Mapping the PSF across Adaptive Optics images

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Abstract

• Adaptive Optics (AO) has become a key technology for all the main existing telescopes (VLT, Keck, Gemini, Subaru, LBT..) and is considered a kind of enabling technology for future giant telescopes (E-ELT, TMT, GMT).

• AO increases the energy concentration of the Point Spread Function (PSF) almost reaching the resolution imposed by the diffraction limit, but the PSF itself is characterized by complex shape, no longer easily representable with an analytical model, and by sometimes significant spatial variation across the image, depending on the AO flavour and configuration.

• The aim of this lesson is to describe the AO PSF characteristics and variation in order to provide (together with some AO tips) basic elements that could be useful for AO images data reduction.
What’s PSF

‘The Point Spread Function (PSF) describes the response of an imaging system to a point source’

Circular aperture of diameter $D$ at a wavelength $\lambda$ (no aberrations) → Airy diffraction disk

\[ I_\theta = I_0 \frac{J_1(x)}{x^2} \]

Where $J_1(x)$ represents the Bessel function of order 1

\[ x = \pi(D/\lambda)\sin\vartheta \]

$\vartheta$ is the angular radius from the aperture center

→ First goes to 0 when $\vartheta \sim 1.22 \frac{\lambda}{D}$

Figure 1.15. The point spread function (solid line) of the Airy diffraction pattern for a circular aperture of diameter $D$ is illustrated both as an image and in cross-section.
Imaging of a point source through a general aperture

Consider a plane wave propagating in the z direction and illuminating an aperture.

The element $ds = dudv$ becomes the source of a secondary spherical wave.

The complex field in $P$ generated by $dS$ is:

$$dE = \frac{\varepsilon_0}{r} e^{i(\omega t - kr)} dS$$

$$R = \sqrt{x^2 + y^2 + z^2}$$

$$r = \sqrt{z^2 + (x-u)^2 + (y-v)^2} = R[1 + \frac{u^2 + v^2}{R^2} - \frac{2(ux + vy)}{R^2}]^{1/2} \approx R[1 - \frac{ux + vy}{R^2}]$$

The PSF is the field intensity distribution in the image plane.

$$E(x, y) \approx \frac{\varepsilon_0}{R} e^{i(\omega t - kR)} \iint e^{ik(ux+vy)/R} dudv$$
Imaging of a point source through a circular aperture

- Spherical coordinates

\[ u = \rho \cos \vartheta \quad v = \rho \sin \vartheta \]
\[ x = q \cos \varphi \quad y = q \sin \varphi \]
\[ ds = \rho d\rho d\varphi \]

\[ E(x, y) \propto \int_0^\alpha \int_0^{2\pi} \rho e^{i(k\rho q/R)} \cos(\vartheta - \varphi) d\rho d\vartheta = 2\pi a^2 \left( \frac{R}{k\rho q} \right) J_1 \left( \frac{R}{k\rho q} \right) \]

\[ I(\alpha) = I(0) \left[ \frac{2J_1(ka \sin \alpha)}{ka \sin \alpha} \right]^2 \text{ where } \alpha = q/R \]

- ...or we can define a function

\[ A(u, v) = \begin{cases} 1 & \text{if } (u, v) \in \text{aperture} \\ 0 & \text{otherwise} \end{cases} \]

\[ E(x, y) \propto \int_0^{+\infty} \int_{-\infty}^{+\infty} A(u, v) e^{i\frac{k}{R}(ux + vy)} \, du \, dv \]

- \[ f_x = \frac{k}{R} x \quad f_y = \frac{k}{R} y \]

\[ E(f_x, f_y) = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} A(u, v) e^{i(f_x u + f_y v)} \, du \, dv = \text{FT}[A(u, v)] \]

- The field distribution in the image plane is the spatial frequency spectrum of the aperture function

\[ I(f_x, f_y) = |E(f_x, f_y)|^2 = |\text{FT}[A(u, v)]|^2 \]
PSF computation using FFT

FUNCTION square_PSF, n, d

\[ x = \text{rebin}(\text{findgen}(n) - n/2, n, n) \]
\[ y = \text{rebin}(\text{transpose}(\text{findgen}(n))) - n/2, n, n) \]
\[ a = \text{abs}(x) \leq d/2 \text{ and abs}(y) \leq d/2 \]
\[ a = \text{shift}(a, -n/2, -n/2) \]
\[ \text{psf} = \text{abs}(\text{fft}(a))^2 \]
\[ \text{psf} = \text{shift}(\text{psf}, n/2, n/2) \]
\[ \text{psf} = \text{psf} / \text{total}(\text{psf}) \]
return, psf
end

FUNCTION circ_PSF, n, d

\[ x = \text{rebin}(\text{findgen}(n) - n/2, n, n) \]
\[ y = \text{rebin}(\text{transpose}(\text{findgen}(n))) - n/2, n, n) \]
\[ a = \text{sqrt}(x^2 + y^2) \leq d/2 \]
\[ a = \text{shift}(a, -n/2, -n/2) \]
\[ \text{psf} = \text{abs}(\text{fft}(a))^2 \]
\[ \text{psf} = \text{shift}(\text{psf}, n/2, n/2) \]
\[ \text{psf} = \text{psf} / \text{total}(\text{psf}) \]
return, psf
end
Circular apertures of different sizes

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Circular aperture with central obstruction

Obstruction = 0.0

Obstruction = 0.5

Obstruction = 0.8
Different apertures

LBT

JWST

Erice School 2015: Science and Technology with E-ELT
**Diffraction in presence of aberrations**

- In the ideal case (red), the incident wavefront is flat; the converging optical element focuses on the focal plane the Fraunhofer diffraction pattern that would be observed at a very long distance.

- In the aberrated case (blue), the wavefront is distorted and the diffraction pattern on the focal plane will be different.

**NOTE** that the aberrations can be introduced by the optical system itself.

In presence of aberrations, the complex field of the incoming wave on the aperture can be expressed as:

\[ E(u,v) = e^{i \phi(u,v)} \]

The function \( \phi(u,v) \) describes the wavefront distortions.

The intensity distribution, in Fraunhofer approximation, becomes:

\[ i(f_x, f_y) = |E(f_x, f_y)|^2 = |\text{FT}[A(u,v)e^{i \phi(u,v)}]|^2 \]
Modal Representation of aberrations

- Wavefront distortions at the entrance of the telescope can be represented as the linear combination of a proper defined basis of functions.
- Zernike polynomials are orthogonal.
- They are defined in polar coordinates on a unit circle as functions of azimuthal frequency $m$ and radial degree $n$, where $m \leq n$, and $n - m$ is even.

\[
Z_{\text{even}, j} = \sqrt{n + 1} R_n^m \rho \sqrt{2} \cos m\theta
\]

\[
Z_{\text{odd}, j} = \sqrt{n + 1} R_n^m \rho \sqrt{2} \sin m\theta
\]

\[
Z_j = \sqrt{n + 1} R_n^0(\rho)
\]
Circular Aperture PSF in presence of aberrations (static)

The first term (piston) does not have any effect on the image. The second term (tilt) produces a shift in the image. The higher orders terms introduce deformation in the PSF.
The Strehl Ratio

The Strehl Ratio (SR) is the ratio of the peak aberrated image intensity from a point source compared to the maximum attainable intensity using an ideal optical system limited only by diffraction over the system's aperture.

\[ SR = \frac{I_0}{I_{0,\text{DIFFR}}} \]

Marechal approximation: SR > 0.1 where \( \sigma_\phi \) is the standard deviation of the phase (Wavefront error)
Circular Aperture PSF in presence of atmospheric turbulence

- Before entering the atmosphere, light from stars forms plane waves (flat wavefronts). Refraction index variations in space and time due to turbulent air cells along the wavefront path, produce local variations in the wavefront phase.

![Incoming flat wavefront](image1)

![Inomogeneous and turbulent medium](image2)

![Distorted wavefront](image3)

- From the Power Spectrum of the Refractive Index it is possible to build a ‘phase map’, that describe, point by point, the phase delay caused by the atmospheric refraction index variation.

- The Refractive index power spectrum follows a $-11/3$ power law (Kolmogorov)
How to build a phase map (screen)

- A turbulent layer can be simulated with the computer multiplying the sqrt of power spectrum by a random phase.

```plaintext
pro makelayer, layer

nsize = 256
npupil = 64
d = 8.0
pixlayer = d / npupil
r0 = 0.5
Dr0 = d/r0
layer = dblarr(nsize,nsize)
f_sampling = double(pixlayer*double(nsize))
u = frequencies(nsize,pixlayer)

ps = double(abs(u)^(-11.d/3.d))
phase = (2.d0*randomu(Seed,nsize,nsize)-1.d0)*!Dpi
CPS = Sqrt(ps)*DComplex(Cos(Phase), Sin(Phase))
layer = fft(CPS,1,/Double)
layer = shift(layer,nsize/2,nsize/2)
layer = layer - (moment(layer, /DOUBLE))[0]
layer = layer * sqrt(1.0299d0*Dr0^(5.d0/3.d0))

return
end
```

The sqrt of the power spectrum is multiplied by sin and cos of the random phase and the fourier transform (from frequency to distance space) represents the phase map.
The Fried Parameter

- The Fried Parameter $r_0$ gives a measure of the strength of the turbulence. It is defined as the following:

$$r_0 = [0.423 k^2 (\sec \xi) \int dh C_N^2(h)]^{-3/5}$$

$$r_0 \propto \lambda^{6/5} (\sec \xi) \int dh C_N^2(h)]^{-3/5}$$

- $r_0$ gets small when turbulence is strong ($C_N^2$ large)
- $r_0$ gets bigger at longer wavelengths (10-20 cm @ 550 nm, 50 cm @ 2200 nm)
- $r_0$ gets smaller as telescope looks toward the horizon
- $r_0$ defines an aperture size over which the mean-square wavefront error is 1 rad$^2$
Circular Aperture PSF in presence of atmospheric turbulence

- We compute the instantaneous PSF remembering that:

\[ i(f_x, f_y) = |E(f_x, f_y)|^2 = |FT[A(u, v)e^{i\phi(u, v)}]|^2 \]

1 px ~ 30 cm
Circular Aperture PSF in presence of atmospheric turbulence

- We compute the instantaneous PSF remembering that:

\[ i(f_x, f_y) = |E(f_x, f_y)|^2 = |FT[A(u, v)e^{i\phi(u, v)}]|^2 \]

The short exposure image consists of a large number of speckles having size $\lambda/D$.
Circular Aperture PSF in presence of atmospheric turbulence

- To produce long exposure PSFs, we need a dynamic atmospheric model.

Each of the layer is characterized by its altitude (h), its altitude and its velocity.

The total phase delay at the telescope aperture is given by the $\sum_{1}^{n} \text{layers}$ in the star direction.
Circular Aperture PSF in presence of atmospheric turbulence

- The size of the turbulence degraded image is due to:
  - Diffraction limit of the aperture ($\lambda/D$)
  - Short Exposure image spread ($\lambda/r_0$)
  - Image motion due to overall tilt (determined by both $D$ and $r_0$)
Seeing limited PSF (D/r₀ ~ 10)

- The long exposure PSF (K band) looks like a 2D moffat function having FWHM = seeing

Moffat distribution: \( I(r) = \frac{1}{1 + \left(\frac{r}{r_m}\right)^2 \beta} \) [King 1971]

where \( r_m \) is the moffat radius and \( \beta \) describes the asymptotic power low of the wings
Seeing limited PSF ($D = r_0$)

- For very small apertures, atmospheric turbulence has little effect on the image size, which is determined by $D$.
- Wavefront distortion is mainly overall tilt.

$r_0$ defines the diameter of a diffraction limited telescope
Adaptive optics concept

Deformable Mirror

Distorted Wavefront

Beam Splitter

Corrected Wavefront

Wavefront Sensor

Control System

1 2 3 ... n

r_0

... n-1 n
Shack-Hartmann WFS (SH-WFS)

- array of lenses on a pupil image (num of sub-apertures $\propto (D/r_0)^2$, $r_0$ of the science observations)
- each lens re-images the source as seen by a small telescope having size $r_0$
- an incoming plane WF is focuses on the center of the sub-apertures
- an aberrated WF causes a spots displacement respect to the reference position prop to the local mean WF
- WF measurement performance depends on the centroiding accuracy (SNR of the spot)
Partial compensation

- Zernike modes to represent the aberrated wavefront: \( \phi = \sum_{1}^{n} a_j Z_j \)
- Subtract the measured wavefront
- Compute the PSF
- Integration in time

Incoming wavefront  Fit with zernike  Residual
Partial compensation

The fraction of light in the central core is related to the degree of correction and can be Roughly approximated with the Strehl Ratio.
Partial compensated PSF

Seeing halo \( \sim \frac{\lambda}{r_0} \)

Fitting error

DL core \( \sim \frac{\lambda}{D} \)

Partial compensated PSF

DL PSF and Partial compensated PSF
What happens across the FoV?

- The turbulence is measured only in the direction of the guide star, but the information is used to correct the wavefronts coming from all the directions within the FoV → This causes a degradation of the correction across the FoV. This error is called anisoplanatic error.
MEASUREMENT OF ISOPLANATISM

ISOPLANATISM ANISOTROPY:

An Intuitive Explanation

“Take an ‘Oreo’ cookie.
Take the wafers apart.
Stick them back together, but decentered a lot.
In which direction is it easiest to tip one wafer with respect to the other against the force of correlation exerted by the cream?”

[McClure 1991]
[Sasiela & Shelton 1993]
How do the data look like?

- **Single Conjugate AO →** Highly structured PSF, small FoV

Galactic center, PUEO@ CFHT, K band

Courtesy of F. Rigaut
How do the data look like?

- Single Conjugate AO $\rightarrow$ Highly structured and variable PSF

M92, FLAO @ LBT, Pisces, J band

Guide Star High SR

1 pixel $= 0.021$ arcsec
Exposure Time $= 6$ s
How do the data look like?

21 arcsec

M92, FLAO @ LBT, Pisces, K band

Guide Star
High SR

1 pixel = 0.021 arcsec
Exposure Time = 6 s
PISCES M92 PSF model

- The simplest analytical model that better represents the PSF is given by a narrow Moffat core, a broader Gaussian/Moffat halo and an external torus.
**PSF model**

- Variation of the PSF parameters across the FoV
  - Width of halo constant across the FoV
  - Width of core variable

![Graphs showing variation of PSF parameters across FoV and distance from GS](image)
Another example: NACO

- Image NACO@VLT of NGC 6440 GC [Origlia 2008]
Another example: NACO

- Adopted PSF model:
  - PSF core: Elongated Moffat with axis varying over the FoV
  - Halo: round Moffat with radius = seeing constant over the FoV
Imaging techniques

• **Photometry**: *is the process of obtaining accurate numerical values for the brightness of objects (aperture phot./ PSF fitting).*
  - Time variability of individual sources
  - Flux ratios or luminosity functions of multiple systems [*Harayama et al. 2008*]
  - Color Magnitude Diagrams of resolved stars (GC age, stellar population, stellar evolution, SFH) […]

• **Astrometry**: *precise measurements of the relative positions of objects and their variations (parallax and proper motion)*
  - Dynamical masses of brown dwarfs [*Dupuy et al 2009*]
  - Our Galaxy’s supermassive black hole [*Ghez et al 2005*]
  - Formation and evolution of young star clusters [*Stolte et al 2008*]…
### Imaging techniques

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Imaging techniques

• Aperture Photometry
  – Measurement of the image volume within an ‘appropriate’ aperture. The background is estimated in an annular outer region and subtracted.
  – The optimal aperture size depends on the PSF FWHM, on the S/N and on the crowding of the field.
  – The star position can be computed as a simple center of gravity.
  – Robust and precise for isolated stars.
  – Risk of contamination between sources.
  – *Sextractor [Bertin 1996]*, …

This method does not give us the possibility to take advantage from the resolution in crowded fields.

*It can be used in crowded fields after deconvolution for the PSF...*
Imaging techniques

- **PSF fitting photometry**
  - Fit of the sources in the image with a PSF model
  - The result depends on the model accuracy and on the background estimation (in case of source contamination and/or PSF variability)
  - Suitable for dense stellar fields
  - Need for isolated and bright stars to model the PSF
PSF estimation

• **PSF estimation from data:**
  – Analytical PSF (constant or variable)
  – Numerical PSF (constant over the entire frame or in subdomains)
  – Hybrid PSF (analytical model + numerical residual map)
  – Product of the Blind deconvolution

• **Implemented in image analysis softwares:**
  – **DAOPHOT** (analytical/hybrid/smoothly variable) [*Stetson 1987*]
  – **Romafot** (Purely analytic) [*Buonanno 1983*]
  – **DoPHOT** (Analytical) [*Schecter 1993*]
  – **PSFex** (analytical, linear combination of basis vectors) [*Bertin 2010*]
  – **STARFINDER** (numerical/analytical/hybrid, possible hacking) [*Diolaiti 2000*]
  – **Dolphot (HSTPhot)** [*Dolphine 2000*], …
SCAO data reduction

- SCAO → small corrected FoV, PSF spatial variation, high SR
  - Crowded-field AO astrometry appears to be limited by the inaccurate modeling of the Point Spread Function (PSF) \[\text{Shoedel 2010}\]
  - astrometry of faint sources is biased by residuals due to the incorrect subtraction of the PSF of brighter stars \[\text{Fritz 2009}\]
  - photometric accuracy is limited by the SNR and by the knowledge of the PSF \[\text{Shoedel 2010}\]
  - detection of elongated sources
  - False detections

Astrometric and photometric measurements with AO systems are mainly limited by errors in the PSF modeling and fitting.

- Many ‘exotic’ solutions have been found to reduce data…
PSF fitting with constant PSF

- When the PSF is invariant across the FoV, the photometric error is due mainly to SNR.
- If the PSF elongation is field dependent, fitting the stars with a constant PSF causes the introduction of another (unknown) error source that is field dependent.

... the software will maybe try to fit the elongated sources with multiple stars.
SCAO data reduction

- **SCAO** → small corrected FoV, PSF spatial variation, high SR
  - **Galactic center (NACO):** Image is first Wiener-filter-deconvolved using a suitable PSF (GS psf). Local variations in PSF kernels and ringing is taken care with locally extracted PSF fitting. \[\text{Schoedel 2010}\]
  - **M15 GC (FLAO):** Modified Romafot software. PSF fitting with variable moffat (no parameters fixed). \[\text{Monelli 2015}\]
  - **NGC6440 GC (NACO):** PSF fitting with starfinder using an analytical model composed by 3 gaussian components. \[\text{Origlia 2008}\]
  - Usage of **calibration images** \[\text{Steinbring et al. (2002)}\]
  - Usage of **calibration HST fields**
  - **Galaxy Survey (NACO):** Estimate local PSF around guide star image and model the PSF in the field as the convolution of the GS PSF and a blurring kernel. \[\text{Diolaiti 2000, Cresci 2006}\]
Multi-reference Adaptive Optics

- Using more reference stars from different directions to analyze the wavefront, one can reduce the PSF variation across the FoV.

**GLAO: Ground Layer Adaptive Optics**
Using multiple reference sources it is possible to retrieve the average contribution of the atmospheric turbulence within the guide stars directions → low SR, big FoV (some arcmin)

**MCAO: Multi-Conjugate Adaptive Optics**
Using multiple reference sources AND multiple deformable mirrors conjugated at different altitudes, it is possible to measure the turbulent wavefronts at specific altitudes and to apply the correction directly where they are generated → medium SR, medium FoV (~1 arcmin)
How do the AO data look like?

- **Multi Conjugate AO** → Improved PSF uniformity across a larger FoV

1 arcmin

ωCen, MAD @ VLT, K band

[Bono et Al 2009]
How do the AO data look like?

- **Multi Conjugate AO** → Improved PSF uniformity across a larger FoV

    FoV = 2 arcmin

    We extract numerically the psf from different subregions of the field to analyze its variation

    → The accuracy of the local PSF depends on the local crowding and on the presence of bright local stars
How do the AO data look like?

• K – band image

Local extracted PSFs

→ Small variation occurs: slightly elongated at the field corners
MCAO data reduction

- **MCAO** → To improve the PSF uniformity across the FoV
  - Suitable to study dense stellar field, galaxy morphology
  - MAD: **Many papers** have been published *[Melnick SPIE 2012 for a review]*
  - GeMs: First papers are coming out
  - **Most diffused software** for image analysis, not optimized for PSF variation across the FoV, has been used

The presence of two red clumps implies the presence of two different stellar populations. *[Ferraro et Al, Nature, 2009]*
MAORY phase A PSF

- Multi conjugate Adaptive Optics RelaY for the E-ELT
- Wavefront sensing based on 6 Sodium LGS and 3 NGS
- Uniform AO correction on a large FoV (2')
MAORY phase A PSF

K band PSF
SR ≈ 0.6
Image size = 2.7"

DIFFRACTION  FITTING + ALIASING ERRORS  SEEING

Airy  Hexagonal Moffat × mask  Moffat × mask  Moffat
Conclusions

• If you want to gain in spatial resolution you need a big telescope
• If you want a big telescope, you have to stay on the ground
• If you want a big telescope on the ground and gain really in resolution, you need adaptive optics
• If you want to take full advantage of the scientific information encoded in AO images, you need to manage the data in the proper way
• If you want to manage data in the proper way, you need to know the PSF structure
• If you want to know the PSF structure, you need a flouring on Adaptive Optics techniques