Adaptive Optics for DAG Telescope

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Adaptive Optics Systems Introduction

- **Ground Based Telescopes**
  - Advantages: Low cost to build and operate.
  - Disadvantages: Low resolution (because of turbulence).

- **Hubble Space Telescope**
  - Advantages: High resolution.
  - Disadvantages: Extremely high cost to build, launch and operate, small aperture size.

- **Ground Based Telescopes with AO Systems**
  - Advantages: High resolution, larger aperture, moderate cost.
  - Disadvantages: Partial correction & LGS requirement for 100% sky coverage.

(a) Conventional Telescope
(b) Hubble Space Telescope
(c) Telescope with AO

Titan - CFAO Image Gallery (Keck & Hubble Telescopes)
Optical Turbulence

FWHM = \lambda/D(1+(D/r_0)^2)^{1/2}

PSF Width:

- No turbulence – diffraction limited
telescope D=4m, at 500 nm, FWHM = 0.026”
- With turbulence
typical value r_0=0.1 m at 500 nm

FWHM=1.04” – 40 times larger

- How fast is the optical turbulence?
  - Turbulent layer wind speed is ≈ 10-20 m/s
  - It takes about 0.01 s for the turbulent layer to move a distance r_0
  - Optical turbulence time scale is ~ 1-10 ms, and this is the typical rate at which AO system must operate
Adaptive Optics refers to optical systems which adapt to compensate for optical effects introduced by the medium and its image.
AO System Dimensioning

AO System Design Depends on the Science Program:

• for extreme correction one needs brights stars,
• for wide field correction one needs several stars with limited correction

• Multi-parameter optimization:
  ➢ WFS lenslet pitch
  ➢ WFS integration time

• WFS lenslet pitch selection (projected in telescope pupil)
  ➢ Spatial frequency correction cut-off on the wavefront is higher in case of using a lower pitch...
  ➢ Tradeoff: lower the photon counts, noise goes up
  ➢ An optimal lenslet pitch calculation exists:

\[ \sigma_{\phi,\text{res}}^2 = 0.274 \left( \frac{d}{r_0} \right)^{5/3} \]
AO System Performance Improvement
Image Formation through Adaptive Optics

PSF can be defined as the response of an imaging system to a point source of light

In Spatial domain

\[ I(\vec{\alpha}) = O(\vec{\alpha}) \otimes PSF(\vec{\alpha}) \]

In Fourier domain

\[ \tilde{I}(\vec{f}) = \tilde{O}(\vec{f}) \cdot OTF(\vec{f}) \]
Importance of PSF Reconstruction in AO

• PSF reconstruction is used in calibrating image analysis techniques for astrometry, and in the deconvolution of images to enhance their contrast.

• Why do we need PSF reconstruction?
  
  ➢ The optical effects of atmospheric turbulence.

  ➢ The partial correction by the AO system.

  ➢ Anisoplanatism.
On and Off-Axis PSF Reconstruction from DAG AO Systems

\[ \varphi_{\text{tot}}(\tilde{\theta}) = \varphi_{\text{turbulence}}(\tilde{\theta}) - \varphi_{\text{turbulence}}(0) - \varphi_{P\varepsilon}(0) + \varphi_{O}(0) \]
PSF Reconstruction from Performance from DAG AO Systems

a) The target object, or objects without AO correction. b) The AO system running in closed-loop. c) The improvement by the PSF deconvolution (CFHT telescope image Gallery)
Conclusions

AO system development at Işık University

- DPT application for building of an AO laboratory has been finalized to gain local experience (via a scaled down experiment for instance)

- Apply this knowledge to the DAG AO systems
  - Classical AO
  - Ground Layer AO (GLAO)

- Testing new & sophisticated control algorithms for different AO schemes to be implemented

- PSF reconstruction tools for improving performance

*and deliver turn key AO systems for DAG*
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Estimation of the Orthogonal Phase ($\varnothing_0$)

The orthogonal component is estimated from Kolmogorov's atmospheric turbulence theory:

- The AoA experiment is used to determine the Fried coherence length ($r_0$);
- Phase screens are generated by Monte-Carlo simulation from the extracted $r_0$;
- The parallel component of the phase (DM phase) is removed from the generated phase screens; and
- The structure function of the orthogonal component of the phase is computed.

The determination of the OTF also leads to the determination of the estimated long-exposure PSF via a single discrete Fourier transform.
Estimation of the Parallel Phase ($\varphi_{P\varepsilon}$)

$$
\varphi_{P\varepsilon}(\vec{r}, t) = \sum_{i=1}^{N_{\text{TT mirror}}} \varepsilon_i(t) M_{\text{TT mirror}}(\vec{r}) + \sum_{i=1}^{N_{\text{woofer}}} \varepsilon_i(t) M_{\text{woofer}}(\vec{r}) + \sum_{i=1}^{N_{\text{tweeter}}} \varepsilon_i(t) M_{\text{tweeter}}(\vec{r})
$$

$$
M_{\text{total}} = \begin{bmatrix} M_{\text{TT mirror}} & M_{\text{woofer}} & M_{\text{tweeter}} \end{bmatrix}
$$
and

$$
N_{\text{total}} = N_{\text{TT mirror}} + N_{\text{woofer}} + N_{\text{tweeter}}
$$

$$
D_{\varphi_{P\varepsilon}}(\vec{r}, \vec{\rho}) = \left\langle \left| \varphi_{P\varepsilon}(\vec{r}, t) - \varphi_{P\varepsilon}(\vec{r} + \vec{\rho}, t) \right|^2 \right\rangle
$$

$$
D_{\varphi_{P\varepsilon}}(\vec{r}, \vec{\rho}) = \sum_{i=1}^{N_{\text{total}}} \sum_{j=1}^{N_{\text{total}}} \langle \varepsilon_i \varepsilon_j \rangle \left[ M_{\text{total}}(\vec{r}) - M_{\text{total}}(\vec{r} + \vec{\rho}) \right] \left[ M_{\text{total}}(\vec{r}) - M_{\text{total}}(\vec{r} + \vec{\rho}) \right] \Rightarrow \bar{D}_{\varphi_{P\varepsilon}}(\vec{\rho}) = \sum_{i=1}^{N_{\text{total}}} \sum_{j=1}^{N_{\text{total}}} \langle \varepsilon_i \varepsilon_j \rangle U_{ij}(\vec{\rho})
$$

$$
U_{ij}(\vec{\rho}) = \frac{F^{-1}\left\{ 2 \text{Real} \left[ F(M_i M_j P)(F^*(P) - F(M_i P)F(M_j P)) \right]\right\}}{F^{-1}(|F(P)|^2)}
$$
Off-Axis PSF Reconstruction

\[ OTF(\hat{\rho}, \lambda)_{\text{Total}} = OTF(\hat{\rho}, \lambda)_{\text{Anisoplanatic}} \cdot OTF(\hat{\rho}, \lambda)_{AO} \cdot OTF(\hat{\rho}, \lambda)_{TEL} \]

\[ OTF(\hat{\rho}, \lambda)_{\text{Anisoplanatic}} = \exp \left[ -\frac{1}{2} \left( D_{\varphi_{AO}}(\hat{\rho}) \right) \right] \]

\[ D_{\varphi_{\text{tot}}}(r_1, r_2) = D_{\text{Ani}}(r_1, r_2) + D_{AO}(r_1, r_2) \]
\[ + 2 \left( \left| \varphi_{\text{Ani}}(r_1) \varphi_{AO}(r_1) + \varphi_{\text{Ani}}(r_2) \varphi_{AO}(r_2) - \varphi_{\text{Ani}}(r_1) \varphi_{AO}(r_2) - \varphi_{\text{Ani}}(r_2) \varphi_{AO}(r_1) \right| \right) \]

\[ D_{\text{Ani}}(r_1, r_2) = 2\Xi k^2 D^{5/3} \]
\[ \times \int_0^\infty C_N^2(z)dz \left\{ 2|\Omega|^{5/3} + 2\left| \frac{2}{D} (r_1 - r_2) \right|^{5/3} - 2\left| \frac{2}{D} (r_1 - r_2) + \Omega \right|^{5/3} - 2\left| \frac{2}{D} (r_1 - r_2) - \Omega \right|^{5/3} \right\} \]

\[ \Omega(z) = \left( \frac{2z}{D} \right) \theta \]