Atmospheric Turbulence and Astronomical Adaptive Optics

Matthew Britton
Caltech Optical Observatories
Outline

• Atmospheric turbulence profiles
• Turbulence and image quality
• Angular anisoplanatism
• PSF estimation and deconvolution
• Differential tilt jitter
• The PSF of a laser guide star AO system
• Wide field adaptive optics architectures
Atmospheric Turbulence
Atmospheric Turbulence

1.25 µm PSF
1.65 µm PSF
2.2 µm PSF
Atmospheric Turbulence Monitors

- Differential Motion Measurement (DIMM)
- Slope Detection and Ranging (SLODAR)
- Sonic Detection and Ranging (SODAR)
- Scintillation Detection and Ranging (SCIDAR)
- Shadow Band Ranging (SHABAR)
DIMM

http://www ociw edu/~birk/CDIMM/cdimm.html
SLODAR

From Wang, Chanan & Schoeck

http://eraserhead.caltech.edu/palomar/MGSU/MGSU.html
Scintillation

\[
z = 0.1 \quad 0.5 \text{ um} \quad 1 \text{ um} \quad 2 \text{ um}
\]

← 5 meters →
http://www.iac.es/galeria/bgarcia/SCIDAR_webpage/SCIDAR_IAC.html
Multi Aperture Scintillation Spectrometry

http://www.ctio.noao.edu/~atokovin/profiler/index.html
DIMM/MASS

http://odata1.palomar.caltech.edu/massdimm/
Fried Parameter and Seeing

\[ r_0 = \left[ 0.423 k_0^2 \int_0^\infty d\zeta C_n^2(\zeta) \right]^{-3/5} \]

The Fried parameter \( r_0 \) is the lateral coherence scale of the wavefront phase

\[ Seeing = \frac{\lambda}{r_0} \]
Fried Parameter Variability
Seeing Variability
Seeing and $r_0$ Statistics
Atmospheric Turbulence and Image Quality
The Long Exposure Point Spread Function

Diffraction limit \((\lambda/D)\)

Seeing limit \((\lambda/r_0)\)

Seeing limit (x40)
Long Exposure Seeing Limited PSF Variability
An AO Simulation

Aberrated Phase

TTM Surface

DM Surface

Residual Phase

PSF

DL PSF
Strehl Ratio vs Time

Strehl History

- Centroid tilt projection
- Actuator tilt projection
- No compensation

Time (seconds)

Strehl Ratio
Guide Star Strehl Variability

• Short term Strehl variability arises from the random realizations of atmospheric turbulence.

• Long term Strehl variability arises from the evolution of the atmospheric turbulence profile and the resulting change in AO system performance. For example, fitting error for an AO system with subapertures of size d is

\[
\sigma_F^2 = \alpha_F \left( \frac{d}{r_0} \right)^{5/3}
\]
Angular Anisoplanatism
Anisoplanatic Wavefront Phase Errors
30 asec separation

http://www.gemini.edu/sciops/instruments/adaptiveOptics/MCAO.html
Isoplanatic Angle

\[ \theta_0 = \left[ 2.91k_0^2 \mu_{5/3} \right]^{-3/5} \]

\[ \mu_{5/3} = \int d\zeta C_n^2(\zeta) \zeta^{5/3} \]

\( \Theta_0 \) is the angular decorrelation scale for wavefront phase aberrations arising from atmospheric turbulence.
Isoplanatic Angle Variability
$\Theta_0$ Statistics
Long Exposure PSF of a Perfect AO System
Trapezium Images from Palomar

Guide star

Stars 1,2

Tue Jan 9 06:21:10 2007

Guide star

Stars 1,2

Tue Jan 9 06:21:10 2007
Astronomical Impact of PSF Variability in Time and Field

• Turbulence profile variability is not stationary on observational timescales, so PSF variability doesn’t average away.

• Variations depend on turbulence and wind profiles, which impact AO system performance and anisoplanatic degradation.

• Variability in Strehl ratio can be factors of several on timescales of a minute or less.
Quantitative Applications of Astronomical Adaptive Optics

• Differential photometry
• Differential astrometry
• High contrast imaging
• Imaging and IFU spectroscopy of resolved objects

To understand the level of precision AO can provide, one must understand the consequences of turbulence profile variability on PSF stability in a particular observational context.
PSF Estimation and Deconvolution
PSF Estimation

• From a PSF calibration star

• From the data

• From a parameterized model

• From a measured turbulence profile
The Anisoplanatic Transfer Function

\[ OTF_{oa}(r) = \exp\left[-0.5 \, D_{apl}(r)\right] \, OTF_{gs}(r) \]

\[ D_{apl}(r) = 2^{8/3} \Xi k_0^2 \int_0^\infty dz \, C_n^2(z) \left\{ 2\left|z\theta_{ab}\right|^{5/3} + 2\left|r\right|^{5/3} - \left|r + z\theta_{ab}\right|^{5/3} - \left|r - z\theta_{ab}\right|^{5/3} \right\} \]
PSF Estimation from $C_n^2$ Profile

$$OTF_{gs}(r) \exp\left[-0.5 D_{apl}(r)\right] = OTF_{oa}(r)$$
Observed and Predicted PSFs

2.12 um Meas GS
Strehl 0.51

2.12 um Meas Cmp
Strehl 0.28

2.12 um Prd Cmp
Strehl 0.27

1.65 um Meas GS
Strehl 0.32

1.65 um Meas Cmp
Strehl 0.11

1.65 um Prd Cmp
Strehl 0.11
Trapezium PSF Predictions

Stars 1,2

Star 3

Star 4
Deconvolution
Observations of a Quadruple
Modelling the Observation

- Observed Triple
- Modeled Triple
- Model Residuals
Differential Tilt Jitter
Differential Tilt Jitter

To leading order

\[
\begin{bmatrix}
\sigma_\perp^2 \\
\sigma_\parallel^2
\end{bmatrix} \approx 2.67 \left( \frac{\mu_2}{D^{1/3}} \right) \left( \frac{\theta}{D} \right)^2 \begin{bmatrix} 3 \\ 1 \end{bmatrix}
\]
Tilt Jitter vs Angular Separation
Probability of the Measurements

\[ P(r) \propto \exp\left\{ -0.5(r - \bar{r})^T \Sigma^{-1} (r - \bar{r}) \right\} \]

\[ \Sigma_{ij} = \left< \left( r_i - \langle r_i \rangle \right) \left( r_j - \langle r_j \rangle \right) \right> \]
Grid Astrometry

\[ S = \sum_i \frac{r_i}{|\langle r_i \rangle|^2} \]

\[ \sum_{s} \rightarrow = A^T \Sigma A \]
Grid Astrometry in Trapezium

25 Images Averaged

\[ \frac{1}{\sqrt{N}} \]

10 stars averaged

\[ \frac{1}{\sqrt{t}} \]

300 uas in 30 sec

Cameron, Britton & Kulkarni, in prep.
Focal Anisoplanatism
LGS Adaptive Optics
Focal Anisoplanatism Parameter

\[ d_0 = \left\{ k_0^2 \left[ .5 \left( \frac{\mu_{5/3}}{H^{5/3}} \right) - .452 \left( \frac{\mu_2}{H^2} \right) \right]^{-3/5} \right\} \]

In the differential wavefront phase between the LGS and the science target, \( d_0 \) is the size of the coherence patch in the pupil plane.
$d_0$ Variability
$d_0$ Statistics
LGS Focal and Angular Anisoplanatism
The LGS PSF

The PSF is stable over a field of view of size

\[ 2\theta_c = \frac{D}{H} = 70'' \left( \frac{D}{30\, m} \right) \left( \frac{90\, km}{H} \right) \]

The PSF core width is

\[ w = \frac{\lambda}{d_0} = 50\, mas \left( \frac{\lambda}{1\, \mu m} \right) \left( \frac{4\, m}{d_0} \right) \]
Wavefront Sensing with Multiple Laser Beacons
Multiconjugate Adaptive Optics
ESO Multiconjugate AO Demonstrator

- Uses two 60 actuator bimorph deformable mirrors conjugated to 0km, 8.5km
- Wavefront sensing performed with three natural guide stars
Multiobject Adaptive Optics

Optically separate the light from each science target and correct wavefront phase aberrations using a deformable mirror.
Summary

• Measurement of atmospheric turbulence profiles
• Effects of turbulence on image quality
• Variability of the AO PSF in time and field
• Estimation of the AO PSF
• Quantitative applications of AO
• The motivation for future wide field astronomical adaptive optics architectures

Thank you