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A NOTE ON THE PLANCK APLANATIC TELESCOPE

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SUMMARY — The optimization of the Planck telescope is one of the purposes of the Planck Teams before the start of the mission Phase B. We have studied an Aplanatic solution that shows significant improvements in the main beam properties with respect to the Dragone-Mizuguchi Gregorian configuration, without degrading the sidelobe contamination. We present in this note a preliminary analisys.

1 Introduction

The optimization of the Planck telescope is one of the goals of the Planck Teams. Among other possible design configurations, an alternative to the Dragone-Mizuguchi Gregorian off-axis solution (in short "Standard") is represented by the Aplanatic Gregorian design (in short "Aplanatic") firstly proposed by Mark Dragovan and the LFI Consortium. This new solution is obtained by changing the conic constants of both mirrors in order to satisfy the Aplanatic Condition. This arrangement of the mirrors (both ellipsoids of rotation) permits to reduce the coma and the spherical aberrations on a large portion of the focal surface.

In this report the far field beams of an Aplanatic configuration have been calculated in order to evaluate which telescope design is better for the Planck scientific objectives.

The Aplanatic configuration is examined for beam tests only and has to be considered a preliminary first design, more than an engineering project.

2 The RAPA Software

To analyze a general dual reflector system a dedicated software has been implemented at Istituto TESRE/CNR. The software called RAPA (Reflector Antenna Pattern Analysis) has been written on ©Macro-PLUS and FORTRAN 77 languages. The code calculates the amplitude and phase distribution on a regular grid of points on the tilted aperture plane (normal to azimuth and elevation directions on the sky).

The amplitude is calculated starting from the feed pattern and takes into account the space attenuation.

The phase is derived by calculating the path length of each ray, from the corresponding point on the aperture plane grid up to the focal point previously calculated (minimizing the wave front error of the spot diagram). Given the path length, the phase can be written as:

$$\delta = \frac{2\pi}{\lambda} \cdot (P - P_0) \tag{1}$$

where P is the path length of a ray starting from a grid point, P_0 is the path length of the chief ray, and λ is the wavelength.

Performing the Fourier Transform of the spatial phase-amplitude distribution on the aperture plane, the far field radiation pattern is readily obtained. When δ is always set to zero, the pattern is symmetric around the view direction. For the Dragone-Mizuguchi telescope this condition is verified on the center of the focal surface only and, in this case, the system is equivalent to an on-axis parabola. In general, outside the focal center, a phase error on the aperture is present and optical aberrations will appear.

The flow chart of the RAPA package is reported in figure 1. The focal point is automatically calculated. Manual input can be required (suitable for decentering tollerances analysis). The feed module subroutine requires an analytical amplitude pattern function of the primary illumination.

3 Aplanatic Design

To minimize the off-axis aberrations a different shape of the mirrors is needed. A solution is to design an Aplanatic (off-axis) telescope where the conic constants of the mirrors are adjusted in a way that minimize the spherical and coma distortions. The conic constants are chosen in order to satisfy the following equations (subfix 1 and 2 are referred to the main- and sub- reflector):

$$(k_{s1})_{aplan} = -1 - \frac{2L}{d_1 m_2^3} \tag{2}$$

$$(k_{s2})_{aplan} = -\left[\left(\frac{m_2 - 1}{m_2 + 1}\right)^2 + \frac{2f'}{d_1 (m_2 + 1)^3}\right] \tag{3}$$

or involving the conic constants of the classical telescope

$$(k_{s1})_{aplan} = (k_{s1})_{cl} - \frac{2L}{d_1 m_2^3} \tag{4}$$

$$(k_{s2})_{aplan} = (k_{s2})_{cl} - \frac{2f'}{d_1 (m_2 + 1)^3} \tag{5}$$

Table 1: Characteristics of the Aplanatic Telescopes

1.5 meter Aperture	
Main Refl. Diameter	1492.40 mm
Main Refl. Focal length	831.421 mm
Overall Focal Length	2078.578 mm
Focal Ratio	1.39
1.3 meter aperture	
Main Refl. Diameter	1292.40 mm
Main Refl. Focal length	720.00 mm
Overall Focal Length	1800.00 mm
Focal Ratio	1.39

where m_2 is the magnification of the secondary mirror, f' is the overall focal length, d_1 is the distance from the mirror vertex, and L is the distance between the vertex of the subreflector and the on-axis focal point.

An off-axis Aplanatic telescope has been designed in order to analyze the main beam shape as a function of the feed position on the focal surface. The characteristics of the design are reported in table 1. The effects on the reflector rim have not studied here. For the main beam shape these effects are quite small.

4 Beam Calculations

Far field beam shapes have been calculated with RAPA at different elevations and azimuths. The contour plots of the normalized patterns of the two Aplanatic configurations are showed in the figures 3, 4, 5, 6, 7, 8, 9, 10, 11. The beams of the Standard 1.3 m Gregorian off-axis telescope are also showed in order to compare the results. Each figure reports a normalized contour plot of the pattern in the azimuth-elevation plane, in radians, approximately centered on the relative beam axis. Each plate covers an angular area of about $1^\circ \times 1^\circ$. The contour lines from -3dB down to -70dB are also displayed. The beams of the 1.5 m Standard telescope are not displayed.

All simulations have been done by considering the $\cos^N(\theta)$ primary pattern with $N = 91$ (for the Standard 1.3 m configuration this gives an edge taper of -30 dB at 22° of angle).

5 Estimate of effective resolutions of the simulated beams

In order to quantify the impact on the effective angular resolution, $\mathrm{FWHM_{eff}}$, of the beams in CMB anisotropy measurements we have compared convolutions of a CDM anisotropy sky with the simulated beams and with a suitable grid of gaussian symmetric beams (see Burigana et al. 1998 and Mandolesi et al. 1997, section 3.2, for further details on the method). In figure 12 we summarize our results for four configurations: two Standard configurations with 1292.4 mm and 1492.4 mm aperture and two Aplanatic configurations with 1292.4 mm and 1492.4 mm aperture. Note that the August 1998 ESA Baseline Planck telescope is a 1492.4 m aperture Gregorian telescope with the secondary (position, shape and size) still optimized for the 1.3 m Standard configuration: the main beam resolution is equivalent to the 1.3 m Standard telescope.

The average of the $FWHM_{eff}$ in the relevant regions (between ~ -2.5 and ~ 2.5 degrees for the 1.3m telescopes and between ~ -2 and ~ 2 degrees for the 1.5m telescopes) are similar for Standard and Aplanatic configurations with same aperture. On the other hand the $FWHM_{eff}$ of beams located at angular distances from the center larger than about 1 degree is somewhat better for the Aplanatic configurations; in addition the spread of the $FWHM_{eff}$'s of the different beams is smaller for the Aplanatic configuration.

6 Conclusion

An Aplanatic telescope configuration has been studied as an alternative design of the Standard telescope for the Planck Surveyor mission. This preliminary study of the beam response on the sky has been performed in order to compare the far field aberrations of both telescope designs. We find that the Aplanatic beam shapes are more regular, and although elliptical, closer to gaussian shapes, due to the strong reduction of the coma. The effective resolutions of the different beams are on average similar for the two designs ($\simeq 10$ arcmin for the $\simeq 1.5$ m telescopes), but for the Aplanatic they improve (with respect to the Standard) for the positions typical of Planck (LFI and also HFI) feeds and the differences between the angular resolutions of the different feeds decrease.

In addition the Aplanatic configuration leads essentially unchanged the edge taper at the bottom edge of the main reflector (~ -30dB for the central feed) with respect to the Standard telescope and allows to improve the edge taper at the main reflector top edge (~ -40dB for the central feed), where the spillover radiation is not shielded. This will most probably lead to an improvement of the top edge straylight.

This preliminary study suggests that the Aplanatic configuration can represent a significant improvement in the main beam properties with respect to the Standard configuration, possibly decreasing the sidelobe contamination. Further studies which include straylight, focal surface and feed positioning optimization, and mirror shapes, need to be done.

7 References

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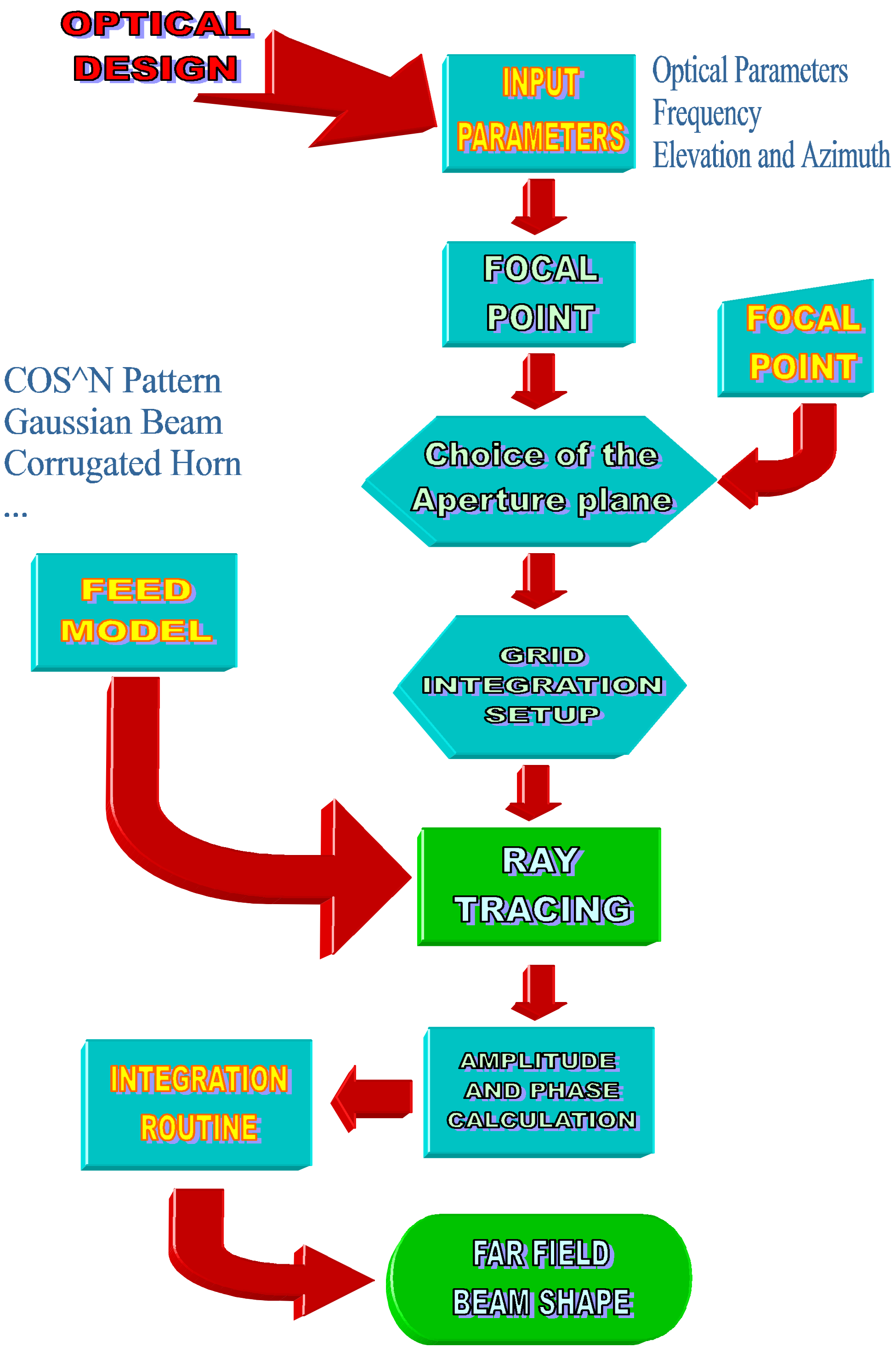
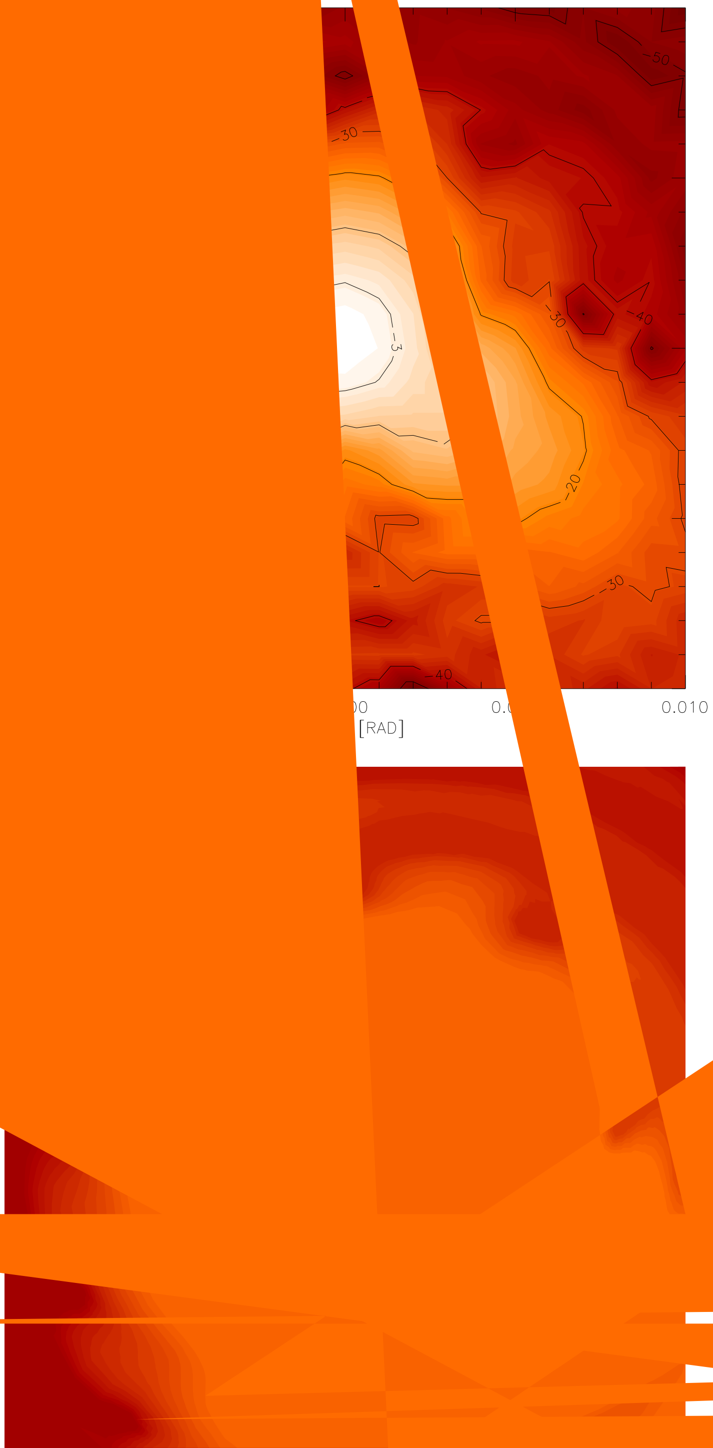


Figure 1: RAPA package flowchart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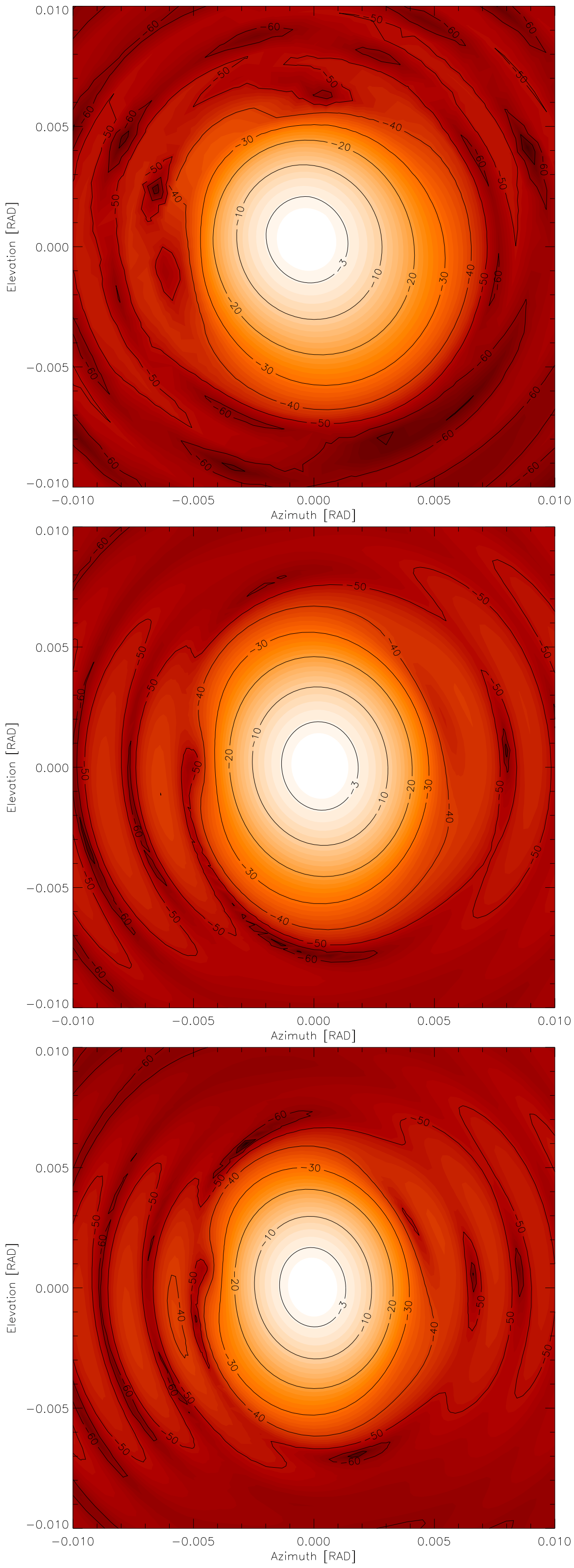

Figure 4: Elevation = −1, Azimuth = +1; Upper plate: Standard 1.3m. Middle plate: Aplanatic 1.3m. Lower plate: Aplanatic 1.5m.

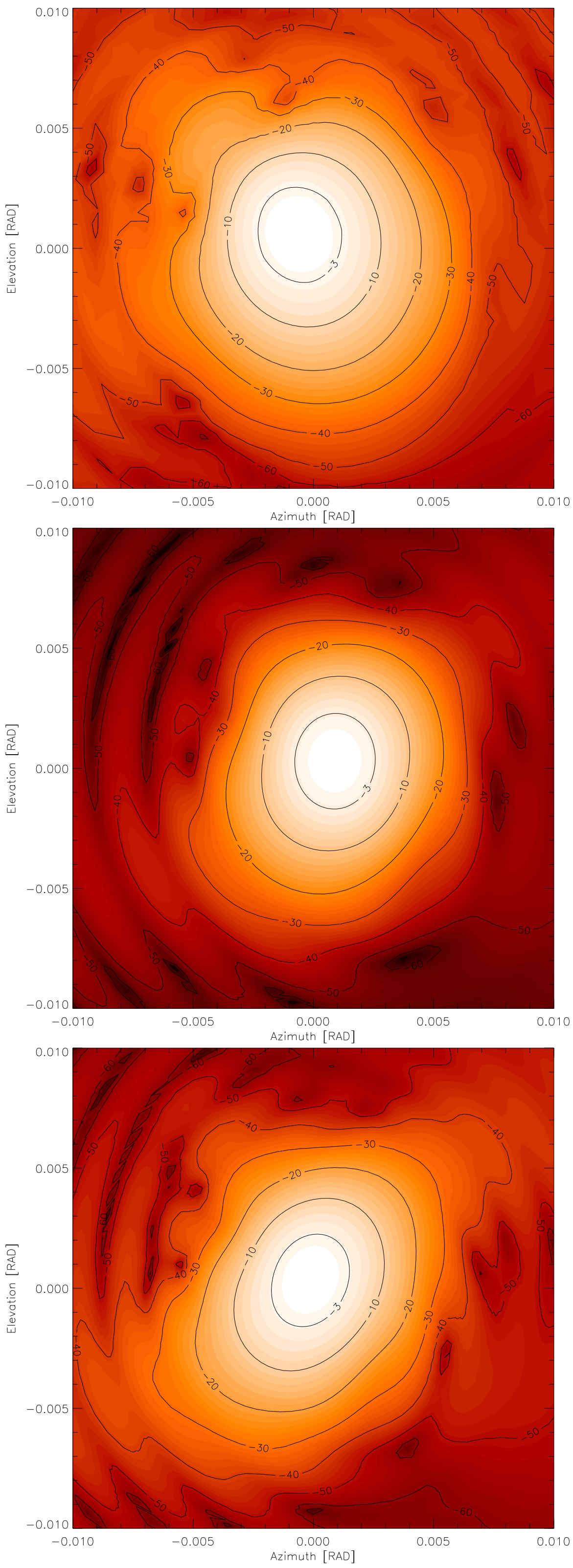

Figure 5: Elevation = −2, Azimuth = +2; Upper plate: Standard 1.3m. Middle plate: Aplanatic 1.3m. Lower plate: Aplanatic 1.5m.

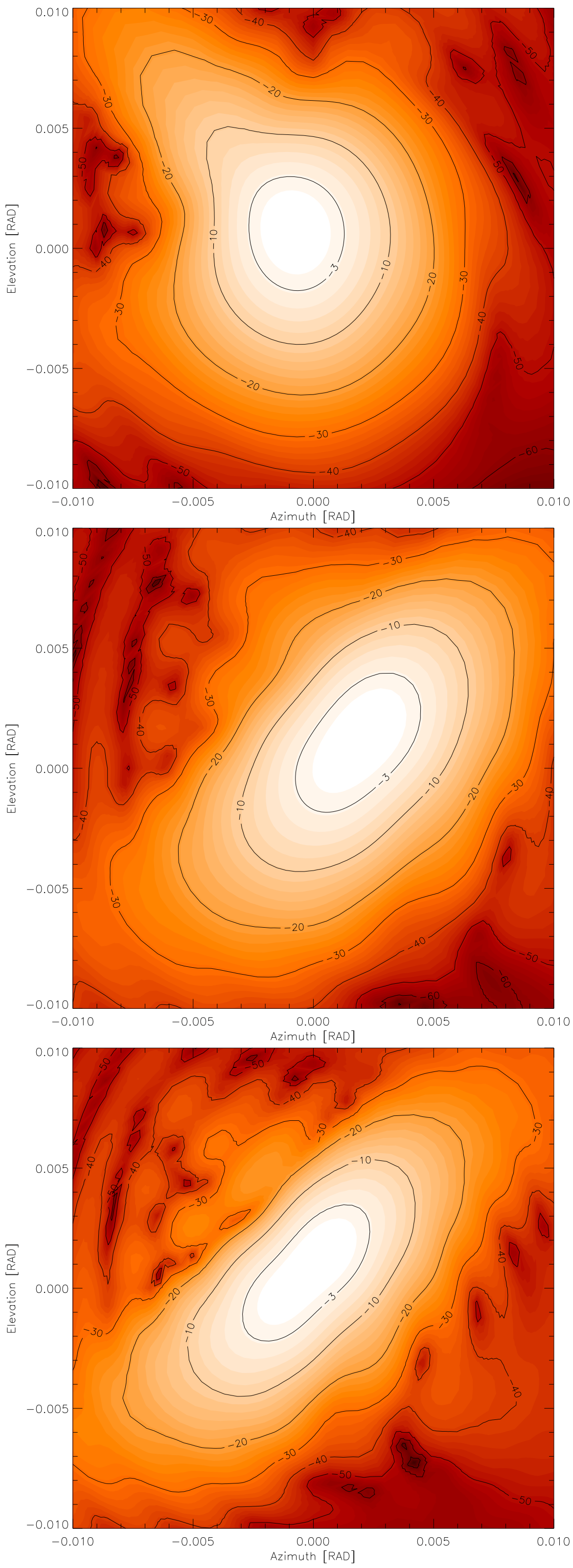

Figure 6: Elevation = −3, Azimuth = +3; Upper plate: Standard 1.3m. Middle plate: Aplanatic 1.3m. Lower plate: Aplanatic 1.5m.

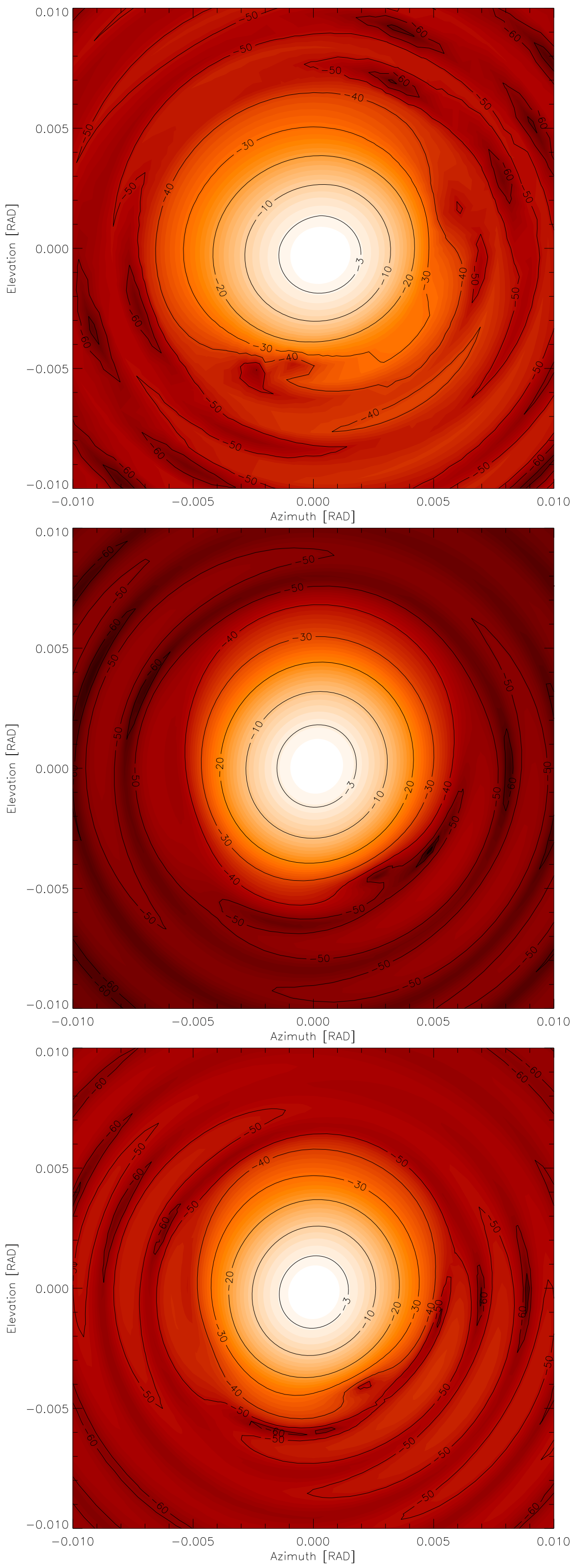

Figure 7: Elevation = +1, Azimuth = −1; Upper plate: Standard 1.3m. Middle plate: Aplanatic 1.3m. Lower plate: Aplanatic 1.5m.

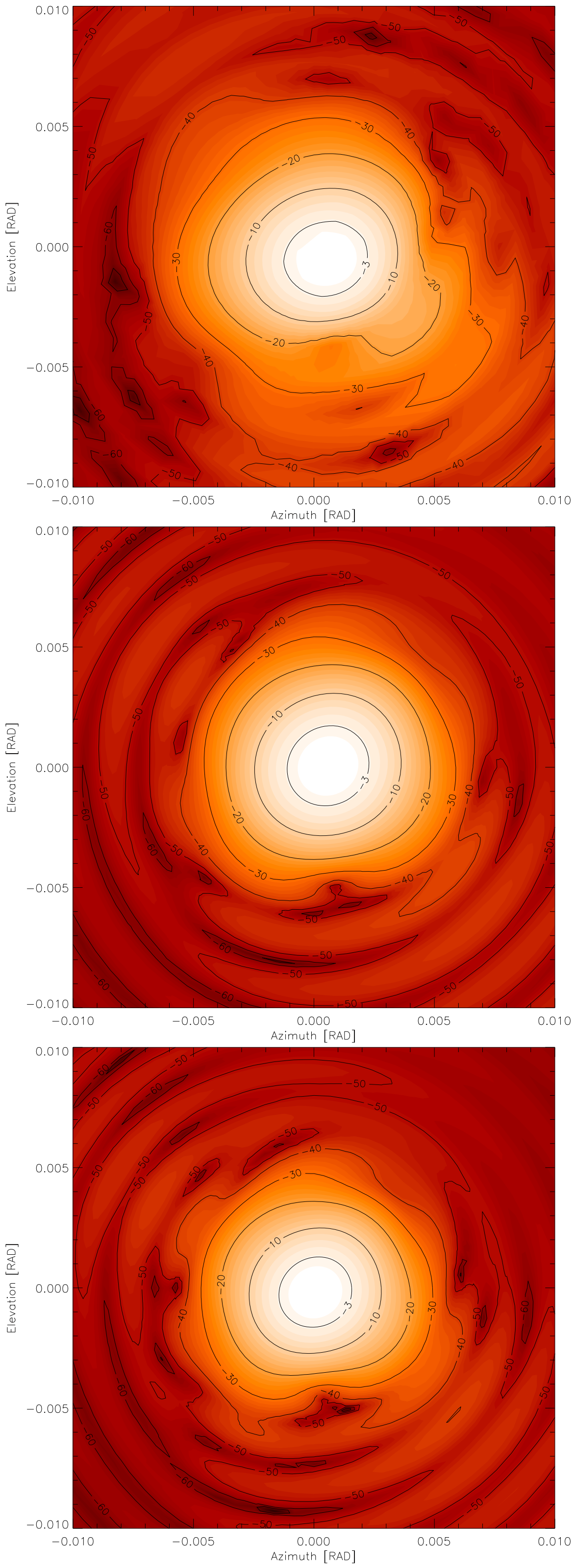

Figure 8: Elevation = +2, Azimuth = −2; Upper plate: Standard 1.3m. Middle plate: Aplanatic 1.3m. Lower plate: Aplanatic 1.5m.

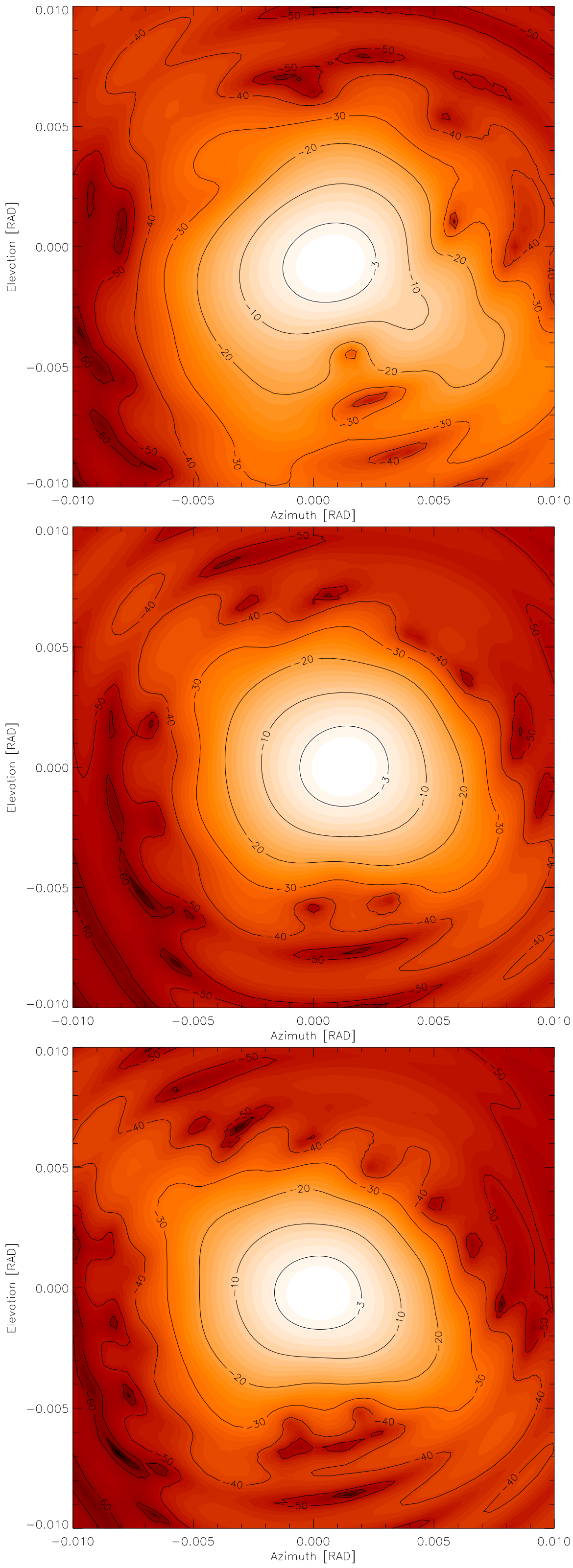

Figure 9: Elevation = +3, Azimuth = −3; Upper plate: Standard 1.3m. Middle plate: Aplanatic 1.3m. Lower plate: Aplanatic 1.5m

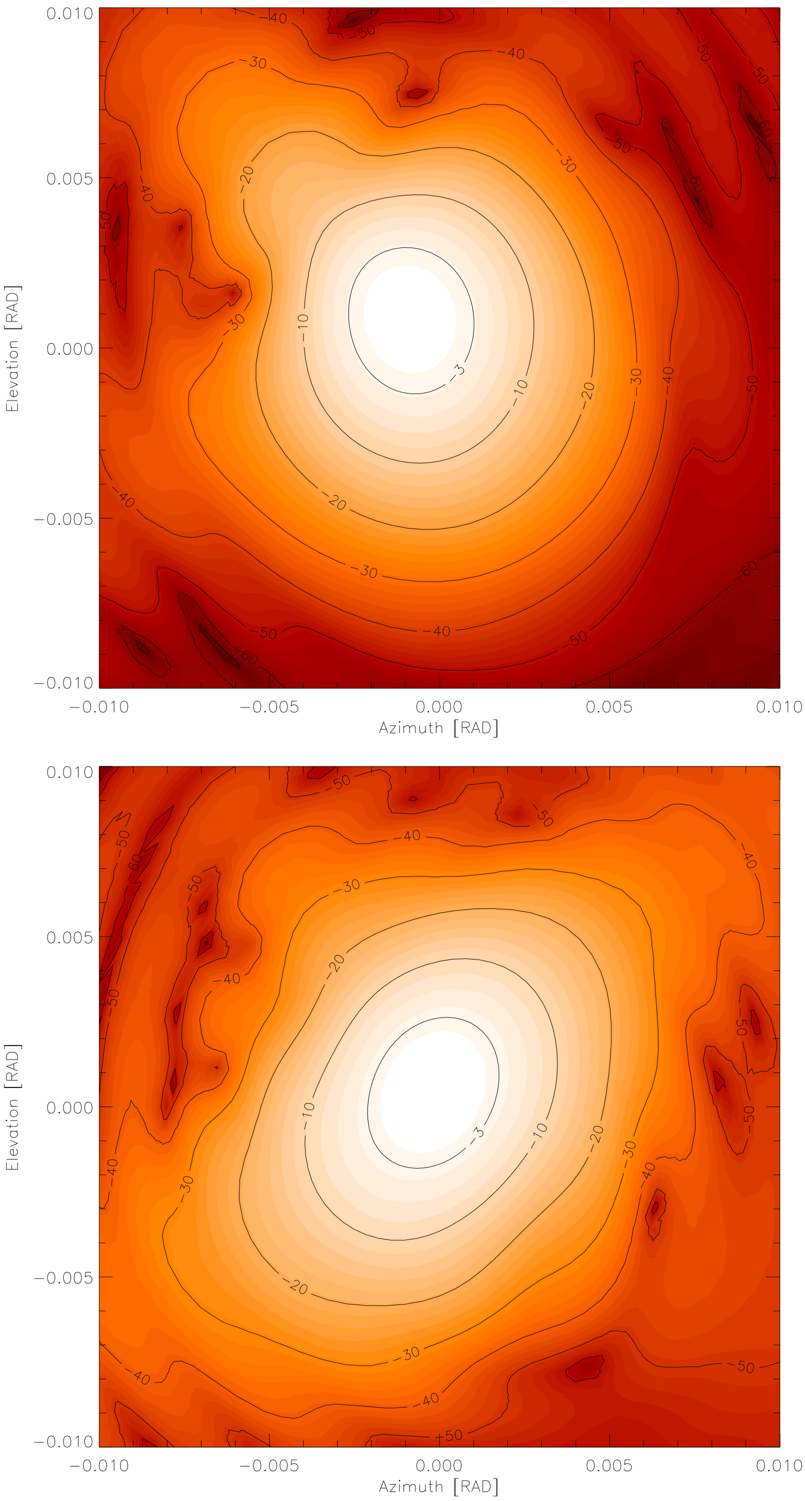

Figure 10: Elevation = −2.5, Azimuth = +2.5; Upper plate: Standard 1.3m. Lower plate: Aplanatic 1.3m.

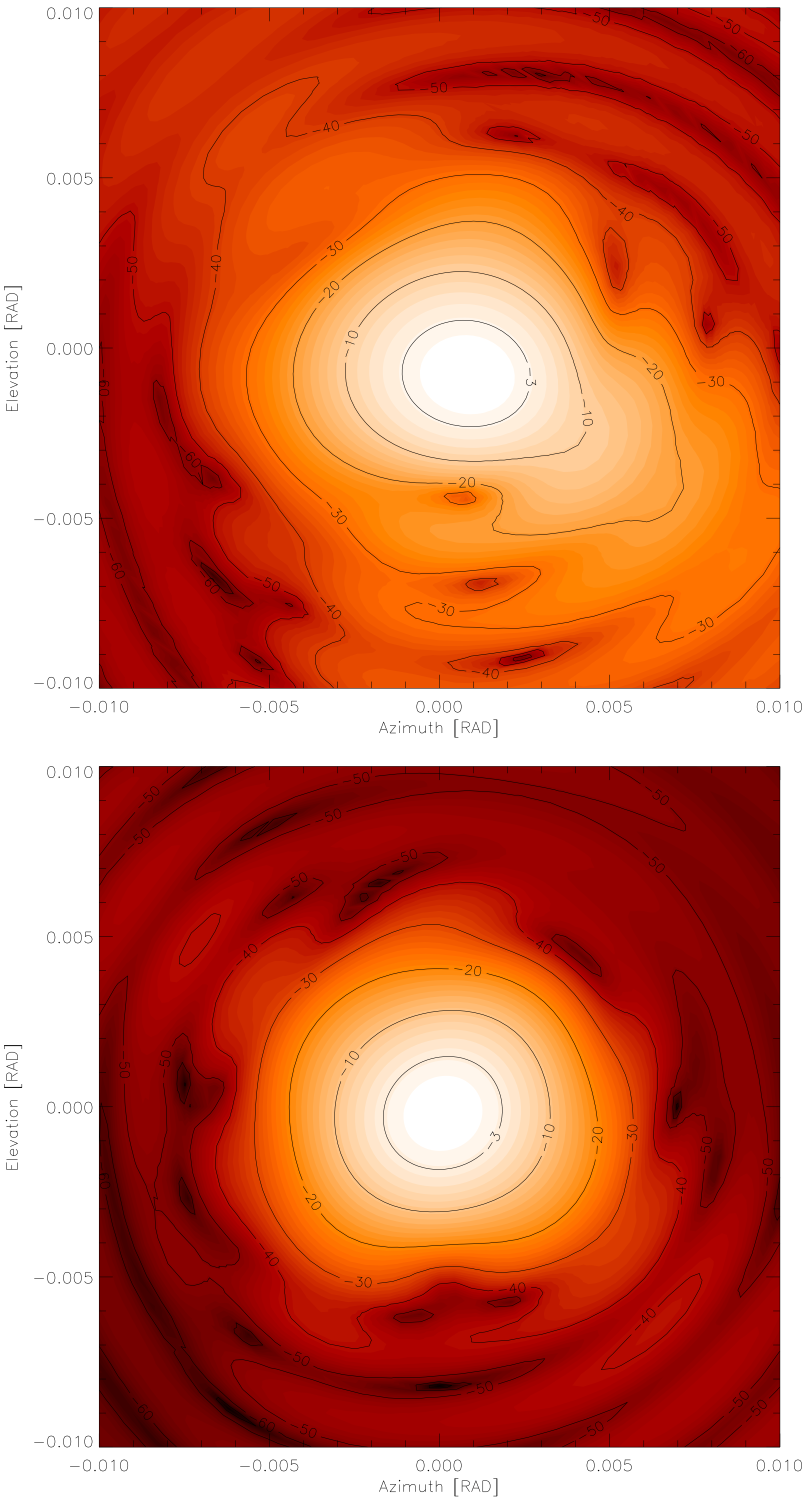

Figure 11: Elevation = +2.5, Azimuth = −2.5; Upper plate: Standard 1.3m. Lower plate: Aplanatic 1.3m.

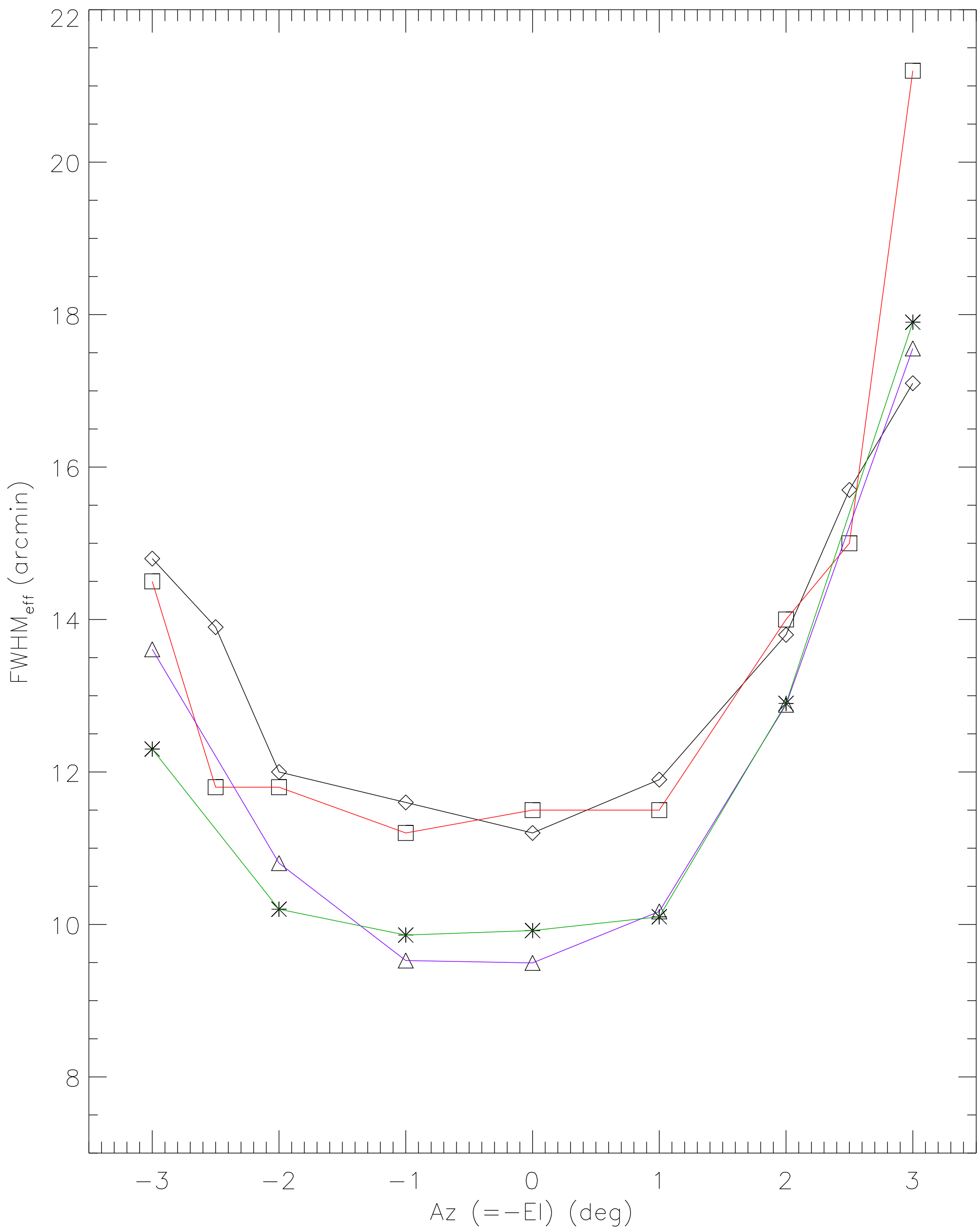

Figure 12: Effective angular resolutions, $FWHM_{eff}$, at different positions for four optical configurations: Standard, 1.3m aperture (diamonds, black line); Aplanatic, 1.3m aperture (squares, red line); Standard, 1.5m aperture (triangles, blue line); Aplanatic, 1.5m (asterisks, green line)