Operational and astronomer support issues in real life AO systems

Jean-Luc Beuzit

Canada-France-Hawaii Telescope, 65-1238 Mamalahoa Highway, Kamuela, HI 96743, U.S.A.

Abstract

Both the ADONIS (at ESO) and PUEO (at CFHT) adaptive optics systems have been in general use for several years, totalizing over 400 nights of scheduled observing time. They are routinely producing near-infrared diffraction-limited images under reasonable seeing conditions and a significant number of papers have now been published reporting astrophysical results obtained with adaptive optics. In this paper, I present the experience we have gained using these two systems, from the user and support astronomer points of view. I review the whole observing process from the preparation of the observations to the data reduction, including the proper calibration of the data, etc.

1 Introduction

During the past 10 years, adaptive optics (AO) systems have evolved from crude and quite complex prototypes like COME-ON and COME-ON-PLUS at ESO (Rigaut et al. 1991; Rousset et al. 1994), to much more powerful and user-friendly instruments: ADONIS at ESO (Beuzit et al. 1997), PUEO (Rigaut et al. 1998) and Hokupa'a, the UH AO system (Roddier et al. 1998), at CFHT. Dedicated imaging cameras have been built to take full advantage of the AO corrected images and complementary modes and instruments such as coronographs, Fabry-Pérot etalons, polarimeters, integral field spectrographs have been coupled to the AO systems to extend their capabilities. As a result, more and more scientific papers are now published, reporting results obtained with these different systems, as demonstrated by this conference. At the same time, we have developed a valuable experience in various fields related to the use of the AO systems, from the optimization of their performances and the understanding of their limitations to the process of data reduction and calibration.

In this paper, I will present some aspects of the experience that we have gained using the ADONIS and PUEO AO systems, from the user and support astronomer points of view. I will review the whole observing process including the preparation of the observing programme (section 2), the actual observations (section 3) and the reduction of the data (section 4).

2 Preparation of the observations

2.1 Observing strategy

The first step for the astronomer is to determine the required instrumental configuration and to clearly establish the observing strategy, based on the scientific rationale of the astrophysical programme, the characteristics of the target objects, the characteristics and performance of the AO system and the typical atmospheric conditions.

The instrumental configuration will be defined according to the following constraints:

- the wavelength(s) of observation to select the imaging camera (visible, near-infrared, thermal infrared above 2.5 μm) and the corresponding dichroic mirror,
- the spectral resolution to choose between filters (broad-band, narrow-band or CVFs) and spectroscopic modes (Fabry-Perot etalons, integral field spectrographs),
- the expected contrast that may dictate the use of a coronograph,
- the need for polarimetric information.

Once the basic instrumental configuration is fixed, the next step is to determine if the considered targets can be used as their own reference for wavefront sensing or if distinct reference objects have to be identified instead. Whenever possible, the programme objects themselves should be used, but this is not always possible, for instance if they are too faint or too extended. The parameters of interest to select the actual reference object are the following:

- magnitude at the wavelength at which the wavefront sensor operates,
- spectral type (colour index),
- angular size (or multiplicity),
- angular separation between the target and any potential reference objects.

The magnitude and spectral type will determine the number of photons available for the wavefront sensing and hence the quality of the correction. The spectral information is important due to the wavefront sensor response which usually peaks in the R photometric band. Then for a given V magnitude, a red object will lead to a better correction. The limiting magnitude for wavefront sensing is usually defined as the magnitude for which an improvement in the image quality can still be seen, and it corresponds to a low-frequency correction of the tip-tilt (and static aberrations of the telescope optics). It has to be pointed out that this limiting magnitude is seeing dependent.

The wavefront sensor field-of-view per sub-aperture is limited (typically $1''$ to $2''$ for PUEO depending of the optical gain, and up to $5''$ for ADONIS). And of course, the reference source should always remain inside the wavefront sensor field-of-view to allow a correct operation of the AO system. As for the limiting magnitude, the limit in angular diameter will depend on the atmospheric conditions. Various Solar System bodies have been successfully used for wavefront sensing as reported by Combes et al. (1997) and Poulet et al. (1997) for the satellites of Jupiter or Saturn, Roddier et al. (1998) for Neptune, Marco et al. (1998) for comets, Saint-Pé et al. (1993) and Hainaut (1994) for asteroids. More complex objects like AGNs and Starburst galaxy nuclei (Marco, Alloin, & Beuzit 1997; Quirrenbach, Eckart, & Thatte 1997; Rouan et al. 1998) or embedded stars (with envelopes) (Beuzit et al. 1994; Roddier et al. 1995) can also be used as their own references. In this case, the important parameter is the contrast between the extended region and the bright nucleus or star.

Due to the limited size of the isoplanatic field, the reference should be located as close as possible to the astrophysical target to allow a good correction. The decrease in Strehl ratio as a function of the separation depends on the wavelength of observation and on the atmospheric conditions (Fig. 1). Under typical seeing conditions at La Silla, for a separation of $25''$ the Strehl ratio decreases by a factor of 3 at 2.2 μm and by a factor of 10 at 1.25 μm. However, under good seeing conditions the Strehl ratio has been measured constant over a $13'' \times 13''$ field in H band (Brandl et al. 1995). The maximum distance between the reference object and the target is ultimately limited by the design of the AO system (maximum amplitude of the wavefront sensor or field mirror offsets), respectively $\sim 35''$ and $45''$ for ADONIS and PUEO.

It is not always possible to find suitable reference objects for a given target. Studies have been conducted to determine the sky coverage ie. the fraction of the sky for which one can find a reference object that will provide a correction better than a given Strehl ratio. These studies ((Rigaut 1994)) show that for the current systems on 4-meter class telescopes, the sky coverage is relatively poor, typically $<$ 5-10%, although it of course depends on the location of the target in the sky (the sky coverage is of course much higher in the direction of the Galactic plane). Laser guide stars can be added to AO systems to overcome this limitation. Also infrared wavefront sensors are currently being developed to allow wavefront sensing when no visible reference can be found (highly obscured regions like the Galactic Center, late type stars, yong embedded objects...). An infrared wavefront sensor will be tested on ADONIS at the end of this year as a prototype of the NAOS one (Lagrange et al. 1998). The use of asteroids as reference sources has also been proposed (Ribak & Rigaut 1994).

2.2 Optimization of the strategy

Once the basic observing strategy has been defined, it can be optimized in different ways. In particular the use of AO performance estimators when they are available (see the PUEO web page at CFHT for instance), or published performance curves otherwise (Fig. 2), can be used to refine the estimation of the image quality, defined by the Strehl ratio or the resolution, that can be expected as a function of the reference object and atmospheric conditions. This can be very usefull to promptly react when actually confronted to the atmospheric conditions at the telescope, and therefore optimize the use of telescope time, for instance by switching to a back-up programme, easier to perform in case of bad seeing conditions. It can also help to decide between using the target itself as the reference object or go to a distinct one.

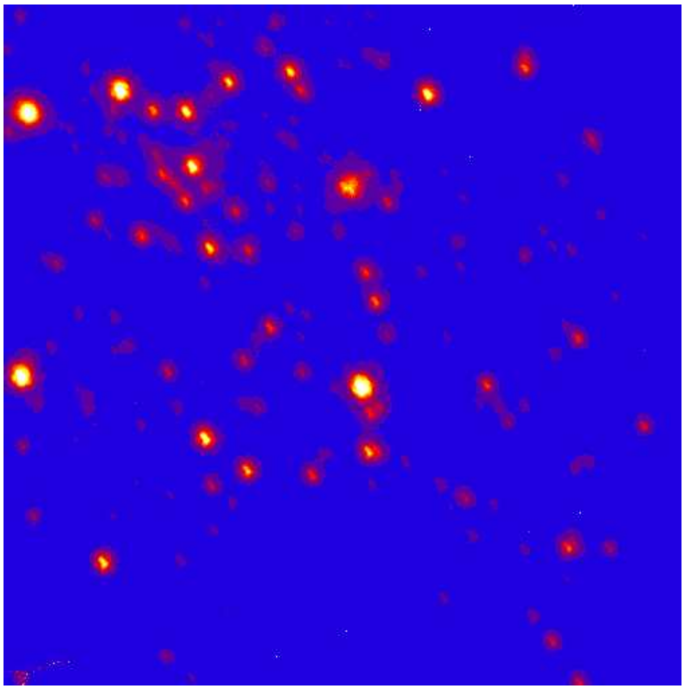
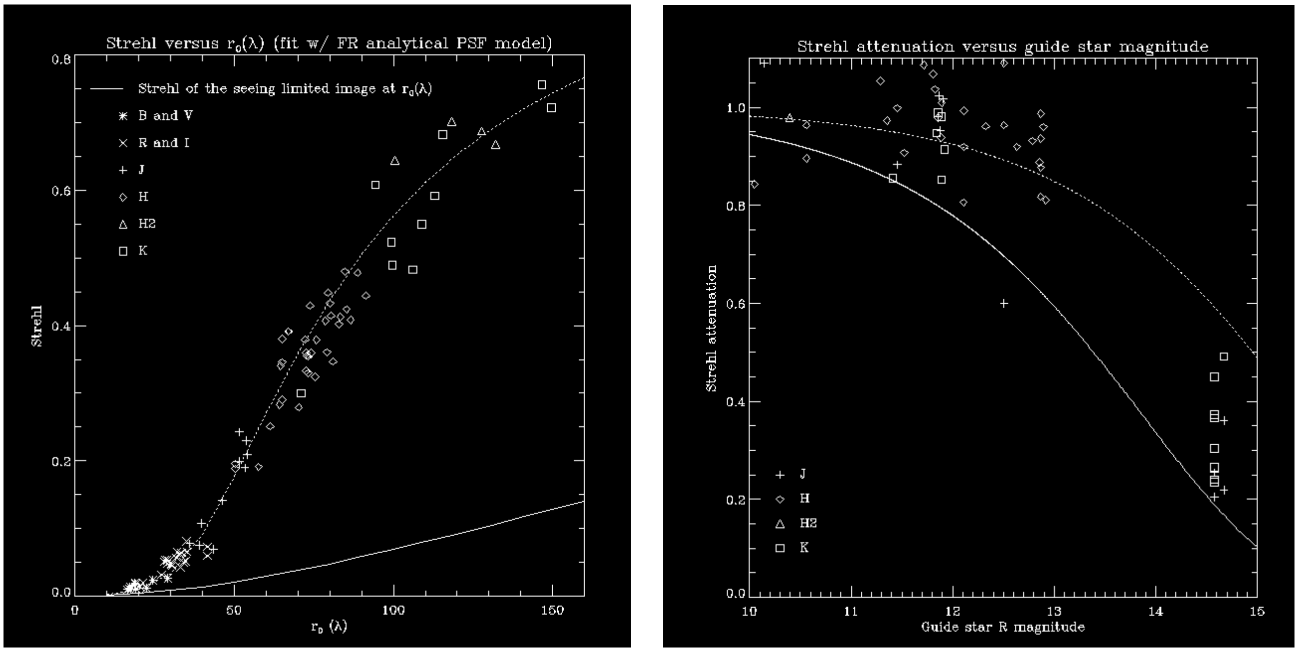


Figure 1: Example of the anisoplanatic effect during an observation of the Galactic Center in K band (Rigaut et al., this conference). A radial elongation of all stars is clearly seen in the direction of the reference star, located 20″ North (up) and 10″ Est (left) from the centre of the field.



(a) Strehl ratio versus r_0 (as r_0 varies with the wavelength, the wavelength dependance of the Strehl ratio is taken into account by considering r_0 for a given wavelength)

(b) Strehl ratio attenuation versus reference object magnitude

Figure 2: Examples of performance curves for the PUEO AO system, giving the Strehl ratio as a function of the Fried parameter r_0 and the magnitude of the object used for wavefront sensing (from the PUEO User's Manual).

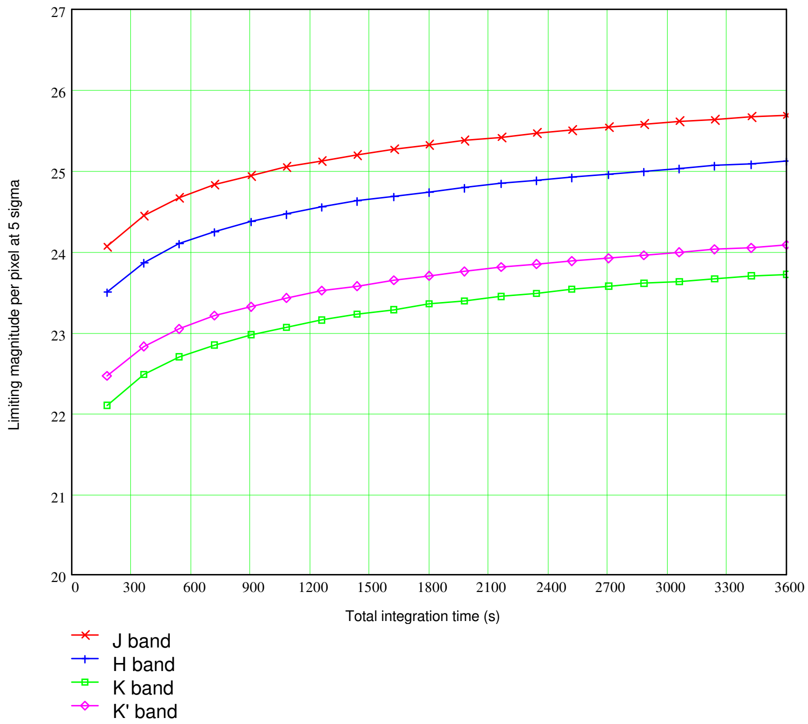


Figure 3: Limiting magnitude per pixel reached by PUEO + KIR for broad-band imaging as a function of the total integration time, with S/N = 5. For each filter, the resulting image was obtained by combining several individual frames. The elementary integration time (per frame) depends on the filter and was selected in order to be limited by the background noise. Typical elementary integration times are 3 minutes in J, 2 minutes in H, 1 minute in K and K'.

The use of S/N calculators or sensitivity curves (Fig. 3 and 4) for the requested intrumental configuration will allow to optimize the observing sequence by selecting the elementary integration times and the number of exposures as a function of the desired S/N or detectivity. This observing sequence can be further specified as a function of the wavelength of observation (need for chopping and/or nodding, and at which frequency, if sky and instrumental background emissions are a limitation, ie. above 2μm), and the type of target (mosaicing possible to record the sky emission in the case of stellar observations but not for very extended objects).

These detailed simulations can also help to further optimize the observing configuration, for instance to decide of the best compromise between the quality of the correction (resolution, Strehl ratio) and the detectivity, depending of the target spectrum.

I would also like to emphasize the need for back-up programmes, especially if the main programme is likely to be very dependent on the atmospheric conditions (faint or distant reference object). This would avoid to completely waste the observing run in case of marginal seeing conditions, by going to brighter reference objects or a less demanding programme in terms of resolution or Strehl ratio. Following this idea, the AO systems on large telescopes will most likely be operated in flexible or queue scheduling modes in order to continuously match the observing programmes to the atmospheric conditions. CFHT is also considering this option for PUEO.

2.3 Calibrations

2.3.1 PSF calibration

An AO system will never be able to fully restore the distorted wavefront and produce perfectly corrected images. Moreover, the system response, or point spread function (PSF), is constantly evolving according to the atmospheric conditions (seeing,

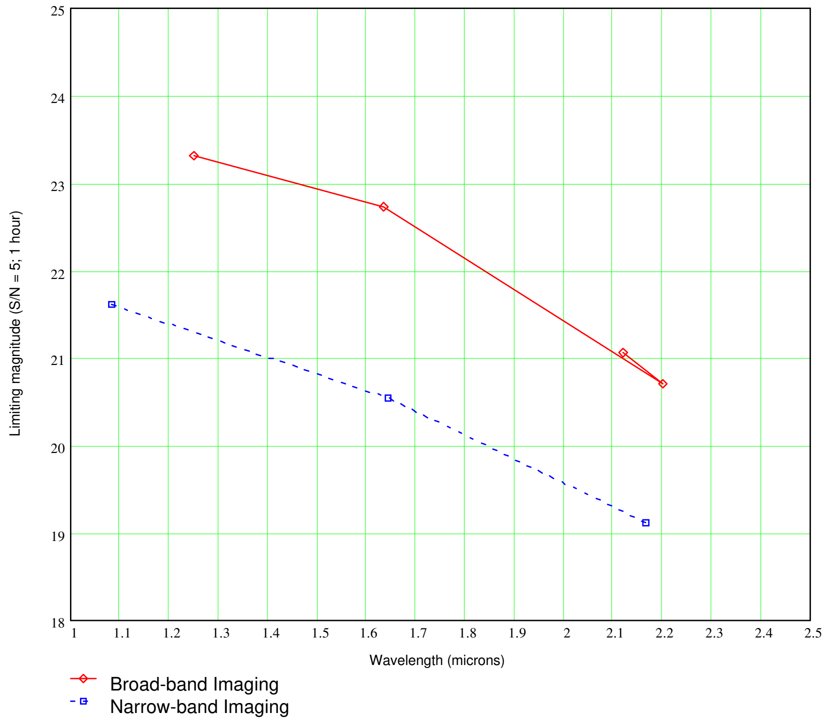


Figure 4: Detectivity reached by PUEO + KIR as a function of the wavelength for broad-band and narrow-band imaging of a diffraction-limited source (1 hour integration, S/N = 5).

coherence time), the characteristics of the reference object (magnitude, morphology, distance to the target), the position of the source in the sky (flexures within the AO system, atmospheric dispersion), etc. And due to the anisoplanatism effect, the PSF is also varying within the field-of-view of the detector.

A carefull calibration of the system PSF is therefore needed, first to get a good estimation of the quality of the AO correction, and also if one wants to be able to deconvolve the images of the astrophysical target as part of the reduction process.

The calibration of the system PSF can be obtained in different ways:

- an unresolved source present within the detector field-of-view can provide a simultaneous estimation of the PSF, although it may slightly differ from the actual object PSF due to the anisoplanatic effect. The magnitude of this effect will depend on the atmospheric turbulence and on the wavelength of observation, but may be difficult to estimate.
- distinct calibration stars can be observed in alternance with the astrophysical targets as illustrated in Fig. 6. These stars will then be chosen with similar magnitudes and spectral types in order to ensure the same degree of correction and they will be angularly close to the corresponding targets to be affected by the same atmospheric effects and to limit the possible flexures of the instrument. If the reference object is not the astrophysical source, it may be interesting to find 2 stars with a similar separation to account for the anisoplanatic effect when calibrating the PSF with this method.
- the last method is to retrieve the PSF from the wave-front sensor data and deformable mirror commands recorded simultaneously with each science image acquisition. In the case of PUEO, tools have been developed (Véran et al. 1997; Thomas, Barrick, & Beuzit 1998) to provide an accurate estimate of the AO-corrected, long-exposure PSF in the direction of the guide source, when this guide source is of magnitude 13 or brighter. This reconstructed PSF has still to be calibrated for non-common path aberrations and high spatial frequency aberrations not following the Kolmogorov model (mirror seeing and polishing defects for instance). As these effects can usually be considered as quasi-static, they can be calibrated using images of a bright point source taken during the night. Of course, more reference images are still useful, for instance to account for temperature variations during the night or flexures if observing at high airmasses, keeping in mind that for optimal PSF reconstruction the calibration sources must be bright, to allow a good correction and to obtain high signal-to-noise ra-

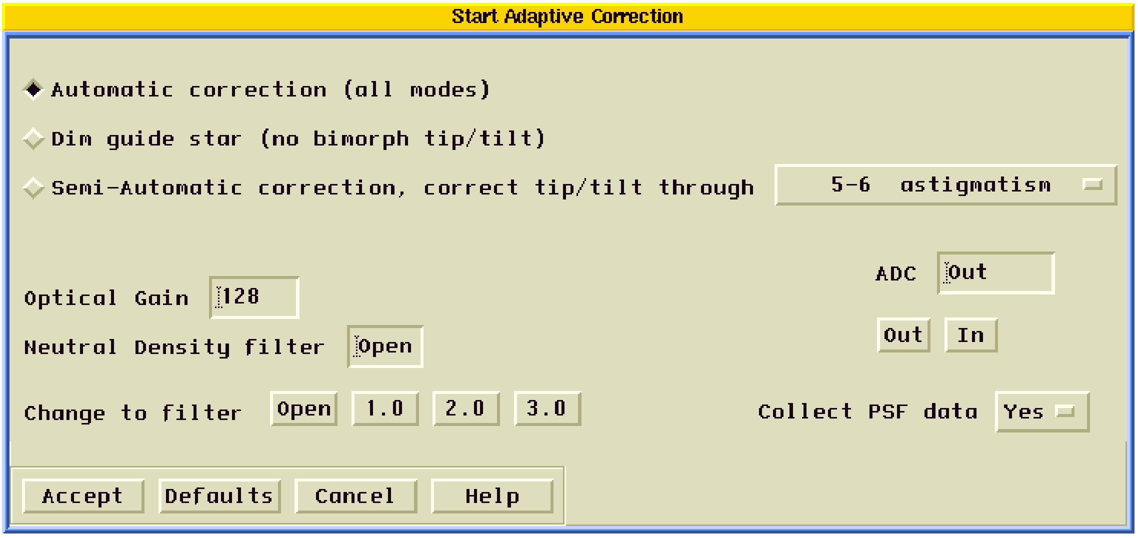


Figure 5: User's interface for the PUEO AO system.

tios on the images. The errors on the estimated PSF are of the order of a few percents on the low and medium frequencies of the modulation transfer function (MTF), increasing up to ten percents at the highest spatial frequencies (Véran et al. 1997). See Véran & Rigaut (1998) and Véran et al. (1998) for applications of this method to actual astrophysical programmes. Similar work is underway for ADONIS as reported in this conference by Harder & Chelli (1998).

2.3.2 Other calibrations

Various calibrations will of course be needed, depending of the ultimate goal of the astrophysical programme. Some of these calibrations are not specific to AO observations and will not be discussed here, for instance flat-fields and dark frames, photometric, spectrophotometric or polarimetric standards. Accurately determining the image scale and orientation on the sky can also be of the highest importance for some programmes, such as the determination of orbital parameters of binary systems. This can be achieved by using well known clusters (as the central region of the Trapezium Cluster in the Orion Nebula, (McCaughrean & Stauffer 1994)) or Hipparcos binaries.

3 At the telescope

3.1 Data acquisition

The way the current AO systems are designed and/or operated makes their use nearly transparent for the observer. In the case of PUEO for instance, the user is presented with a very simple interface represented in Fig. 5. Most of the time, the only AO-related parameters to be set by the observer are the neutral density filter, to adapt the flux of the reference object to the wavefront sensor linearity range, and the optical gain (proportional to the amplitude of vibration of the membrane mirror) which can be reduced to help closing the loop on extended objects or binary stars. A modal control optimization of the servo-loop continuously adapt the AO correction to the magnitude of the reference object and the state of the turbulence (Gendron & Léna 1994; Rigaut et al. 1994). Typically new gains for the system modes are calculated every minute. The whole process of starting the AO correction, once the reference object has been acquired, usually takes less than 1 minute and the observer is then left with the control of the science camera or instrument.

A typical observing sequence is illustrated by Figure 6. It consists, for each filter, in observations of the astrophysical target, alternated with observations of the PSF calibration star and the needed sky background estimations. Of course, the required calibrations (photometric, astrometric...) will also be acquired during the night, or before/after the night for flat-fields and dark

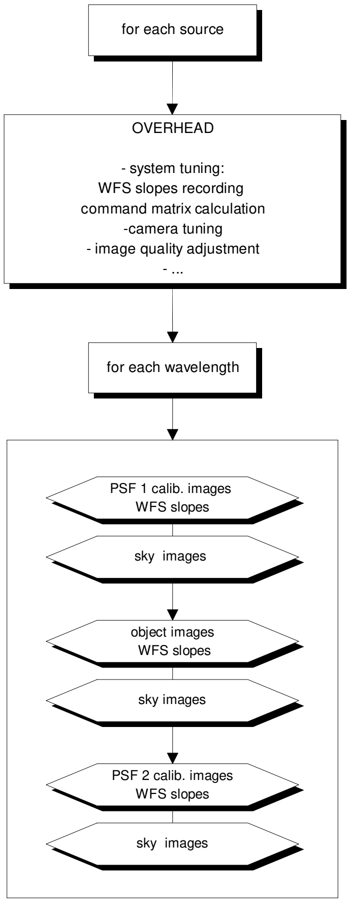


Figure 6: Adaptive optics typical observing sequence.

frames.

3.2 During acquisition

Both PUEO and ADONIS can provide on-line measurements of the current uncorrected atmospheric seeing (and atmospheric coherence time for ADONIS) and estimations of the degree of AO correction (Fig. 7). This is a very valuable tool for the observer, especially when the astrophysical target does not allow a direct control of the quality of the correction (faint and/or extended object). Real-time decisions concerning the optimization of the observing programme can be made based on these informations.

4 Data reduction

There is no standard procedure to reduce the data obtained with AO systems and the actual reduction sequence will of course vary according to the ultimate goal of the scientific programme and the experience of the astronomer. We can still try to identify the main steps of the reduction process. See also Quirrenbach (1998) in these proceedings.

Instrumental signature removal This first step is not specific to AO data reduction and mainly consists in removing the instrumental and sky contributions. This will usually include sky subtraction, flat-fielding, dead or noisy pixels removal,

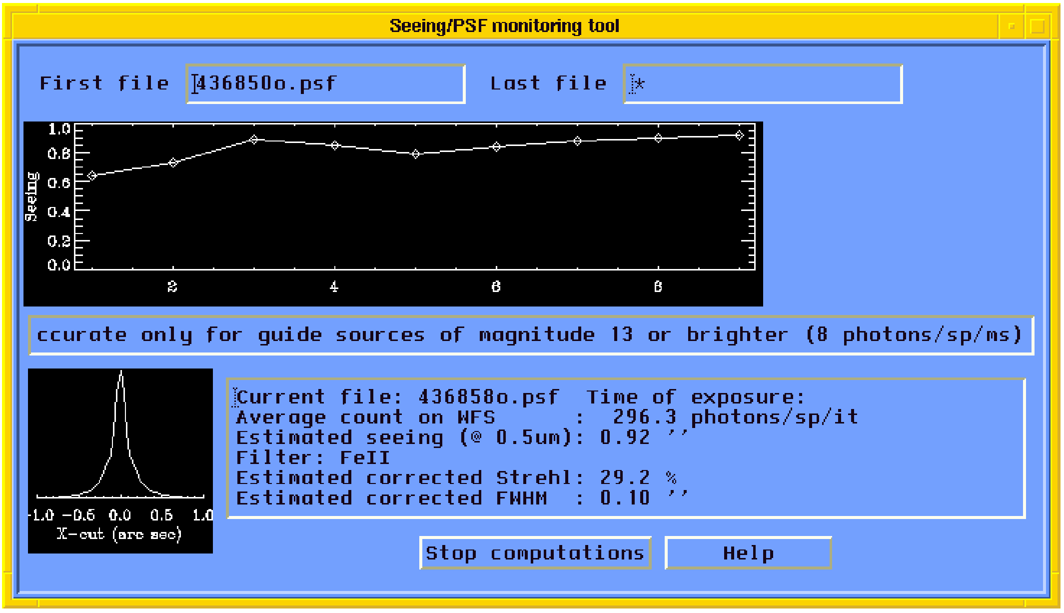


Figure 7: PUEO seeing and PSF monitoring tool.

suppression of correlated noise, etc.

Data selection and combination The cleaned data can be directly combined or, alternately, a selection can be made amongst a given set of data, using one or several criteria such as the Strehl ratio, the FWHM, the encircled energy, the value and the location of the image maximum, etc. This can be usefull for instance if the AO correction has significantly changed during the observations. Statistics are then calculated for each individual image in the data set and thresholds applied. In both cases, the images are finally combined according to the acquisition sequence used at the telescope: co-addition with or without accurate re-centering (a shift-and-add algorithm can be used for instance), mosaicing...

Deconvolution If needed (for instance to reduce overlapping of sources in a crowed region), the data can then be deconvolved using a large variety of algorithms such as CLEAN, Wiener filtering, Lucy-Richardson, Maximum Entropy, blind or myopic deconvolution, etc. Most of these methods require a good estimation of the PSF as input (see section 2.3.1) whereas some deconvolution algorithms (blind of myopic deconvolutions) will be able to derive the PSF from the actual data. The selected deconvolution method may also depend of the final use of the data, as some algorithms will conserve the photometry and other ones will not. It good be a good idea to apply several different deconvolution methods to the same set of data, to test for possible reduction artifacts. See Christou (1998) in these proceedings for a more complete description of the deconvolution methods.

A model fitting approach is also possible when the geometry of the source is known *a priori* and simple enough to be represented by a small set of parameters, as in the case of binary systems, star clusters and disks (Véran & Rigaut 1998; Véran, Beuzit, & Chaytor 1998).

Specific modes Peculiar reduction procedures, broadly available or "home-made", may also be needed for particular observing modes such as coronography (Beuzit et al. 1998), polarimetry, Fabry-Perot or integral field spectroscopy (Le Mignant et al. 1998; Chalabaev et al. 1998).

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