

# 1 Point Spread Function analysis of the NACO instrument at the VLT

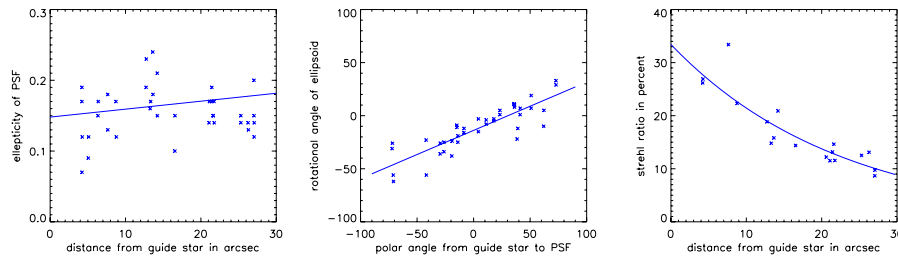
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In this work an analytical description of the NACO PSF with a minimum number of parameters is sought. These parameters are governed by the observational characteristics and the location of the PSF with respect to the guide star. The first order approximation of the PSF can then be used for image deconvolution. The analysis and modelling of the PSF was performed using images of a given position in the Galactic bulge collected in the Ks-band ( $2.00\text{--}2.36\mu\text{m}$ ) with the S27 camera on 19/08 (seeing 1.1 arcsec) and 23/08/2002 (seeing 0.9 arcsec) during the science verification period of NACO.

## 1.1 Analysis of the PSF properties

As a first step, the dependency of the PSF on its position with respect to the guide star was analysed. Twenty test-stars distributed over the entire frame were selected. The parameters determined include: x- and y-coordinate on the frame, the peak value of the profile fit, the ellipticity of the PSF, the angle of the ellipsoid in degrees (between  $-90$  and  $+90$  with  $0$  along the x-axis) and the FWHM of the fit.



**Fig. 1.1.** **Left:** Increase of ellipticity with distance to the guide star. **Middle:** Dependence of the orientation of the ellipsoid on the direction to the guide star. **Right:** The Strehl ratio decreases with growing radius following an exponential decay law.

The left panel in Fig. 1 shows how the ellipticity of the PSF increases slowly with distance from the guide star. In total the ellipticity reaches a value of about 0.15 to 0.2. The FWHM displays a similar behaviour (not shown here). The relative orientation of the ellipsoid to the positional angle from the guide star is a linear relation as can be seen in the middle panel. The decrease of the Strehl ratio (quality of AO correction) follows an exponential decay law as predicted

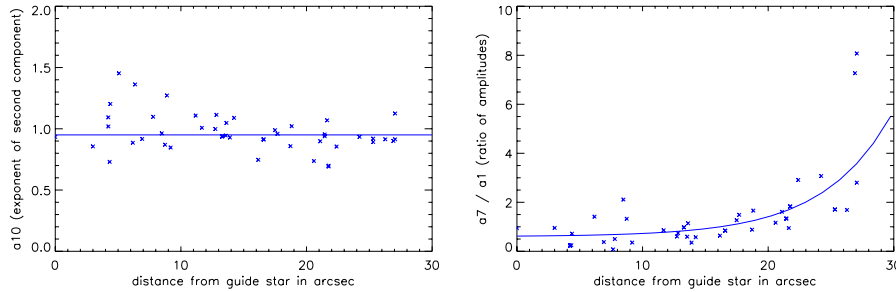
by theory (c.f. Fig. 1, right panel). In the data analysed the central Strehl ratio is approximately 30 % and it drops to 15 % at the edge. The anisoplanatic angle thus is  $20''$ .

## 1.2 Analytical model for the PSF

The approach was to fit the PSF of the stars in the NACO frame by an analytical two dimensional function  $Z(x, y, A_1, A_2, \dots, A_n)$  and deduce dependencies within the free parameters  $A_n$ . The final function used for the model consists of an elliptical Gaussian and an elliptical decaying exponential function with varying exponential. This ansatz does not contain any physical assumptions and is motivated by simple analysis of the radial profile of the PSF and the parameter dependencies discussed in section 1. The functional form used is given by

$$Z = A_0 + A_3 \cdot e^{-\frac{1}{2} \left[ \left( \frac{(x-A_1) \cdot \cos(A_6) - (y-A_2) \cdot \sin(A_6)}{A_4} \right)^2 + \left( \frac{(x-A_1) \cdot \sin(A_6) + (y-A_2) \cdot \cos(A_6)}{A_5} \right)^2 \right]} + A_7 \cdot e^{-\frac{1}{2} \left[ \left( \frac{(x-A_1) \cdot \cos(A_6) - (y-A_2) \cdot \sin(A_6)}{A_8} \right)^2 + \left( \frac{(x-A_1) \cdot \sin(A_6) + (y-A_2) \cdot \cos(A_6)}{A_9} \right)^2 \right]} e^{-\frac{A_{10}}{2}}$$

The free parameters are  $A_0$  to  $A_{10}$ .  $A_0$  corresponds to the sky background.  $A_1 = x_{star}$  and  $A_2 = y_{star}$  are the coordinates of the star.  $A_3$  corresponds to the amplitude of the first, elliptical Gaussian component,  $A_7$  to that of the second component.  $A_4 = \sigma_{1x}$  and  $A_5 = \sigma_{1y}$  are the widths of the gaussian ellipsoid in  $x$  and  $y$  direction respectively,  $A_8 = \sigma_{2x}$  and  $A_9 = \sigma_{2y}$  similarly for the exponential component.  $A_6$  is the angle at which the entire profile is rotated. Finally  $A_{10}$  is the exponent of the second exponential component.



**Fig. 1.2. Left:** Exponential of the second component. The exponential was fixed to the value  $A_{10} = 0.95$ . **Right:** Ratio of the amplitudes of the two components. The second component grows stronger with increasing distance to guide star.

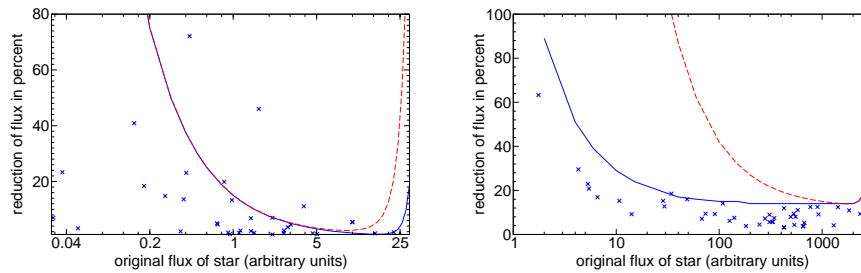
The function hence contains eleven free parameters. For a best guess of the PSF these have to be reduced to the really independent parameters: the sky background ( $A_0$ ), the two coordinates for the position with respect to the guide

star ( $x_{star}$  and  $y_{star}$ ) and the total amplitude ( $A_3 + A_7$ ). In this analysis, which is limited to two frames taken at different nights, external parameters such as seeing were neglected.

We reduced the number of free parameters that are fitted in several steps: we successively fixed the dependent parameters one by one. By analysing the parameter dependencies after every fixation we set up constraints for the next parameter and hence eliminated it. Figure 2 shows two examples in this process of parameter reduction. In both cases the parameters are fixed by the curve shown. With this method we managed to eliminate all but the four parameters mentioned above. Given an arbitrary position on the frame a best guess PSF is produced, which will then be scaled to a specific flux.

### 1.3 Quality of the model

To be able to make an objective judgement on the quality of the model, several stars in the field were fitted with the derived PSF model. Two criteria were addressed: the maximum deviation from zero between the star and the PSF fit and the residual flux after subtracting the PSF fit. For the original stars the maximum deviation is the peak of the PSF, while after subtraction the maximum deviation comes from the residual or the background. The following behaviour can be observed (c.f. Fig. 3): For faint stars (peak value of less than 100 counts) the deviations are due mainly to the background scatter. For intermediate stars (100 to 2500 counts) the maximum deviation is less than 15%. Similarly the flux is efficiently suppressed to less than 10% in average. For very strong stars (more than 2300 counts) the quality of the fit diminishes because of saturation effects.



**Fig. 1.3. Left:** Reduction of the peak count value after subtraction with the model plotted versus maximum counts of the object. **Right:** Reduction of flux in star plotted versus the initial flux of the star. Dashed curve: upper limits for model with `daophot`.

The continuous curves represent an upper limit to the residuals. For comparative purposes, a PSF model derived from the IRAF routine `daophot` was applied to the same field and stars. The dashed curve is an upper limit obtained when using `daophot`.

## 1.4 Final remarks

With the proposed ‘training method’, a model PSF can be derived from a frame containing a number of point sources. The model can then be applied to other science frames taken with the same instrumental configuration. The main problem with this approach is, as expected, the inherent temporal variations of the PSF, which we are not considering. Using the trained PSF as derived from a given Galactic bulge frame, its application to the same Galactic bulge image position taken on a different night is limited.

The quality and stability of the AO correction has dramatically increased since the time the data used in this work (Aug. 2002) was observed. Diffraction limited and relatively high Strehl images are being regularly provided by NACO. Implementing a first order Bessel function in the analytical description of the NACO PSF is hence manifest. We plan to test the new description on science frames where object and guide star are the same.