Motivation

• The Giant Segmented Mirror Telescope (GSMT), the committee’s top ground-based recommendation and second priority overall, is a 30-m-class ground-based telescope that will be a powerful complement to NGST in tracing the evolution of galaxies and the formation of stars and planets. It will have unique capabilities in studying the evolution of the intergalactic medium and the history of star formation in our galaxy and its nearest neighbors. GSMT will use adaptive optics to achieve diffraction-limited imaging in the atmospheric windows between 1 and 25 μm and unprecedented light-gathering power between 0.3 and 1 μm. The committee recommends that the technology development for GSMT begin immediately and that construction start within the decade. Half the total cost should come from private and/or international partners. Open access to GSMT by the U.S. astronomical community should be directly proportional to the investment by the NSF.
Effects of turbulence on a stellar image

Hardy 1998 (fig 2.1)

Atmospheric Distortion (seeing)
Phase Structure Function

- The phase structure function
  - Characterizes the changes in the phase at the surface of a collection aperture – first derived by Fried
  - In MKS units

\[
D_\psi(r) = \frac{115}{\lambda^2} r^{5/3} \sec(z) \int C_n^2(h) dh
\]

where \( z \) is the zenith angle and the integral is performed over the beam path
Coherence Length

- The will be some length scale, \( r_0 \), over which the gross wavefront distortion is limited to a uniform tilt.
- This distance is called the coherence length (or Fried parameter).
- Fried derived this as:

\[
D_s(r) = 6.88 \left[ \frac{r}{r_o} \right]^{3/5}
\]

where

\[
r_o = 0.185 \left\{ \frac{\lambda^2}{\sec(z) \int_C C_n(h) dh} \right\}^{3/5}
\]

Seeing

- If we think of this as producing a diffraction-limited image, then the angular resolution limit due to "seeing" will be

\[
\theta = \frac{1.2 \lambda}{r_o} \propto \lambda^{-0.2}
\]

So that the seeing gets better in the infrared compared to the visible.
Coherence Time

- Another useful quantity is the coherence time, $\tau_o$
- **Coherence time**
  - The time over which the near-field phase and far-field beam are relatively constant
  - In MKS units

$$
\tau_o = 0.058 \left[ \frac{\lambda^2}{\sec(z) \int C_n^2(h) h^{5/3} dh} \right]^{3/5}
$$

- Where $v(h)$ is the vertical wind velocity profile.
- This expression is obtained by modeling the atmosphere as a set of phase sheets that are wind driven across the atmosphere.

Isoplanatic Angle

- Isoplanatic angle, $\theta_o$
  - Define the cone in which the optical path measured by a fixed point on the aperture will be constant
  - Again, in MKS units

$$
\theta_o = 0.058 \left[ \frac{\lambda^2}{\sec(z) \int C_n^2(h) h^{5/3} dh} \right]^{3/5}
$$

- This angle represents the maximum tolerable separation between a path sensed (by say a star) and the corrected path (the source).
**Origin of Anisoplanism**

- To source 1
- To source 2
- Overlap region
- Image Plane
- Instrument

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**Atmospheric Characterization**

- \( r_o \) = Coherence (or Fried) length
  - Length over which the gross wavefront distortion is limited to a uniform tilt
  
  \[ r_o \propto \lambda^{6/5} \]

- \( \tau_o \) = Coherence time
  - Timescale over which atmospheric variations are frozen
  
  \[ \tau_o \propto \frac{r_o}{\bar{v}} \]

  \( \bar{v} \) = characteristic wind speed (~ 10 m/sec)

- \( \theta_o \) = Isoplanatic angle
  - Maximum separation between source and guide star
  
  \[ \theta_o \propto \frac{r_o}{h} \]

  \( h \) = characteristic height (~ 6 km)
Atmospheric Layers

Techniques

Hardy 1998 (fig 3.1)

Palomar “Seeing” Parameters

<table>
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<tr>
<th>Band</th>
<th>Wave (µm)</th>
<th>Diff. Limit (&quot;)</th>
<th>Seeing (&quot;)</th>
<th>r_o (cm)</th>
<th>theta_o (&quot;)</th>
<th>tau_o (msec)</th>
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*Assumes 1.0” seeing at 0.5 µm
Why Adaptive Optics?

- The punch lines:
  - Improved image “quality” (smaller PSF)
  - Improved sensitivity (lower background)
- What are the potential gains?
  - Suppose seeing improves from 1” → 0.1”
- What is the sensitivity gain?
  - For BLIP (point sources), \( f \propto \theta/D \)
    \[
    \Rightarrow f_{AO} = f_{PAL} \left( \frac{\theta_{AO}}{\theta_{PAL}} \right) = 0.1 f_{PAL}
    \]
- How big a telescope would you need to build to achieve this without improved seeing?
  \[
  D_{big} = D_{PAL} \left( \frac{\theta_{PAL}}{\theta_{AO}} \right) = 50 \text{ meters}
  \]

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Lick adaptive optics system at 3m Shane Telescope

Wavefront sensor
Off-axis parabola mirror
IRCAL infra-red camera
Real Data

Strehl Gain
Adaptive Optics

Performance NGS AO system

A natural guide star is used for both wavefront and tilt compensation.

The wavefront sensor operates at 0.55 µm. The servo loop is optimized for each reference star magnitude.

Hardy, Fig. 9.28
Natural Guide Star Limits

Compensated field angles achievable vs. stellar magnitude and observation wavelength. The wavefront sensor operates at 0.55 \( \mu \text{m} \).

Density of stars brighter than a given magnitude. Hardy, Fig. 9.29, 9.30

Sky Coverage

Sky coverage of AO system using natural stars. The wavefront sensor operates at 0.55 \( \mu \text{m} \). Hardy, Fig. 9.31
Wavefront Reference Sources

Techniques
- Natural guide star(s)
  - Use nearby star at some λ
- Laser scattering
  - Scatter a laser beam of the atmosphere and sense distortions in return signal

Laser Scattering Techniques
- Rayleigh scattering
  - Continuum scattering, 4-10 km
  - Light not parallel => focal anisoplanism
- Na Layer scattering
  - Resonant scattering off Na layer in upper atmosphere
  - Strong resonant fluorescence at 5890 A
  - [Major contributions to wavefront distortions are < 20 km]

NGS Systems
- Always preferred over LGS systems
  - Simpler, cheaper AO system
  - Passive, no scattered light problem
  - No tilt problem
  - No focal anisoplanism

Reference source
- Objects themselves
- Nearby object

Problem
- For any given object you may not have a guide star close enough (within the isoplanatic patch)
LGS Errors

Can use multiple lasers and/or multiple natural guide stars to "fix"

Hardy, Fig. 7.14

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Na Layer Characteristics

Characteristics of mesospheric sodium layer.

Hardy, Fig. 7.8

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**Expected signal from a 3.3 µs (1 km) laser pulse as a function of height.**

**Hardy, Fig. 7.7**

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**Na LGS in operation**

- CHAOS - laser guide star experiment at the National Solar Observatory's Vacuum Tower Telescope (VTT). The photo was taken during the night of Nov 20, 1997. The telescope was lit up by moonlight and the laser beam was launched from the top of the VTT. The constellations Orion and Taurus are also visible in this photo.

From [http://astro.uchicago.edu/chaos/](http://astro.uchicago.edu/chaos/)
LGS Systems

✓ Need tilt correction
  ✓ Can not take out DC (drift) term since LGS is not tied to the celestial sky

✓ Problems
  ✓ Current lasers for Na scattering are huge & expensive (still being worked)
  ✓ Systems are extremely complicated & difficult to operate

✓ The Future
  ✓ Multi-conjugate AO (MCAO)
  ✓ Multi-object AO (MOAO)
  ✓ Tomographic wavefront sensing
  ✓ AO is an active area of research