Introduction

Adaptive optics for filled apertures

Interferometry

Adaptive optics for sub-mm interferometry

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Some example science drivers for high resolution astronomy:

▶ Active Galactic Nuclei – understanding physics of massive black holes
▶ Formation of planetary systems from dust disks
▶ Galaxy structure at intermediate/high z – when/how did galaxies form?
▶ Overcoming source confusion – simply telling different sources apart for follow-up at other wavelengths
Galactic centre high resolution imaging

High resolution imaging over a long period of time allows tracking orbits of stars in close proximity to the central black hole

Simulation of sub-mm observation of proto-planetary systems

Observability of gaps with ALMA telescope [Wolf & A’Angelo, 2005. (50+100pc, 1+5 $M_{\text{jupiter}}$)]
What limits resolution?

- Diffraction is the absolute limit
- Atmosphere often degrades resolution to much worse than diffraction limit
- Sometimes resolution is high but it is not easy to make an image – too little information (closure phase interferometry, speckle interferometry)
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‘Seeing’ – simulation of turbulence

Astronomical wavefront
The turbulent troposphere
Corrupted astronomical wavefront

The apparent direction of incoming radiation changes as function of time and position
Turbulence – properties

- Turbulence is to a good approximation ‘self-similar’ – only one intrinsic parameter: “strength” of the turbulence
  
  \[
  D_n(\vec{\rho}) \equiv \left\langle |n(\vec{r}) - n(\vec{r} + \vec{\rho})|^2 \right\rangle \quad (1)
  \]

  \[
  D_n(\vec{\rho}) = C_n^2 |\rho|^{2/3} \quad (2)
  \]

- Strength often expressed as **Fried parameter**: 
  
  \[
  r_0 = 0.185 \lambda^{6/5} \left( \int dh C_n^2 \right)^{-3/5} \quad (3)
  \]

- Size of image of point source depends on turbulence strength: \( \text{FWHM} \sim \lambda / r_0 \propto \lambda^{-1/5} C_n^{6/5} \)

- Typical Fried parameter at visible wavelengths \( r_0 \sim 10 \text{ cm} \)
Turbulence simulation – entire realisation
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Translating a frozen phase screen
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation
Seeing simulation – averaged PSF
Adaptive optics – Principles

- Atmosphere corrupts the wavefront through refractive index variations
- Use incoming light from a *strong reference* source to *measure* the effects of the atmosphere
- Correct for these on fast time scales (e.g., 2 milliseconds) using one or more deformable mirrors
- Bring the light to an imager/spectrograph after correction for atmospheric effects
Turbulence – additional important quantities

When trying to correct seeing, two more quantities become important:

- Iso-planatic patch $\iff$ height of turbulence layer
  \[ \theta_0 \sim 0.314 r_0 / H \] (4)
  Governs the angular distance over which wavefront correction can be transferred

- Characteristic timescale $\iff$ wind-speed
  \[ \tau_0 \propto r_0 / V \] (5)
  Governs the frequency at which adaptive optics must update the correction
Measuring the wavefront errors

- The wavefront is approximately flat over $r_0$ – divide the wavefront arriving at primary mirror into sections $\sim r_0$ size
- Image these individual sections – reference will form a point source image for each section
- The position, size (and shape to some extent) of the reference source images tell us about deformations in that section

[Note: in sub-mm we measure the properties of the atmosphere and infer wavefront errors]
Shack-Hartmann principle of operation
Shack-Hartmann principle of operation
Shack-Hartmann principle of operation
Lenslet apertures
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Deformable mirror technology

These are images for an ESO deformable secondary mirror:

Actuators

‘Voice coils’

Deformable glass shell

Credit: ESO/http://www.eso.org/sci/facilities/develop/ao/sys/dsm.html
Limitations of Adaptive Optics

1. Need relatively bright stars as reference sources (e.g., NAOS/VLT: $V \sim 16$ mag)

2. They need to be quite close (for best performance as close as 5 arcseconds!)

3. Artificial reference (‘laser guide stars’) sometimes used

4. It usually not possible to achieve diffraction limited performance at visible wavelengths

5. Multiple layers of turbulence require multiple correction mirrors (“Multi-conjugate” adaptive optics)

6. High degree of complexity!
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(Aperture Synthesis) Interferometry

- Overcomes the **mechanical** limits on practical telescope size
- Allows very high resolution, i.e., $\lambda/B$ where $B$ is separation between telescopes
- More sparse the arrays $\rightarrow$ lower the surface brightness sensitivity
- See R. Bolton’s lectures!
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Atacama Large Millimetre Array (ALMA)

19 Antennas in compact configuration

credit: ALMA/ESO/NAOJ/NRAO/W. Garnier

Atmospheric Phase Fluctuations

Astronomical wavefront

The turbulent troposphere

Corrupted astronomical wavefront
Atmospheric Phase Fluctuations

Astronomical wavefront

The turbulent troposphere

Corrupted astronomical wavefront

\( R(t) \)
Atmospheric Phase Fluctuations

Astronomical wavefront

The turbulent troposphere

Corrupted astronomical wavefront
Path fluctuations due to the atmosphere

Path fluctuation on a baseline of $\sim 500$ m inferred from ALMA observations of a quasar at $\lambda = 3.3$ mm.
Water Vapour cm/mm/sub-mm lines

1 mm precipitable water vapour

\[ T_b (K) \]

\[ \nu (GHz) \]
Water Vapour cm/mm/sub-mm lines

1 mm precipitable water vapour

183 GHz Water Line – ALMA WVR system

22 GHz Water Line – previous WVR systems
The 183 GHz Water Vapour Line

Blue rectangles are *nominal* WVR filters
Astrophysical Techniques III

B. Nikolic

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WVR in the ALMA receiver cabin
Data-set A002_Xb9f5d_X1: Long baseline
Red: uncorrected phase; Blue: corrected phase
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