The Nulling Coronagraph

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Abstract

Adaptive Optics can yield to sharp PSFs in which the light distribution from the center of the PSF to a few Airy rings is dominated by the diffraction of light through the entrance pupil of the telescope. Using a Lyot coronagraph after an adaptive optics system can improve detection of light sources beyond the third Airy ring. The nulling coronagraph, first proposed by Roddier and Roddier (1997) uses a small mask (less than half the size of the central Airy spot) that shift the phase of the incoming light by 180 degrees, instead of blocking light as the mask used in a Lyot coronagraph. This leads to destructive interference which strongly attenuates the Airy spot as well as the rings. We report on both theoretical and laboratory performance. Unlike the Lyot coronagraph, the nulling coronagraph is able to strongly attenuate the first Airy rings, which are covered by the opaque mask in the Lyot coronagraph, while any light source farther than one Airy spot diameter from the optical axis is unaffected by the coronagraph. From the set of laboratory measurements, we derive estimates of the performance of a nulling coronagraph used on a telescope equipped with an adaptive optics system, based upon the performance of the University of Hawaii Adaptive Optics system. The University of Mexico made the mask and laboratory measurements were carried out at the Institute For Astronomy, University of Hawaii.

1. How the nulling coronagraph works

1.1. Overview of the Lyot and the nulling coronagraph

To understand how the nulling coronagraph works, one can compare it to a Lyot coronagraph. Figure 1 compares the two coronagraphs. The Lyot coronagraph, developed by Bernard Lyot for solar corona imaging (Lyot 1939), is the most common coronagraph used in astronomy. In this paper, we will consider stellar coronagraphs only. The Lyot stellar coronagraph uses an opaque mask in the image plane to remove almost all the light of the star (only the Airy rings outside the mask are still present). The mask is usually at least 3 Airy rings wide. Of course, at this point, no improvement has been made yet on the detection of faint light sources near the star, which is the purpose of a coronagraph.

To understand how the Lyot coronagraph works, the image of the star in the image plane has to be seen as being the Fourier transform of the pupil illumination (a uniformly bright disk). Putting a opaque mask on the central part of the Airy pattern removes the low frequency components of the Fourier transform of the pupil illumination. High frequency components of the Airy pattern are created by interference between points of the pupil that are far from each other, just as high frequency fringes are obtained by Young holes far from each other. Hence, putting an opaque mask on the center of the Airy pattern increases the relative intensity of the edges of the pupil in comparison to the center (the edge of the pupil corresponds to points that are farther away and is hence responsible for the high-frequency components of the Airy pattern).

The use of a stop in the second pupil plane (after the mask) can suppress the light contribution of the edge of the pupil to the final image. Hence, the Airy rings that were still present in the first image

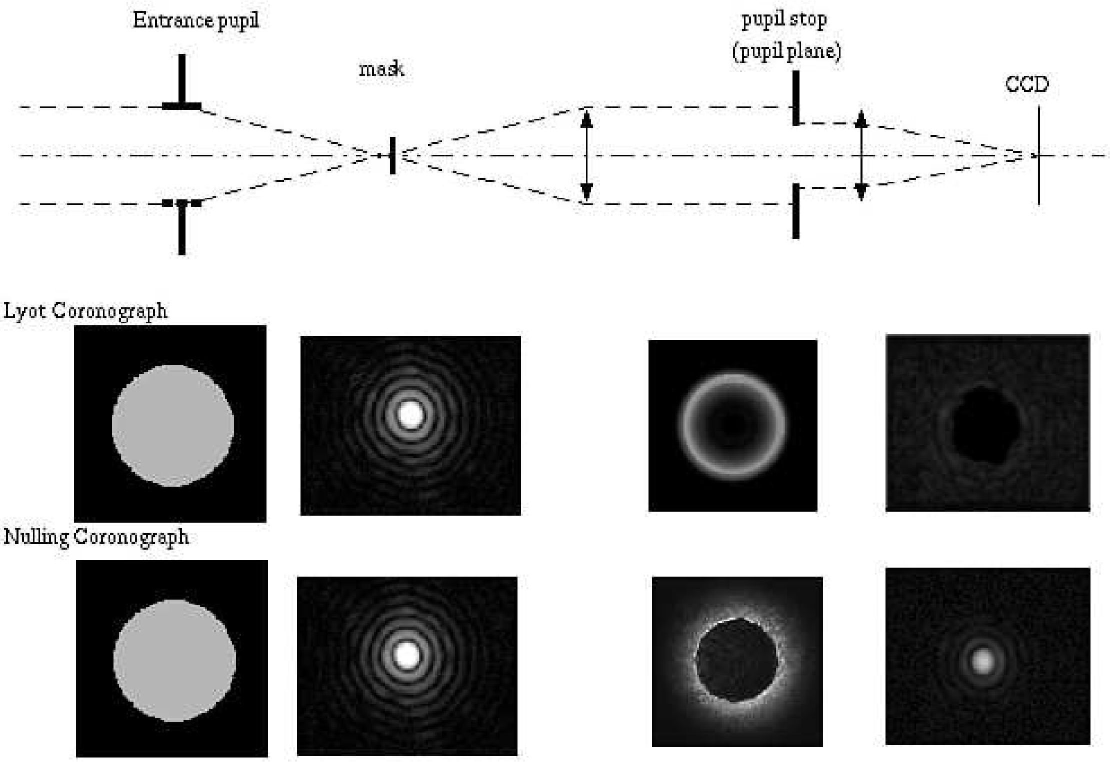


Figure 1: The Lyot coronagraph uses an opaque mask in the image plane while the nulling coronagraph uses a phase mask. Light repartition in the pupil is very different for the two coronagraphs: the light is concentrated on the inside edge of the pupil for the Lyot coronagraph while the phase mask puts the light of the occulted star outside the pupil.

plane, outside the mask, are attenuated. The final image of the occulted star will be a dark disk (the mask) surrounded by very faint diffraction rings. If a light source is far enough from the star so that its image is outside the mask, its light distribution in the second pupil plane will be a uniformly bright disk of light and the pupil stop will remove only a small fraction of its light. The offset light source will then be attenuated by a factor which is far lower than the attenuation of the Airy rings of the central occulted star, making it easier to detect.

The nulling coronagraph works differently. The mask is not opaque: it is a phase mask which shifts the phase of the light by 180 degrees. When the phase mask has the right size, destructive interference occurs in the pupil and the light of the star is sent outside the pupil in the second pupil plane (see Fig. 1). The nulling coronagraph is not the only mean to use destructive interference on a star in order to image faint light sources very close to it. The achromatic interferometric coronagraph (Gay 1996) can cancel out efficiently the light of a star but the obtained image is superposed with its 180 degrees rotation around the optical axis.

Because a simple phase mask has a wavelength-dependent phase shift and because the Airy spot size is wavelength-dependent too, the nulling coronagraph cannot work over a wide range of wavelength at once.

1.2. Theoretical aspects

Figure 2 shows what is the effect of the phase mask in the pupil plane. Because the phase mask shifts the phase of the light by 180 degree, it induces interference between the light that passes through it and the light that passes around it. The light passing through the mask is a narrow peak in the image plane, no bigger than the size of the mask itself. Its Fourier transform, which is the light distribution in the pupil plane, is a broad peak, represented as being of negative value in Fig. 2 because the light has been shifted by 180 degrees. The light distribution in the pupil arising from the light that doesn't pass through the phase mask is then the normal uniformly bright disk (Fourier transform of the Airy pattern) minus this broad peak. When the two light distribution (inside + outside) are added together (along with their sign to take account for the interference) the inside of the pupil is even further lowered (in the same representation) and the outside has negative values. The square of this curve gives the light distribution in the pupil and it appears that by choosing the right value for the phase mask size, the light can be cancelled out in the inside of the pupil. This theoretical optimum size is 43% the Airy spot size. Then, as shown in Fig. 3, destructive interference occurs in the pupil while constructive interference puts the light outside the pupil.

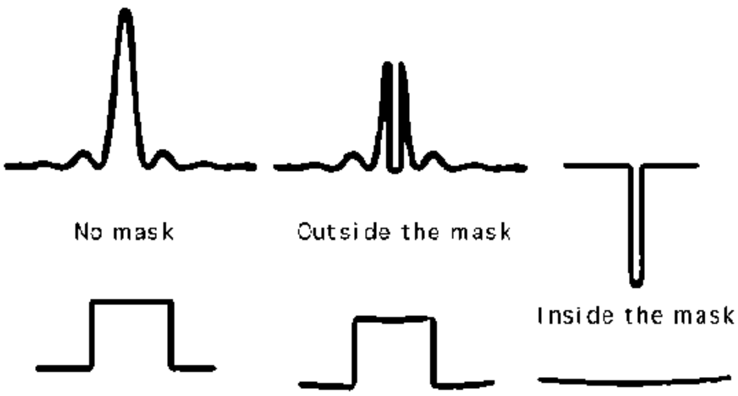
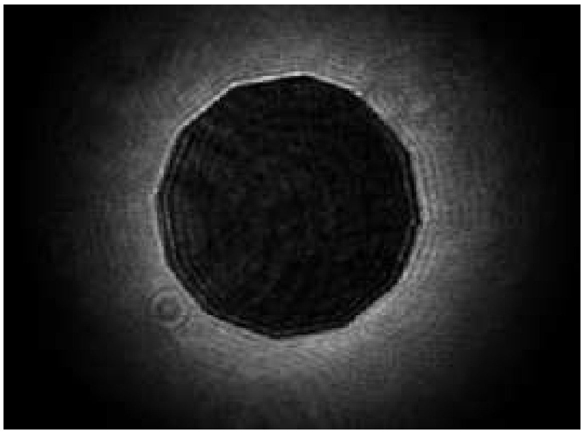


Figure 2: The effect of the phase mask in the pupil plane. The top row represents light distribution in the image plane and the bottom row is the corresponding light distribution in the pupil plane, which is the Fourier transform of the top row curves. By choosing the right size for the phase mask, the sum of the two lower right curves (pupil light distribution for the light that passes inside and outside the mask) can be brought to zero inside the pupil: this is the correct size for the phase mask. This then leads to the light distribution in the pupil shown in Fig. 3.

Figure 3: CCD image of the light distribution in the pupil plane in the nulling coronagraph. When the phase mask size is 43% the size of the Airy spot, destructive interference cancels out the light inside the pupil and constructive interference brings this light outside the edge of the pupil. Because the phase mask is transparent to light, no light is absorbed: the light is just "moved" out of the inside of the pupil.



2. The nulling coronagraph experiment

2.1. The fabrication of the phase mask

The phase mask was made at the University of Mexico by a close collaboration between two laboratories: the Microwave Laboratory, at Centro de Instrumentos, and the Detectors Lab. at the Instituto de Astronomia. The photolitography work was made at the Microwave lab and thin layers deposition was made at the Detectors lab. The thickness e of the mask is given by the relation

$$2(n-1)e = \lambda \tag{1}$$

where n is the SiO_2 refraction index and λ the wavelength of the used light, in this case He-Ne laser light. In this first test the mask thickness was 700 +/- 1 nm. The diameter of the mask is a factor 0.43 of the size of Airy spot corresponding to the used wavelength and the f/ number of the optical system. In Tab. 1 diameters and thickness of the mask for different usual filters are indicated.

Table 1: Diameters and thickness for SiO_2 phase masks correspondent to different astronomical filters and a f/33 beam.

Filter	$\lambda\mu$**m**	diameter(μm)	thickness (nm)
I	0.9	31	1000
J	1.2	41	1333
OII	1.23	42	1366
H	1.5	56	1666
[FeII]	1.64	57	1822
He IB	2.05	71	2277
K	2.27	78	2522

The fabrication steps are:

a) Copper film deposition is made over a substrate

b) Deposition of a photosensitive resin layer

c) Ultraviolet illumination of the resin layer through an adequate photographic generated mask. A hole in this case.

d) Chemical removing of the copper layer over the hole.

e) Sputtering deposition of SiO_2 over the hole

f) Chemical removing of the SiO_2 and copper excess.

2.2. Optical setup

Several masks of different sizes were available on the same glass plate. For our experiment, we choosed to use only one of them, so that the optical alignment wouldn't have to be done too often. Instead of changing the size of the mask, we changed the size of the pupil, hence modifying the size of the Airy spot. Our Airy spot was created using a Helium Neon laser and a beam expander. The parallel light beam was then focused using a lens. The Airy pattern at the image plane was very sharp, thanks to the monochromatic laser light, and numerous Airy rings could be seen on the images.

The phase mask was mounted on a xy stage. Because of the very long focal length of the beam, the position of the phase mask along the optical axis was not so critical. A single CCD camera (1024x1024

CCD chip) was used to record both image plane images and pupil images. Swapping from the image plane to the pupil plane was done by sliding a lens in the optical train. A second iris was used as the pupil stop (the equivalent of the Lyot stop in the Lyot coronagraph, this stop being also referred as a Lyot stop in this paper). We choosed to have this iris opened at 90% of the pupil size for each image we took. Each measure was done with a different pupil size. After having set the pupil size, a first image of the pupil was taken to measure the size of the pupil on the CCD image. This was done by moving the phase mask out of the way, opening the Lyot pupil stop iris (to see the actual pupil) and sliding in the lens to image the pupil. Then, the phase mask was carefully centered by looking at the pupil image while moving the mask and a second pupil image was taken (mask in). The Lyot pupil stop iris was then closed to 90% of the pupil aperture and a third image was taken at the pupil plane. Finally the last 2 images taken were in the image plane, phase mask in and phase mask out.
The measurements presented below have been obtained by using this set of images.

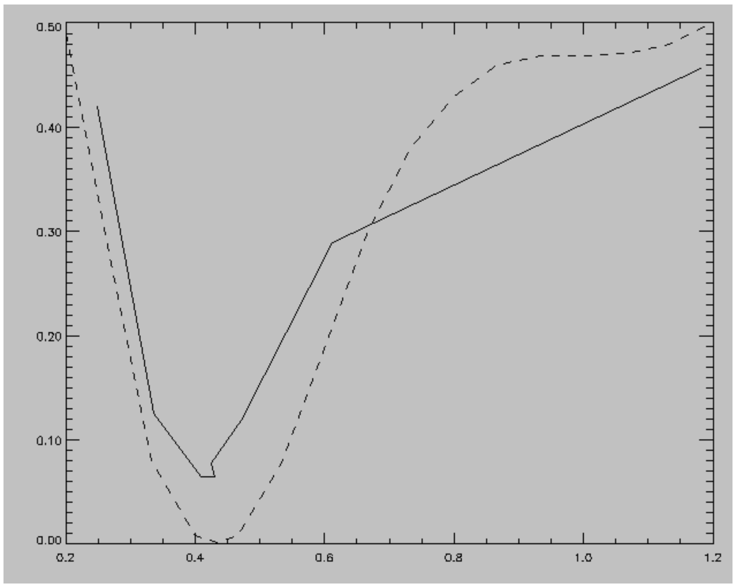


Figure 4: This plot shows the PSF peak intensity normalized brightness for different sizes of the phase mask. The dashed curve is the theoretical curve and the full line curve has been obtained with the optical setup described earlier. Allowing to the non-perfect thickness profile of the phase mask, the deep theoretical minimum has not been reached, but the overall shapes of the two curves match very well.

2.3. Laboratory measurements

Being able to acquire image in both the pupil plane and the image plane allowed us to check that the nulling coronagraph performs well according to the theory. By changing the pupil size it was possible to draw a curve of the PSF peak intensity attenuation versus the phase mask size relative to the Airy spot size (diameter of the first dark ring in the Airy pattern). This curve fits very well with the theoretical curve (see Fig. 4) and the maximum PSF peak extinction position is very close to the predicted pupil size value. However, it was impossible to reach the theoretical attenuation (a factor of 550 for a phase mask 43% as big as the Airy spot) because of the imperfect thickness profile of the phase mask we used : when the phase mask was put in one arm of a Michelson interferometer, the fringes showed that the mask thickness was maximum at the center.

The maximum attenuation we could reach was a factor of 16 (3 magnitudes) as shown in Fig. 7. Figure 6 shows the image of our artificial star when extinction is maximum. The theory predicts that the first dark Airy ring disappears when maximum extinction is achieved (Fig. 5), but our images don't show this phenomenon because this maximum efficiency point was “missed”. However, the extinction curve obtained in the experiment has been reproduced by computer simulation with a mask of uneven thickness. A mask with rounded edges (thinner at its edges) but of the right central thickness produced a extinction curve very close to the one obtained in the experiment. The mask was then put in a Michelson interferometer and the interference fringes showed that the thickness profile of our mask was close to the simulated profile.

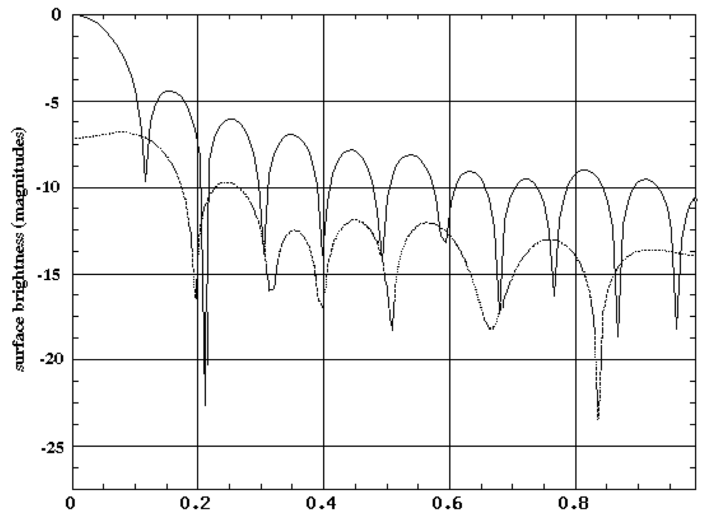


Figure 5: Theoretical PSF profiles in magnitude scale with no nulling coronagraph (upper curve) and with nulling coronagraph at maximum extinction (lower curve).

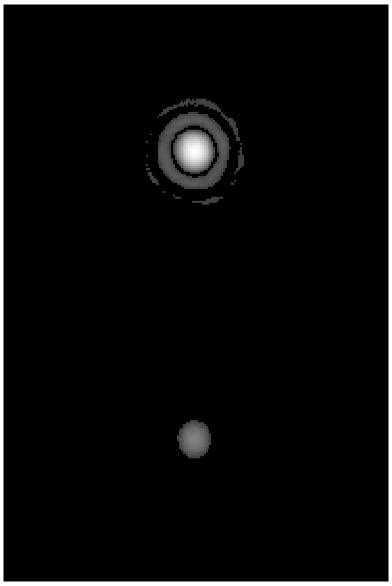


Figure 6: The top image was taken with the phase mask out of the way and the bottom one with the phase mask in. The nulling coronagraph can attenuate both the central Airy spot and the rings as demonstrated here. Brightness scale is not linear in this image.

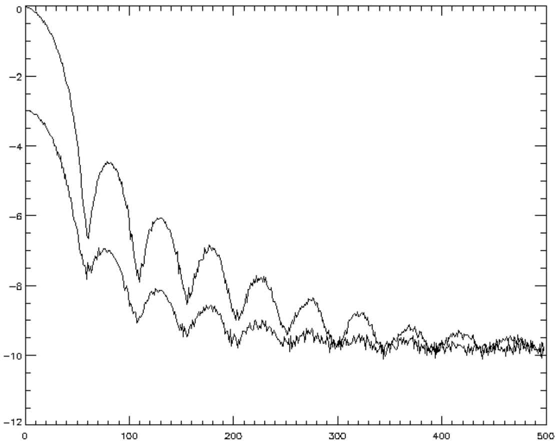


Figure 7: Light profile of the two images of Fig. 6. The peak intensity of the PSF is lowered by about 3 magnitudes (a factor of 16) by the nulling coronagraph.

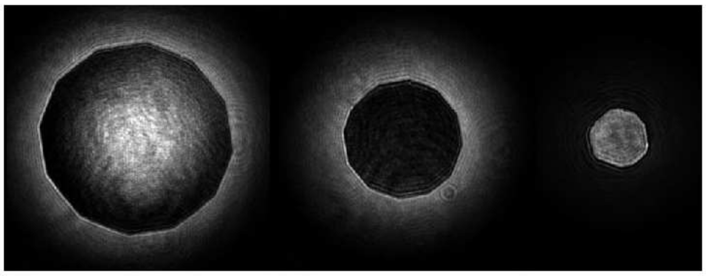


Figure 8: This set of 3 pupil images shows what is the effect of the pupil size (same phase mask size) on the pupil plane light distribution. If the pupil is too large (left), or the phase mask too large, the light inside the pupil is not cancelled out very well but part of the light is put outside the pupil edge. When the pupil size is optimum (middle), very little light remains inside the pupil. If the pupil is too small (right), the Airy spot is bigger and the phase mask is too small to have a significant effect on the light distribution in the pupil.

The pupil plane images show very well how the phase mask induces destructive interference inside the pupil while putting the light outside the pupil (see Fig. 8). The pupil size is a very critical adjustment to reach maximum extinction. It would have been even more critical with a better mask, with which the maximum extinction would have been greater.

3. The nulling coronagraph at the telescope

3.1. Using the nulling coronagraph with an AO system

The phase mask in the nulling coronagraph being only 43% the size of the first dark Airy ring, its use is limited to astronomical instruments yielding sharp and steady PSFs. On a large telescope without AO, the phase mask would be inefficient since atmospheric turbulence would spread the light over an area far bigger that the Airy spot size, and the tip-tilt would move the star over great distances in the image plane. Hence, the phase mask can only be used on space telescopes or on telescopes on the Earth equipped with efficient AO systems.

Figure 9 shows how AO can efficiently reduce the brightness of the PSF between 0.07" and 1" on a 3.6 meter telescope in H band (1.65μm). On such a telescope, the diffraction rings are responsible for most of the light found up to 1" away from the star. The scattering induced by the telescope optics is then the most important contribution at greater distances. That's why using a nulling coronagraph can be very efficient for faint light sources detection in the first Airy rings of the PSF, where the Lyot coronagraph cannot be of any help because the Lyot mask usually covers the first 3 or 4 Airy rings. Using a nulling coronagraph on a telescope requires very fine optical alignment since the phase mask is smaller than the Airy spot size. The use of narrow-band filters might be useful to avoid decreasing the performance of the coronagraph which works best for monochromatic light. The most important degradation of the performance of the nulling coronagraph might arise from residual tip-tilt : this is the subject of the following chapter.

3.2. Tip-Tilt and the nulling coronagraph

Using computer simulations, it is possible to create PSFs obtained by offsetting the image of the star

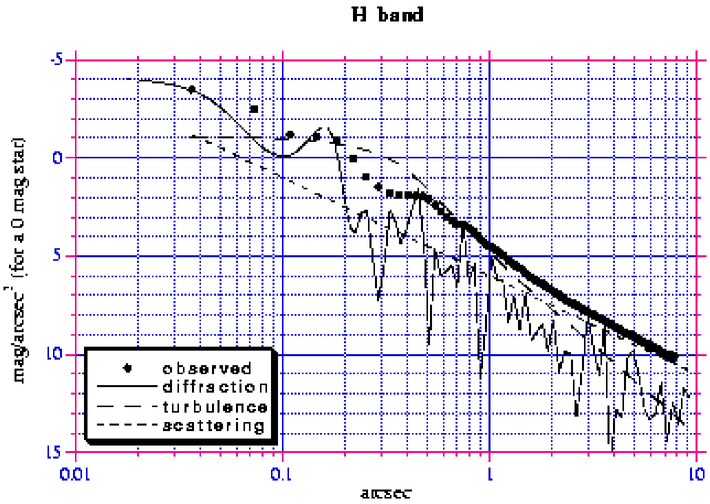


Figure 9: Different contributions of the radial brightness of a PSF obtained on a 3.6 meter telescope in H band (1.65μm). The brightness profile of a PSF obtained with Hokupa'a is plotted on this graph.

on the phase mask. Then, if we assume that the turbulence is moving the star in the image plane with a Gaussian probability density (which is a very good approximation), we can simulate the effect of residual tip-tilt for the nulling coronagraph.

The results of the computer simulations for a 3.6 meter telescope at a wavelength of 1.65μm are shown in Fig. 10, 11 and 12. The effect of tip-tilt seems to be very important and the center of the PSF (where the phase mask is) appears very dark compared to the bright ring induced by the tip-tilt. On Hokupa'a, the residual tip-tilt is thought to be around 15 milliarcsec for bright stars.

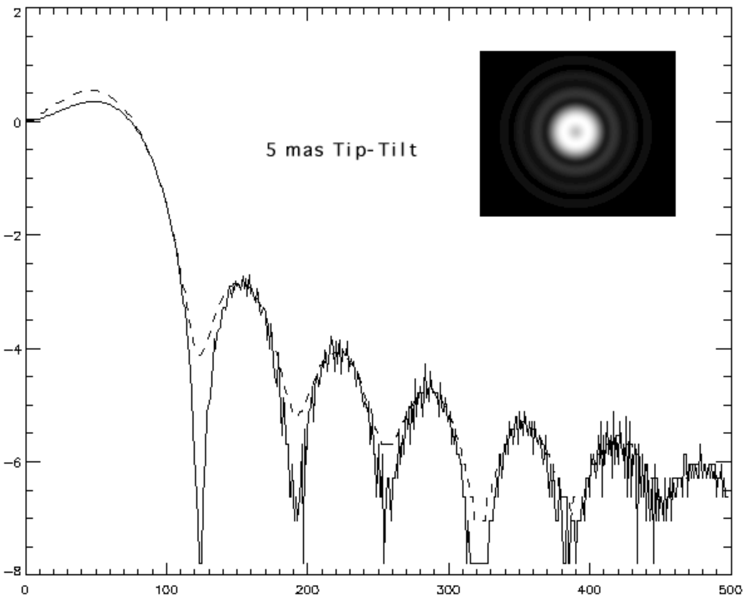


Figure 10: Theoretical PSF obtained on a 3.6 meter telescope at 1.65μm using the nulling coronagraph with a residual tip-tilt of 5 milliarcsec. The full line curve is the PSF profile when no tip-tilt is present. The brightness scale is in magnitude (logarithmic scale, one magnitude equals a 2.5 factor in brightness.

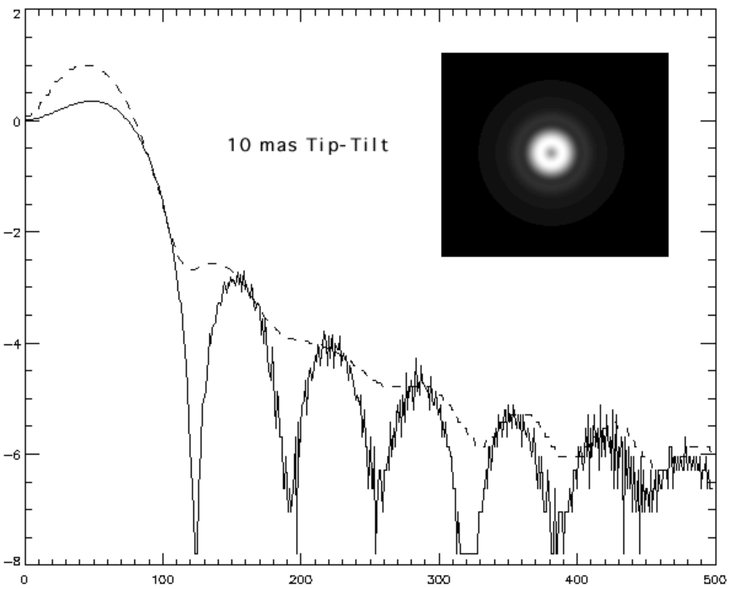


Figure 11: Theoretical PSF obtained on a 3.6 meter telescope at 1.65μm using the nulling coronagraph with a residual tip-tilt of 10 milliarcsec.

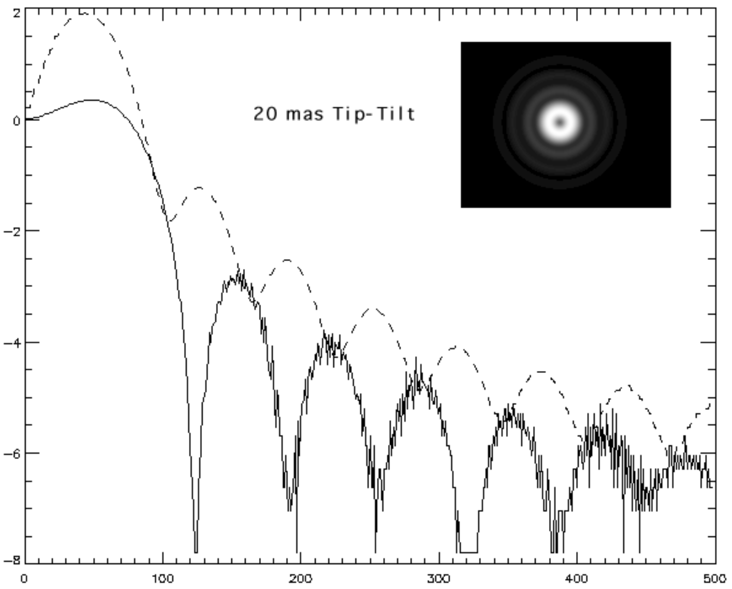


Figure 12: Theoretical PSF obtained on a 3.6 meter telescope at 1.65μm using the nulling coronagraph with a residual tip-tilt of 20 milliarcsec.

3.3. Chromatism

The use of the nulling coronagraph in broadband imaging encounters two problems. First, the mask itself doesn't induce the same phase shift for all wavelengths. The other problem is that the Airy spot size is wavelength-dependent and the nulling coronagraph only performs well when the mask size is 43% the size of the first dark Airy ring.

The first problem can be solved by using a more sophisticated phase mask, stacking layers of materials having opposite refraction index wavelength dependence. It is reasonable to think that such masks can be built to offer the same phase shift over the wavelength range of a common IR filter (H, J or K filters for example). Figure 13 shows that the Airy spot wavelength dependent size then limits the performance of the coronagraph. However, optical designs offering a wavelength-dependent magnification and wavelength-independent focal plane exist and could be used to solve this problem.

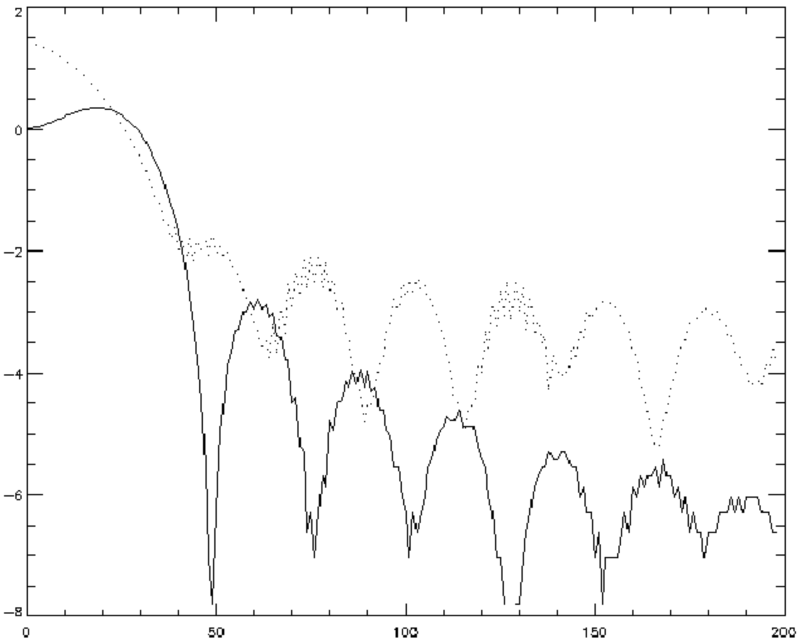


Figure 13: Theoretical PSF obtained on a 3.6 meter telescope using the nulling coronagraph through a H filter (dotted line). The phase mask is considered as perfectly achromatism (same phase shift for all wavelength) but the Airy spot wavelength-dependent size has been taken into account. The full line curve is the PSF obtained in monochromatic light (1.65μm).

4. Conclusion

The nulling coronagraph experiment results were very well matched by computer simulations. The deep extinction maximum predicted by the simulation could not be reached in the experiment because of the imperfect thickness profile of our phase mask. However, computer simulations using an unperfect phase mask with bend edges match extremely well the measurements obtained.

Those results give us confidence that a better phase mask can yield results very close to the theoretical simulations with a perfect mask. However, a good nulling coronagraph would be very sensitive to residual wavefront errors. This makes it more easy to use this type of coronagraph in the infrared, where the compensation achieved by adaptive optics systems is better and the Airy spot is bigger. Moreover, the objects that such a coronagraph would try to image would be brighter in the infrared (Protoplanetary disks, Planets ...).

The use of such a coronagraph on a space telescope would not suffer from atmospheric turbulence, hence making it easier to use. The Chromatism of such a coronagraph appears to limit its use in broadband imaging, but technological solutions exist to solve this problem.

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