OSA Training
Outline of the talk

• Day 1
  – Why AO?
  – What is AO correcting?

• Day 2
  – How does AO work?
  – How is LBT AO unique?
Disclaimer

- This is 'world according to AI'
- Some audience members (and students!) are world experts ... my introductions will initiate some discourse ... and (eventually) the true story will be revealed!
Why Adaptive Optics?

• Why build bigger telescopes?
• Is it to see more distant and therefore fainter objects, or is it to see all objects more clearly?
• Before the early 1980s the answers to these two questions were: Yes and no, respectively.
• Why? Should a bigger telescope not see more clearly than a smaller one?
• Yes, were it not for the blurring effect of the Earth’s atmosphere.
• Without adaptive optics, an 8-meter telescope does not “see more clearly” than a 0.4 meter telescope (because of the atmosphere).
• Why? …
• The blurring effects of the atmosphere limit resolution on an 8-meter to what can be achieved on a 0.4 meter:
• The wave front generated by the star light coming into the atmosphere is flat:

The atmosphere effectively “crops” our aperture

• But the blurring effects of the atmosphere turn it into a crumpled bed sheet:

• How big are the flat spots on in the bed sheet?
• About 20 cm, or on a great site on a great night, about 40 cm.
• These 20 cm to 40 cm “flat spots” are usually called:
  • Seeing cells
  • But there are other names (next slide)
• Their diameter (20 cm to 40 cm) is called:
  • The Fried parameter
  • or $r_0$ (pronounced “R-naught”)

(There’s another important parameter ($\tau_0$, pronounced tau naught), also called the “coherence time,” which is important, but we do not discuss.)
About terminology

• What is our *Lingua Franca*
• In previous slide:
  – “Seeing cell”
  – But for some, “Fried cell”
• Proposal ...
• When we differ on terminology, refer to Tyson Field Guide ...
Where can I find the Field Guide?

Third Floor Steward ...

First book shelf on the right ...

There it is ...

Fried coherence length
While we are on the subject of “other reading”...
So back to our bed sheet analogy ...

- AO let’s us in increase the size of these flat spots to be as big as our aperture (in broad terms) … 8.4 meters for LBT
- So then we can see more clearly
- What does it mean to “see more clearly”?
- First we give a qualitative look …
Level of detail observable at a distance.

**No AO**

(a) A 2-euro coin at 5km
(b) Jupiter’s moon Io at $7 \times 10^8$ km

**Today’s AO**

(c) Seeing the inscription of the British isles on the coin
(d) A 700 km square patch on Io

**Tomorrow’s high angular resolution**

(e) The center of the letter E on the coin
(f) The details of a volcano only 70 km in diameter
• What does it mean to “see more clearly” quantitatively?
• To answer this question we have to look at this ratio from optics:

\[ d_{\text{lim}} \approx \frac{\lambda}{D} \]

The left hand side is an angular measurement that quantifies “see more clearly” or “observe at higher resolution”

The top is the wavelength (e.g. K-band)

The bottom is the size of the aperture (the diameter of the primary mirror; 8 meters for example)

Let’s look at these two parameters on the right hand side one at a time ...
$D$ is the effective aperture ...

Without AO $D = r_0 < 0.4$ meters

With AO $D = 8$ meters

\[ d_{\text{lim}} \approx \frac{\lambda}{D} \]
For wavelength, the near-infrared bands (JHK) are the current sweet spots for AO

\[ d_{\text{lim}} \approx \frac{\lambda}{D} \]

In particular, K-band (2.2\(\mu\)m)

SHARK-VIS go-ahead!
5 messages

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Cc: Julian Christou <christou@lbito.org>, LBT Management <management@lbito.org>

Hello Fernando,

Just a short note to let you know that you can move ahead with the construction of SHARK-VIS.

The Board endorsed LBTO’s recommendation.

Congratulations!

Cheers,
Christian

Two telescopes of the same size (“D”) get 4 times better image quality (“see more clearly”) at 0.55\(\mu\)m than at K-band (d-lim of approx 60 mas becomes approx 15 mas)
The figure of merit for an AO system is the “Strehl ratio”

\[ d_{lim} \approx \frac{\lambda}{D} \]

- SR = 1.0 => “perfect correction”
- SR = 0.3 (30%) => “pretty good”
- SR = 0.01 (1%) => “no correction”
• Tomorrow we will continue, starting with “How AO works”
• As a preview we’ll today look at this nice movie from Gemini ...
Hidden slides follow
Active Optics

Why was the 200-inch (5m) Hale telescope at Palomar the biggest telescope for so long?

Square-cube Law

• You cannot just keep scaling up the same basic structural design
• The strength goes up with the square; but the weight goes up with the cube
• Computers (and computer software) brought in the era of telescopes that are bigger than Palomar.
• Approx 8+ meters today; approx. 25+ tomorrow
• Two approaches for “light-weighting” the mirror so that computer-controlled actuators can keep the shape
• (at a much slower rate than adaptive optics … typically about 2 Hz)
Kolmogorov Model

Large masses of heated air transfer kinetic energy to smaller and smaller scales. The largest size is called the outer scale $L_0$. When the scale size becomes small enough, the kinetic energy of the air is dissipated as heat. This small size is called the inner scale $l_0$.

Solar heating

Outer scale $L_0$
(one meter to hundreds of meters)

Mixing — energy transfer to fluid motion

Transfer to smaller scales

Progression over time

Energy dissipated to heat and not to further turbulence

Inner scale $l_0$ (a few millimeters)
Atmospheric Turbulence Models

One of the most widely used models for the atmospheric turbulence structure constant as a function of altitude is the H-V model:

\[
C_n^2(h) = 5.94 \times 10^{-23} h^{10} \left( \frac{W}{27} \right)^2 \exp(-h) + 2.7 \times 10^{-16} \exp(-2h/3) + A \exp(-10h)
\]

where \( h \) is the altitude in kilometers, and \( C_n^2 \) is in units of m\(^{-2/3}\). The parameters \( A \) and \( W \) are adjustable for local conditions. For the most common **H-V 5/7 model** (leading to \( r_0 = 5 \) cm and \( \theta_0 = 7 \) μrad), the structure constant at the surface \( A \) is \( 1.7 \times 10^{-14} \), and the wind velocity aloft \( W \) is 21.

For conditions other than the 5/7 model, we can calculate \( A \) and \( W \) from

\[
A = 1.29 \times 10^{-12} r_0^{-5/3} \lambda^2 - 1.61 \times 10^{-13} \theta_0^{-5/3} \lambda^2 - 3.89 \times 10^{-15}
\]

\[
W = 27(75r_0^{-5/3} \lambda^2 - 0.14)^{1/2}
\]

where the **coherence length** \( r_0 \) is in centimeters and the **isoplanatic angle** \( \theta_0 \) is in microradians.

Other models are layered, such as the **SLC-Night model**:

<table>
<thead>
<tr>
<th>Altitude (above ground)</th>
<th>( C_n^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h \leq 18.5 \text{ m} )</td>
<td>( 8.40 \times 10^{-15} )</td>
</tr>
<tr>
<td>( 18.5 &lt; h \leq 110 \text{ m} )</td>
<td>( 2.87 \times 10^{-12} h^{-2} )</td>
</tr>
<tr>
<td>( 110 &lt; h \leq 1500 \text{ m} )</td>
<td>( 2.5 \times 10^{-16} )</td>
</tr>
<tr>
<td>( 1500 &lt; h \leq 7200 \text{ m} )</td>
<td>( 8.87 \times 10^{-7} h^{-3} )</td>
</tr>
<tr>
<td>( 7200 &lt; h \leq 20,000 \text{ m} )</td>
<td>( 2.00 \times 10^{-16} h^{-0.5} )</td>
</tr>
</tbody>
</table>
Turbulence models are site-specific because climate and geography play an important role in the $C_n^2$ profile.