	system_g	500.00	0.00	0.00	0.00	0.00	0.00
system_d	system_g	0.00	0.00	450.00	90.00	0.00	0.00
system_d	system_g	300.00	0.00	900.00	180.00	0.00	0.00
system_fb	system_g	1144.34	0.00	250.00	60.00	180.00	0.00
system_ft	system_g	686.60	0.00	850.00	150.00	180.00	0.00
system_l1	system_g	1000.00	400.00	0.00	90.00	–90.00	–180.00
system_l2	system_g	1000.00	–400.00	0.00	90.00	90.00	180.00
system_l3	system_g	300.00	400.00	450.00	90.00	–90.00	–180.00
system_l4	system_g	300.00	–400.00	450.00	90.00	90.00	180.00
system_l5	system_g	800.00	400.00	250.00	90.00	–90.00	–180.00
system_l6	system_g	800.00	–400.00	250.00	90.00	90.00	180.00
system_l7	system_g	600.00	400.00	500.00	90.00	–90.00	–180.00
system_l8	system_g	600.00	–400.00	500.00	90.00	90.00	180.00

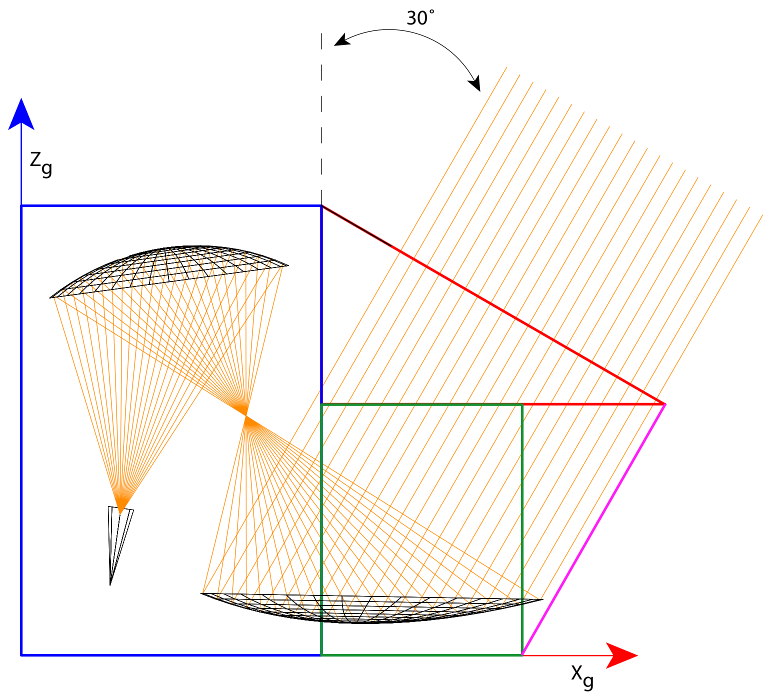

Figure 2: Structure geometry.

Table 4: Rectangular rims.

Reflector	Side Lengths X (mm)	Side Lengths Y (mm)
reflector_b	1000.00	800.00
reflector_d	900.00	800.00
reflector_t	600.00	800.00
reflector_fb	577.35	800.00
reflector_ft	200.00	800.00
reflector_l3	600.00	900.00
reflector_l4	600.00	900.00
reflector_l5	400.00	500.00
reflector_l6	400.00	500.00

Table 5: Triangular rims.

Reflector	Corner 1		Corner 2		Corner 3	
	X (mm)	Y (mm)	X (mm)	Y (mm)	X (mm)	Y (mm)
reflector_l1	0.00	0.00	–288.68	–500.00	0.00	–500.00
reflector_l2	0.00	0.00	–288.68	500.00	0.00	500.00
reflector_l7	0.00	0.00	–688.68	0.00	0.00	–400.00
reflector_l8	0.00	0.00	–688.68	0.00	0.00	400.00

3 Optical Simulations

The simulations are performed by considering the feed as a source and by computing the pattern scattered by both reflectors on the far field using GRASP8. The main beam simulations have been performed using Physical Optics (PO) and Physical Theory of Diffraction (PTD) on both reflectors. The full beam at the lower frequency, without considering the structure surrounding the telescope, has been computed with PO/PTD on both reflectors [1]. The most relevant contributions in the sidelobe region have been computed using Multi-Reflector Geometrical Theory of Diffraction (MrGTD) taking into account the shielding structure.

3.1 Main Beam

Main beams have been computed assuming a Gaussian feed with a taper of 30 dB at 25 degrees (about 22.5 dB at 22 degrees) located in the centre of the focal surface. Co– and cross– polar components are shown in Fig. 3 and the relevant characteristics are reported in Tab. 6.

Table 6: Main beam characteristics of the Gaussian feed horns at 35, 44, and 94 GHz (ET 30.0 dB @ 25°) X polarised. The angular resolution (FWHM), the ellipticity (e), the directivity ($\mathcal{D}$), the cross polar discrimination factor (XPD), and the main beam depolarization parameter (d) are reported.

ν (GHz)	FWHM (arcmin)	e	τ (°)	$\mathcal{D}$ (dBi)	XPD (dB)	d (%)
30	72.86	1.00	0.0	44.01	40.41	0.02
44	58.12	1.00	0.0	45.99	42.38	0.02
94	27.28	1.00	0.0	52.57	48.96	0.00

3.2 Sidelobes

The feed considered in these simulations is the 33 GHz feed horn specified by its spherical wave expansion provided by Alcatel Space Industries for PLANCK LFI. Among the available LFI feed horn models, this one has the higher sidelobe and can be considered as a *worst case*. Furthermore, at this frequency a full PO analysis (without considering the shielding structure) is still possible.

In Fig. 4 the co– and cross– polar components of the resulting 4π beam are shown. The main beam pointing direction is at about $\phi \simeq 0°$ and $\theta \simeq 30°$ and the straylight is mainly due to the feed sidelobe (at about –50 dB) coming directly in the far field without any interaction with the reflectors. This relevant contribution has been computed separately considering the effect of the structure around the telescope. The results are reported in Fig. 6 with (and without) considering the front-top shield.

In Figures 9 – 12 are reported the relevant contributions in the planes with ϕ equal to 0, 45, 90, and 135 degrees.

[1]The *po_points* used in the simulations are: $po1 = 80$ and $po2 = ptd = 320$ on the sub reflector and $po1 = 160$ and $po2 = ptd = 640$ on the sub reflector.

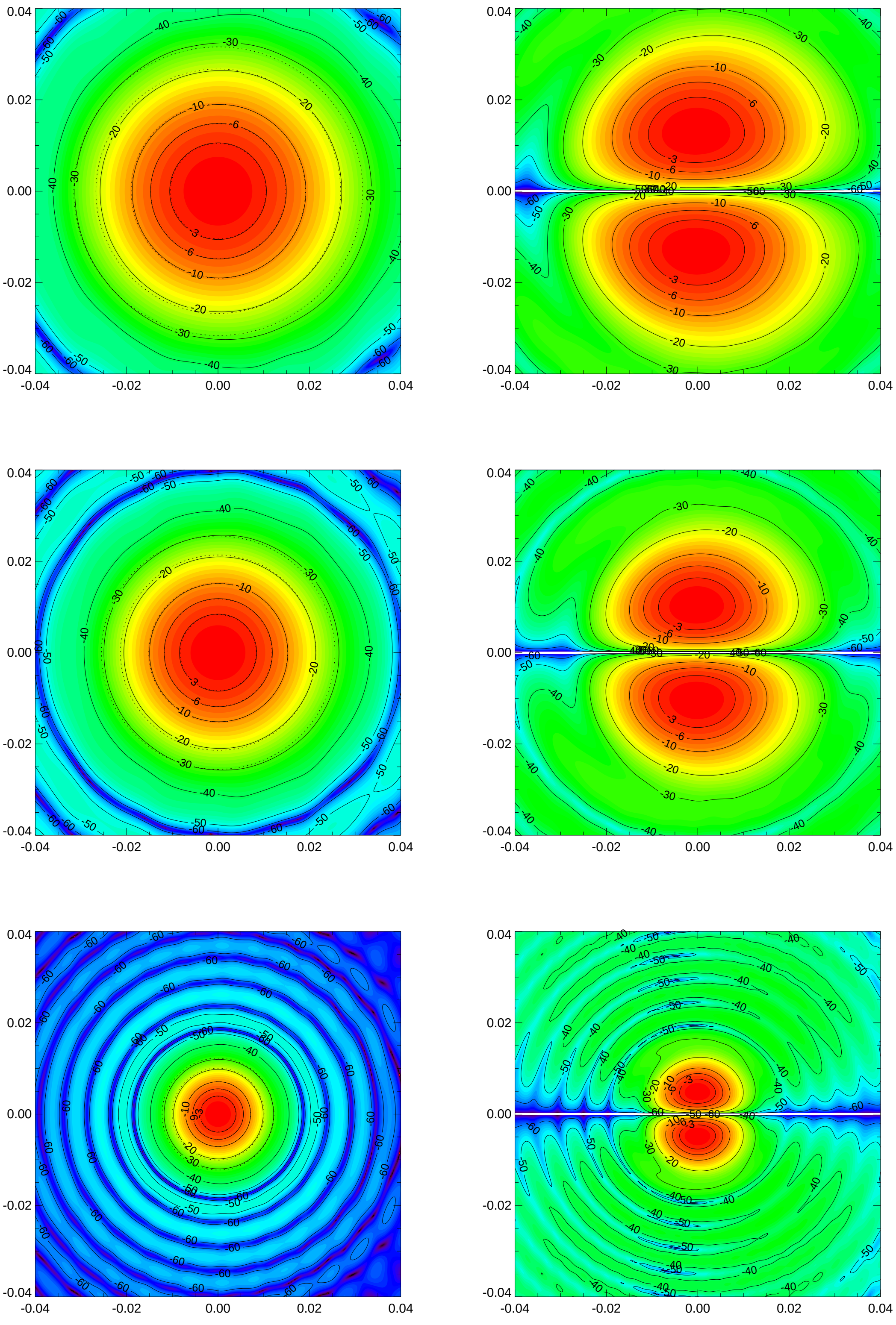

Figure 3: Co– and cross– polar components of the main beams at 35, 44, and 94 GHz.

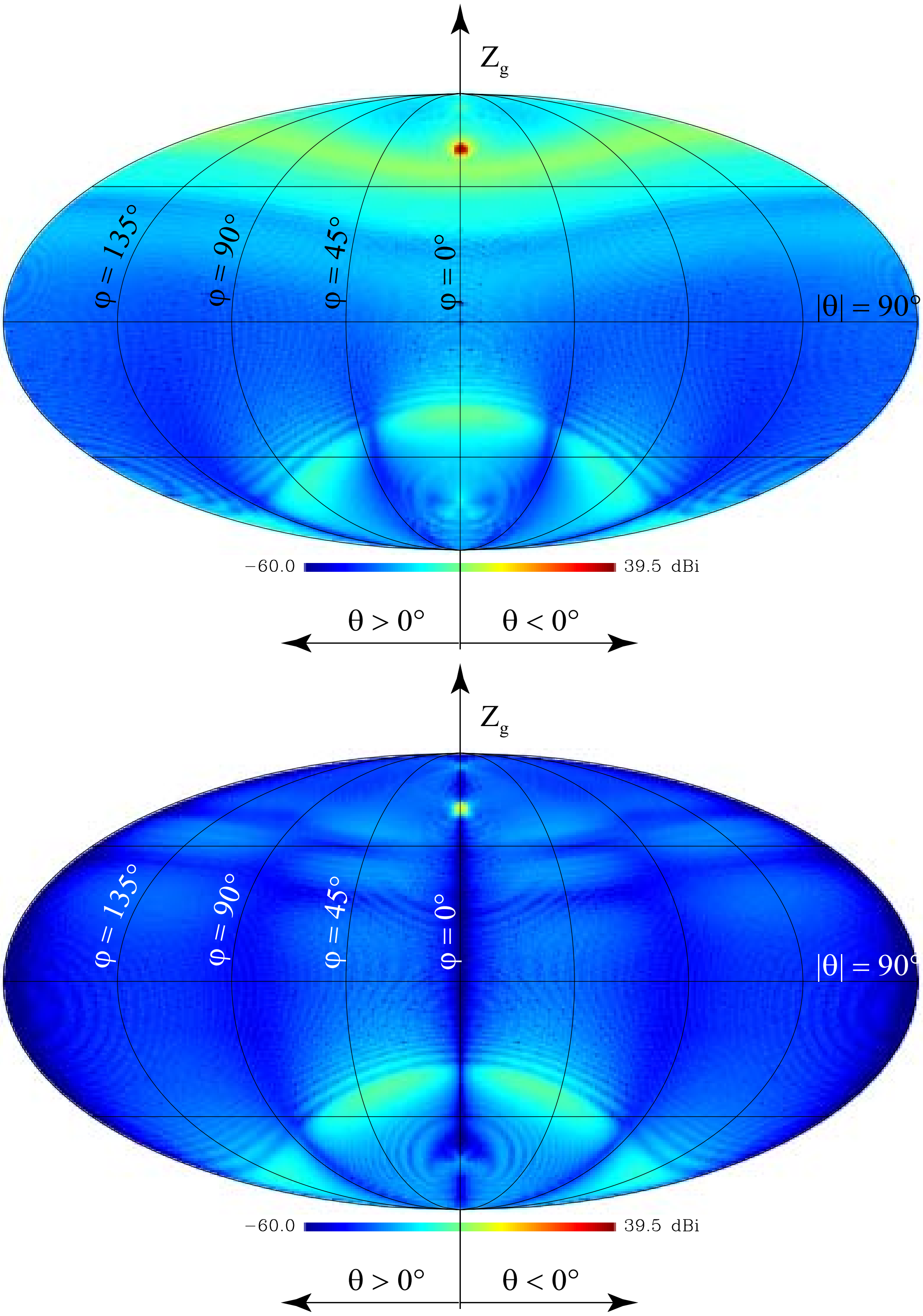

Figure 4: Co– and cross– polar component of the beam computed with PO/PTD, without shields.

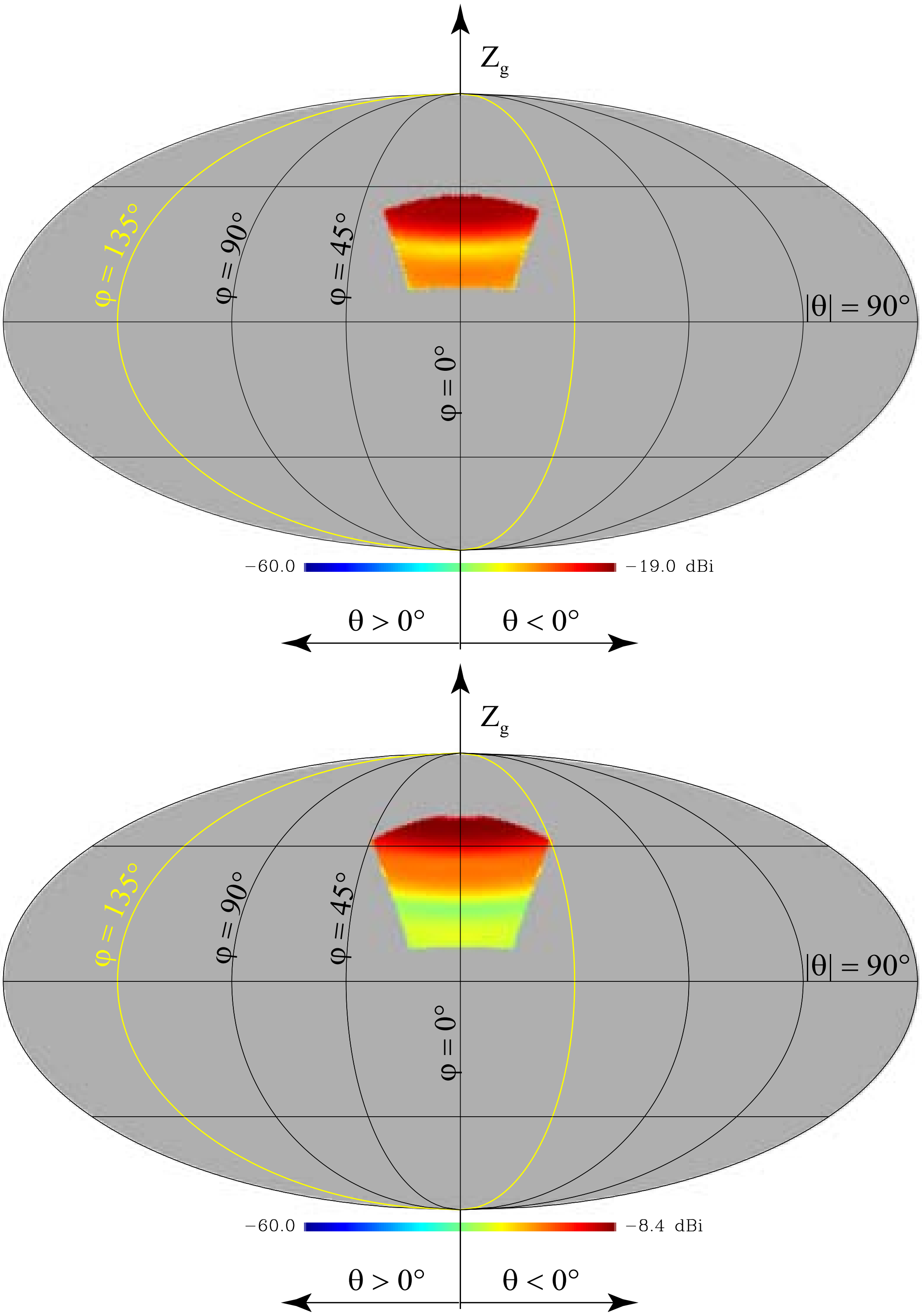

Figure 5: Co– polar component of the MrGTD contribution due to the rays coming directly from the feed with (*top panel*) and without (*bottom panel*) considering the rectangular shield (`reflector_ft`) at the top of the structure.

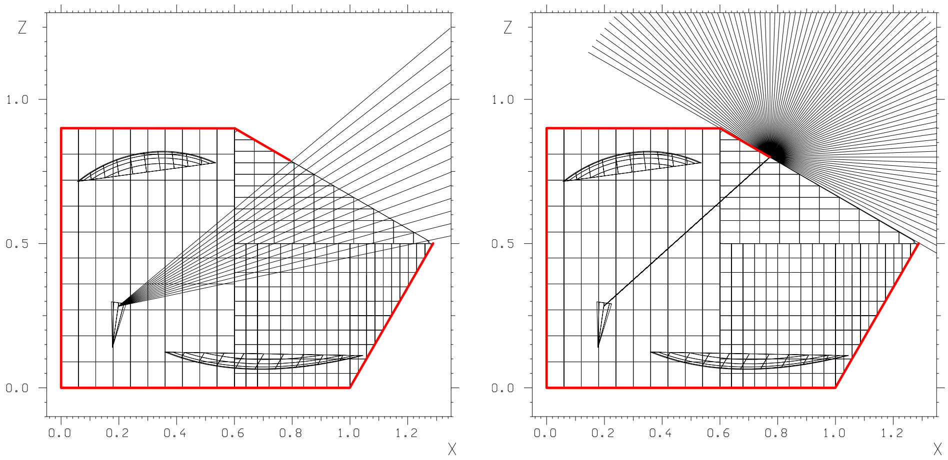

Figure 6: *Left side*: direct contribution from the feed. *Right side*: contribution due to diffracted rays from the front-top panel (`Dft`).

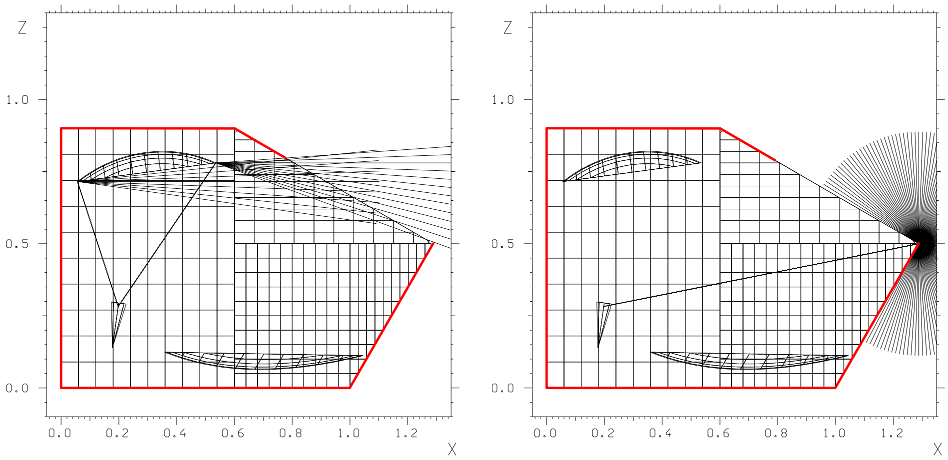

Figure 7: *Left side*: contribution due to diffracted rays from the sub reflector (`Ds`). *Right side*: contribution due to diffracted rays from the front-bottom panel (`Dfb`).

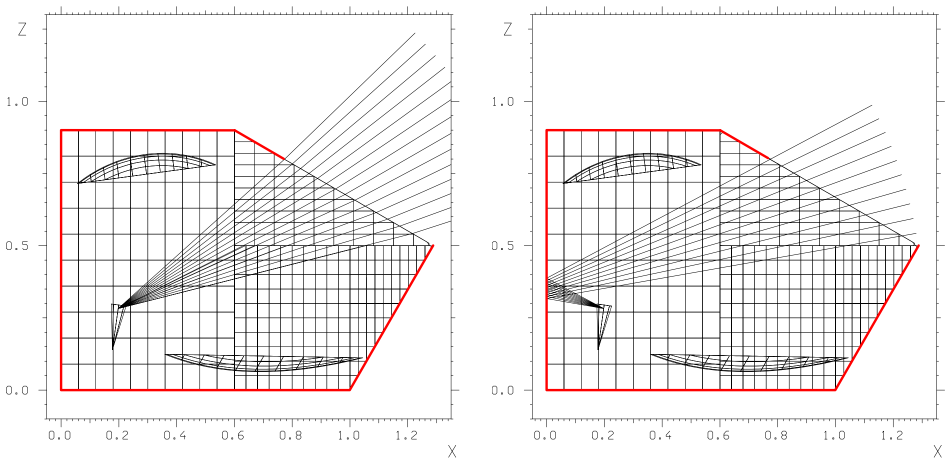

Figure 8: *Left side*: contribution due to diffracted rays from the lateral panel (`Dl7`). *Right side*: contribution due to rays reflected by the panel `reflector_d (Rd)`.

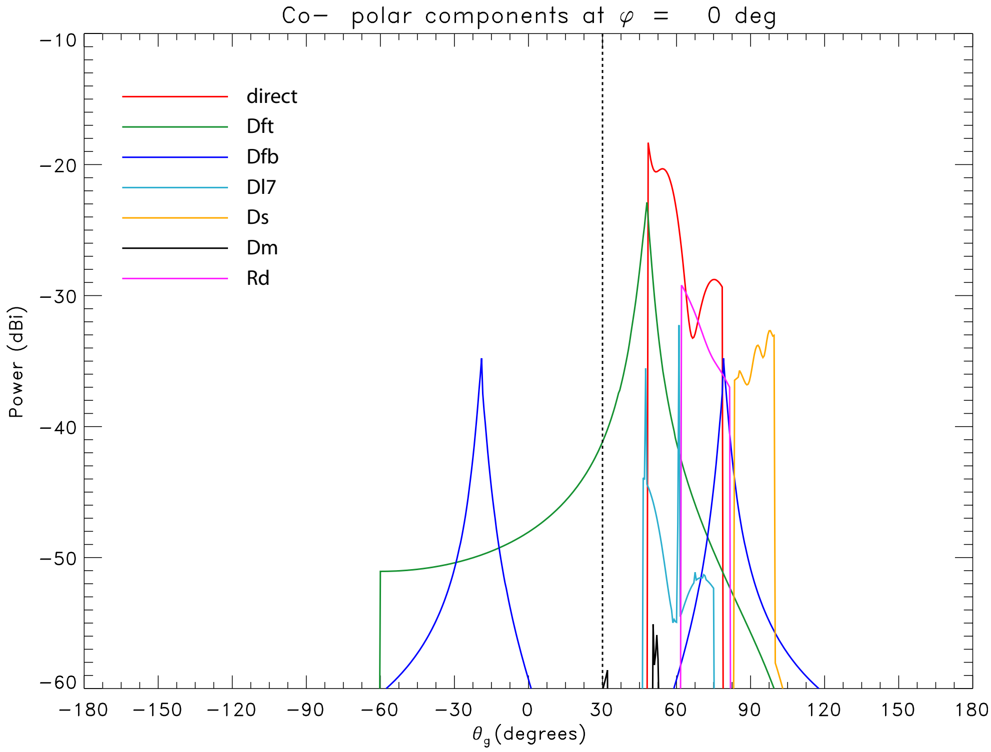

Figure 9: Relevant MrGTD contributions in the plane $\phi = 0°$.

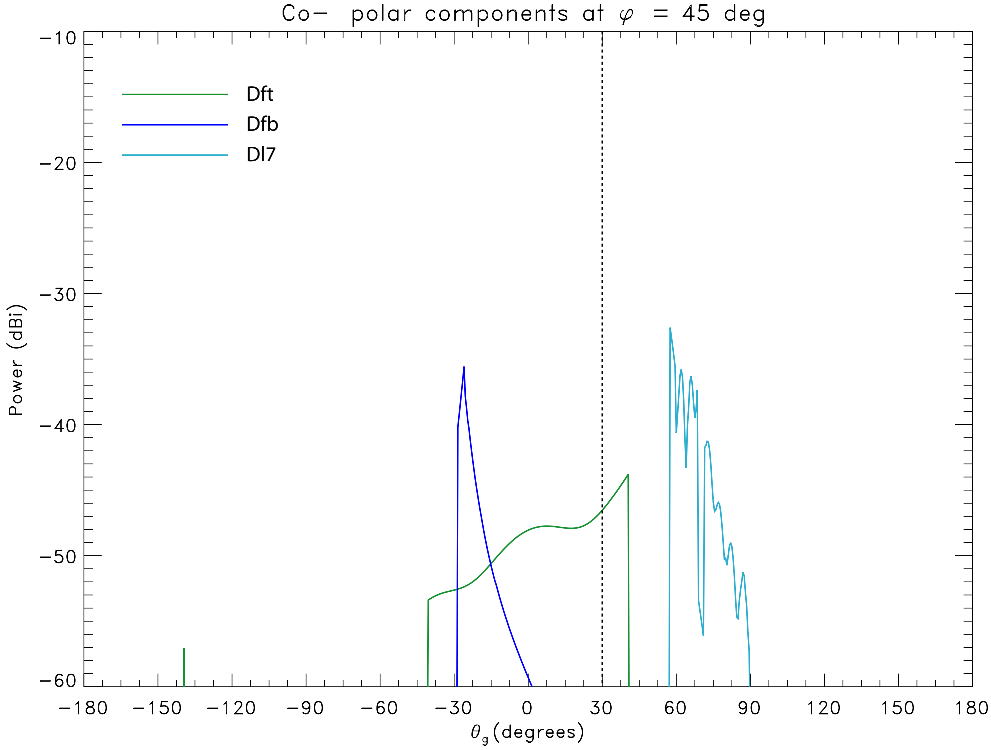

Figure 10: Relevant MrGTD contributions in the plane $\phi = 45°$.

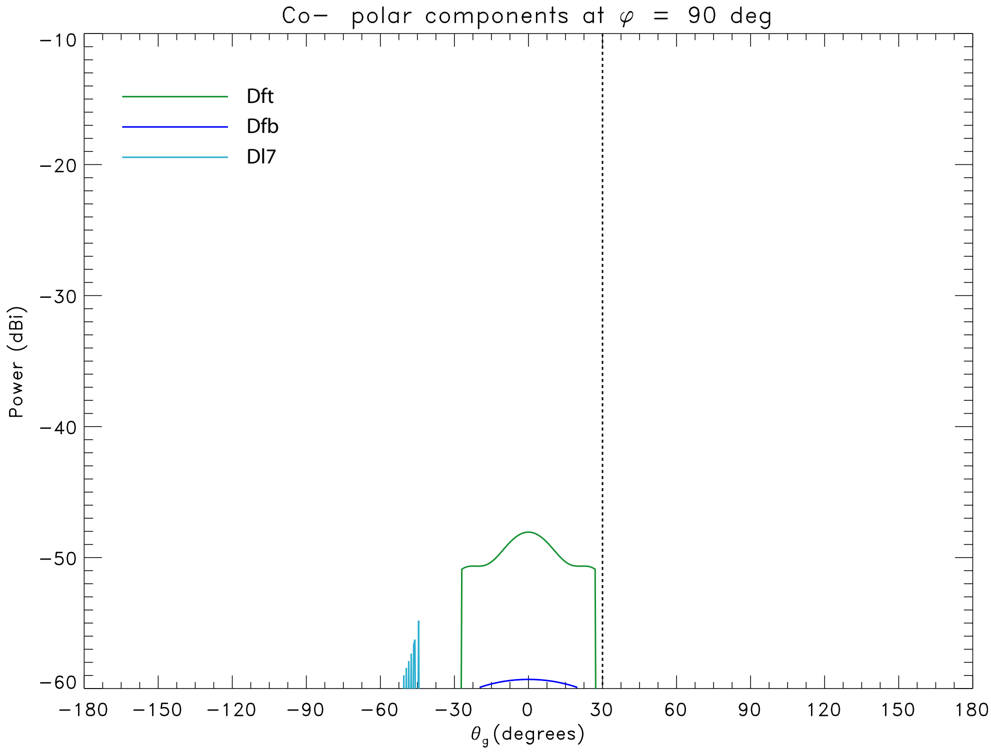

Figure 11: Relevant MrGTD contributions in the plane $\phi = 90°$.

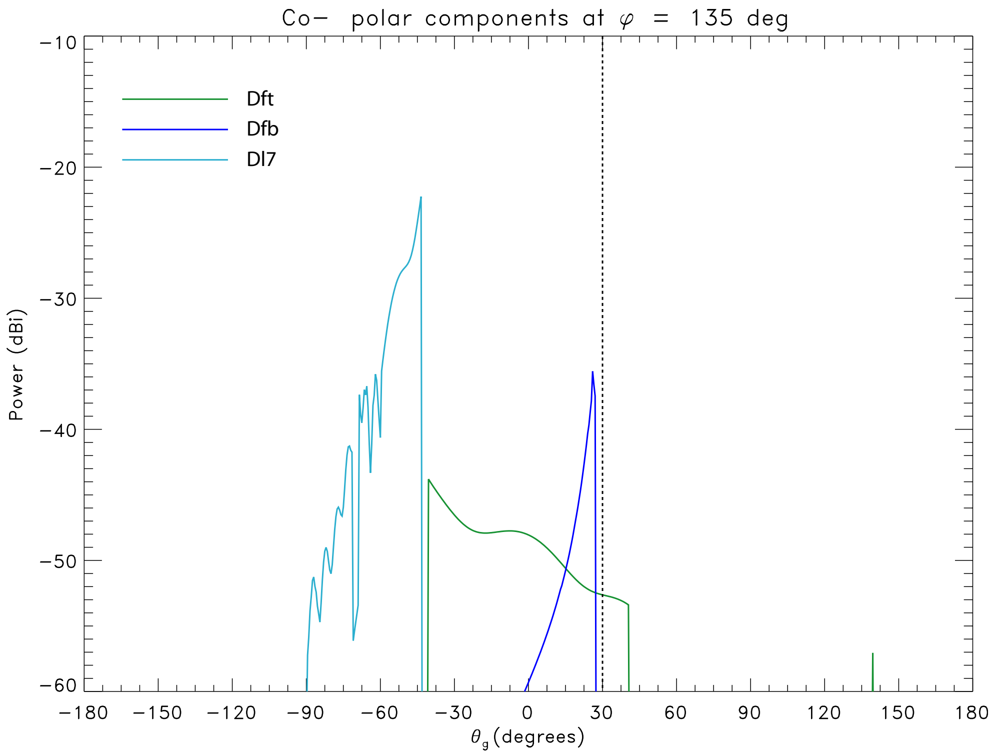

Figure 12: Relevant MrGTD contributions in the plane $\phi = 135°$.

3.3 Focal Surface Evaluation

The focal surface has been evaluated minimizing the weighted wave front error:

$$WFE_{rms} = \sqrt{\frac{\sum_n (L_n^2 T_n)}{\sum_n T_n} - \left(\frac{\sum_n (L_n T_n)}{\sum_n T_n}\right)^2}$$

where L_n is the optical path length ($n < 6.000$) computed with GRASP8 and T_n is the taper applied to each ray according to:

$$T_n = e^{-\frac{\tan^2 \theta_n}{2\sigma^2}}.$$

The plane wave incoming directions considered in this analysis are $0.08 < u, v < 0.08$.

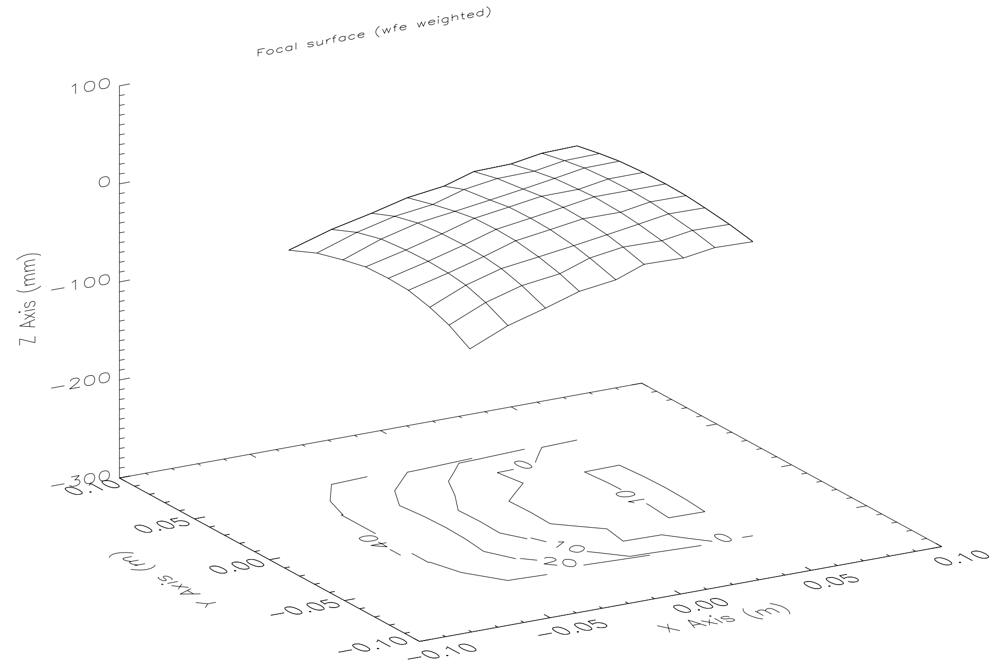

Figure 13: Focal surface that minimize the weighted wave front error.

3.4 Discussion and Conclusions

A Gregorian off-axis configuration, satisfing the *Dragone-Mizuguchi* condition, has been designed as a test case for the B-POL telescope, starting from the size of the projected aperture, the location of the focal plane unit, and the requirement of a quite large focal surface. For this configuration, main beams have been computed at 35, 45, and 94 GHz assuming Gaussian feed horns located in the centre of the focal surface. At the lower frequency, the full beam has been computed using a realistic feed horn pattern (the 30 GHz LFI feed horn defined by its spherical wave expansion) with PO/PTD analysis.

A structure around the telescope has been analysed. For this configuration a preliminary optical study has been evaluated computing some relevant MrGTD contributions. The direct radiation coming from the feed seems to be the main contribution in the far field, except the main beam. So, the feed pattern has to be accurately control in the design phase.

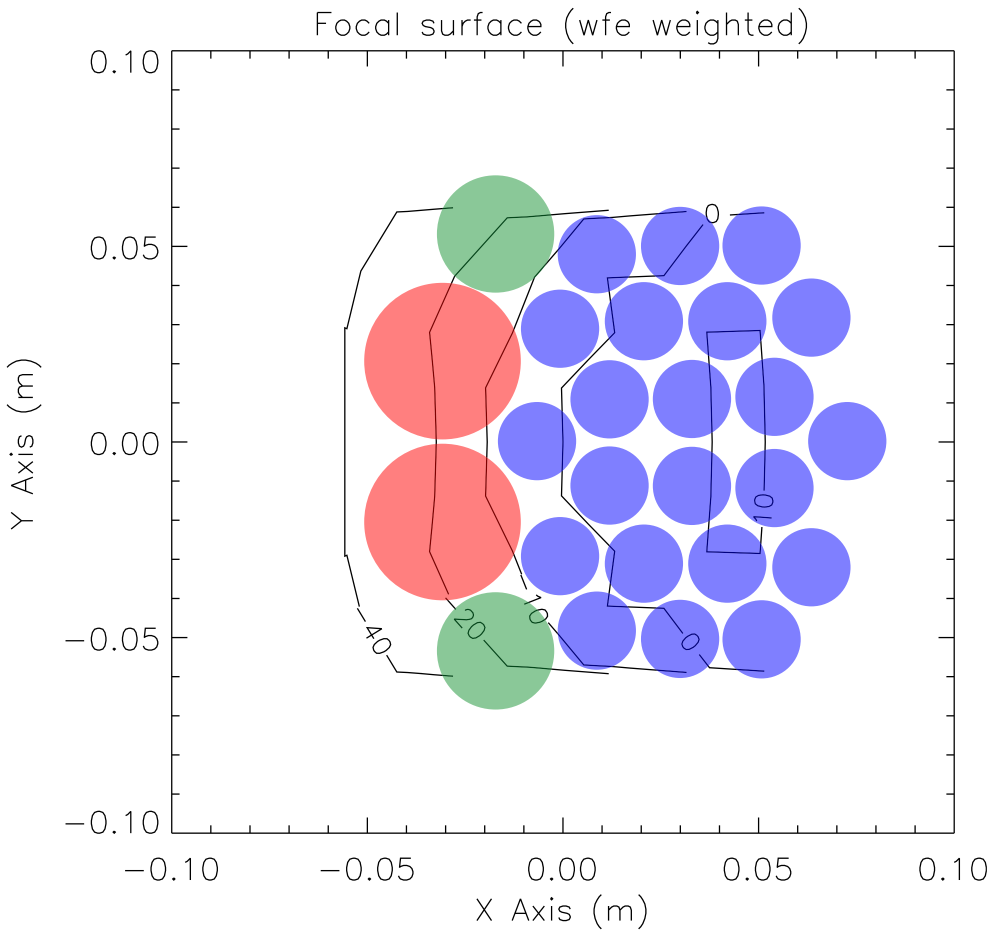

Figure 14: A possible focal plane with 2 feed horns at 35 GHz (in red), 2 feed horns at 45 GHz (in green), and 22 feed horns at 94 GHz (in blue).

The focal surface of the telescope has been evaluated minimizing the weighted wave front error. On this surface 26 feed horns (2 at 35 GHz, 2 at 45 GHz, and 22 at 94 GHz) have been located, as example of a possible focal plane unit.

Before going on any further, the telescope should be optimized. Moreover, the geometry of the structure surrounding the telescope has been designed taking into accoung the feed located in the centre of the focal surface and the dimension and tilt of the frontal panels should be changed.

4 References

1. F. Villa, M. Bersanelli, N. Mandolesi, L. Valenziano, 1997, *New Design of* PLANCK *Telescope*, Internal Report ITESRE 197/1997

2. Knud Pontoppidan, 1999, *Technical Description of GRASP8*, TICRA. Doc.No.S-894-02