Characterisation and Simulation of Atmospheric Seeing

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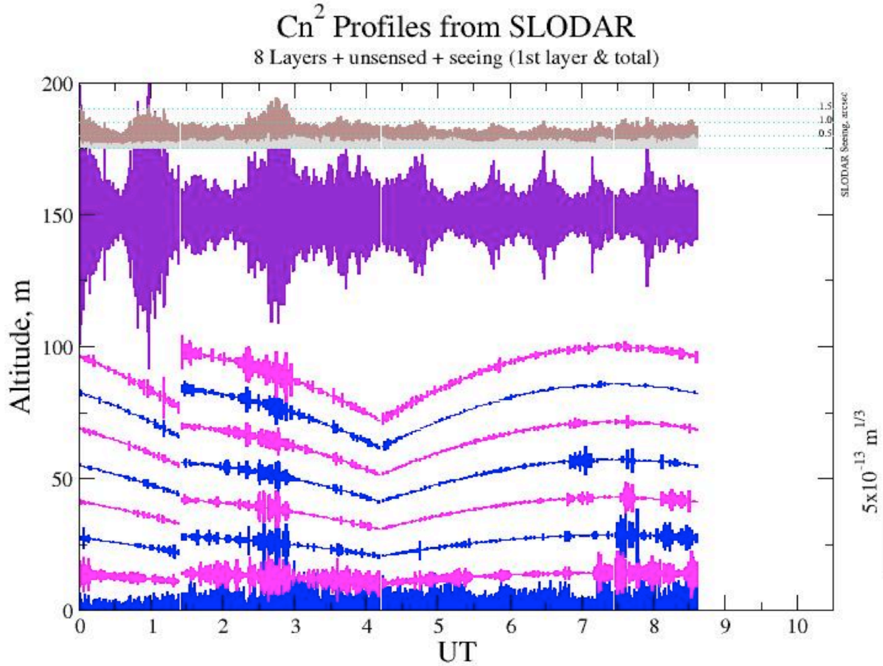
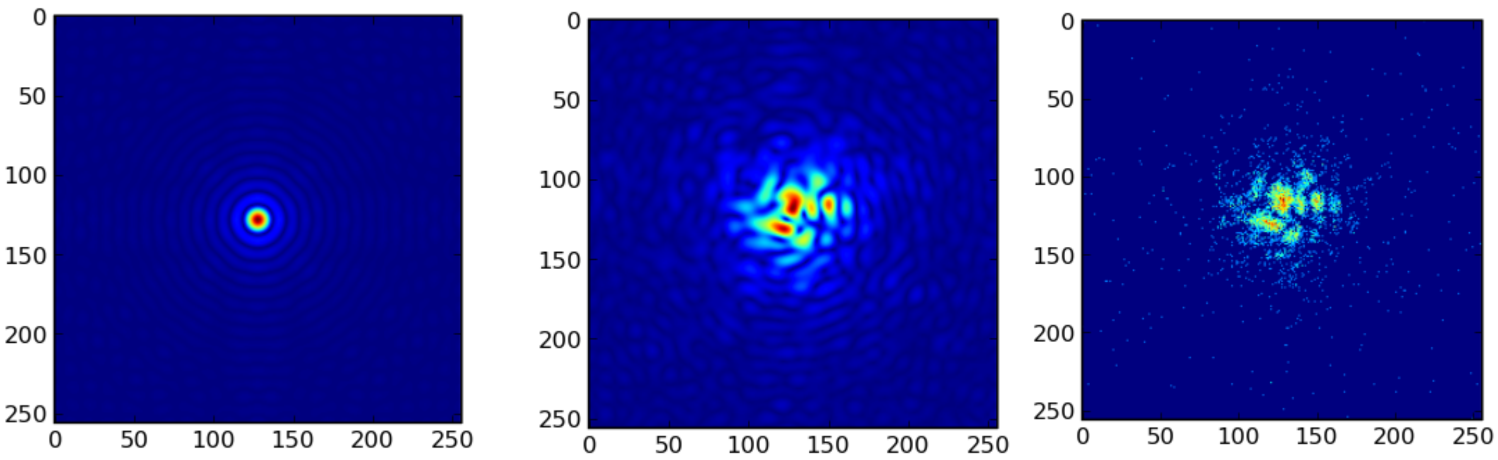
SLODAR Turbulence Profiler
ESO Paranal Observatory



Turbulence profile sequence, Paranal

The Need for Simulations of Optical Turbulence

- Adaptive optics: system design and optimisation, performance modelling
  - **Complex noise propagation: analytic solutions are not always available…**
- Model anisoplanatism, fitting error, WFS noise etc.

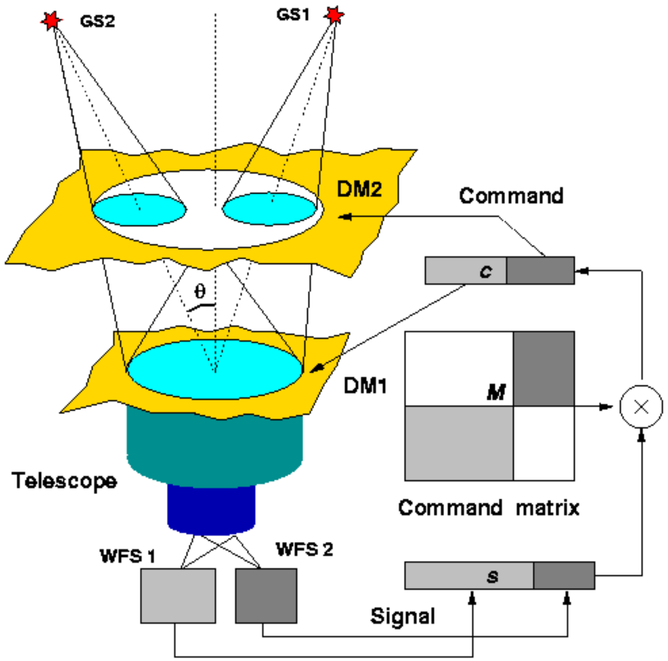


Diffraction Seeing Noise

Computer Simulation of Seeing

The Usual Assumptions:

1. Thin layers, geometric propagation
2. Kolmogorov statistics for phase aberrations
3. Taylor approximation (fixed, translating pattern)
4. (Weak turbulence - neglect scintillation effects)



Computer Simulation of Seeing

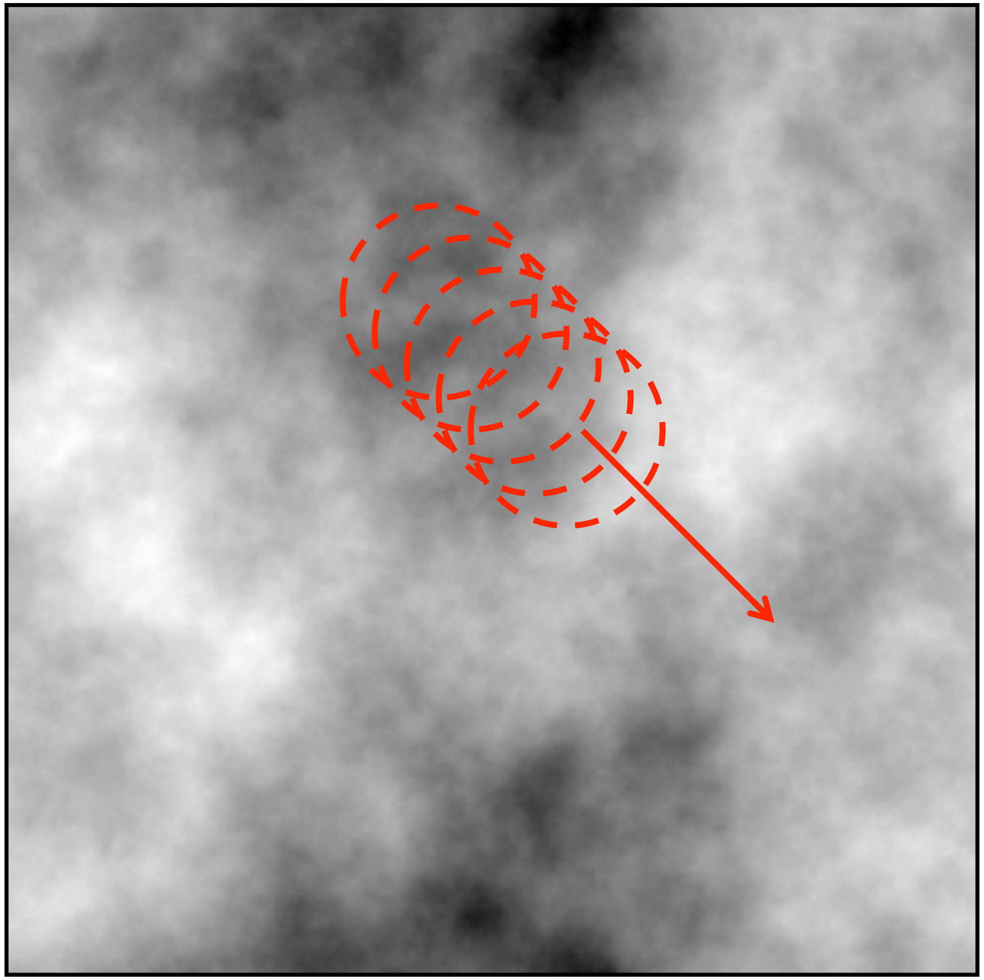
- **Creating a random turbulent ‘phase screen’**

- Power spectrum of phase aberrations after propagation through Kolmogorov turbulence:

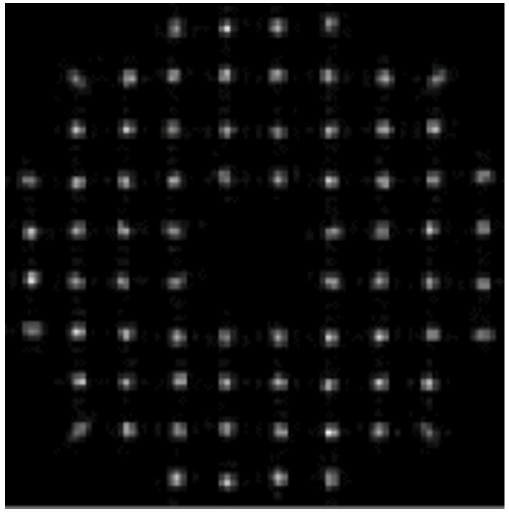
$$\Phi(\underline{k}) = 0.0229\ r_0^{5/3}\ \underline{k}^{-11/3}$$

1. Create a 2d array of random numbers (normal distribution, mean = 0, variance =1)
2. Multiply by $\sqrt{\Phi(\underline{k})}$
3. Fourier transform to get an array of ‘phase’ fluctuations with the correct spatial structure function (almost).

Computer Simulation of Seeing



Kolmogorov ‘phase’ screen



Simulated Wavefront-sensor pattern

Computer Simulation of Seeing

- **Creating a speckle image:**

The instantaneous PSF is the squared Fourier transform of the (complex aperture) function $T(\rho)$:

$$I(x) = \mathbf{F}^2[T(\rho)]$$

1. Create a complex array to contain $T(\rho) = Ae^{i\phi(\rho)}$
2. Set phase of $T(\rho)$ equal to values from Kolmogorov phase screen
3. Amplitude of T is constant within a aperture (zero outside)
4. FFT^2 gives speckle image
5. Now move the aperture across the phase screen to simulate wind-blown motion of the turbulence…

AO Numerical Simulations

- Monte Carlo simulations of AO typically make use of this basic method, but have become highly complex:
  - Multiple WFS and science ‘light paths’, e.g. MOAO
  - NGS and LGS propagation
  - WFS noise, DM hysteresis, etc…
  - 8m/ELT scale AO -> Parallel programming

What is the Atmosphere Really Like ?

1. Thin Layers – incl. surface layer
   - Is isoplanatism modeled correctly ?
2. Kolmogorov statistics (spatial structure)
   - Is DM fitting error modeled correctly ?
3. Taylor approximation ?
   - Are temporal effects modeled correctly ?

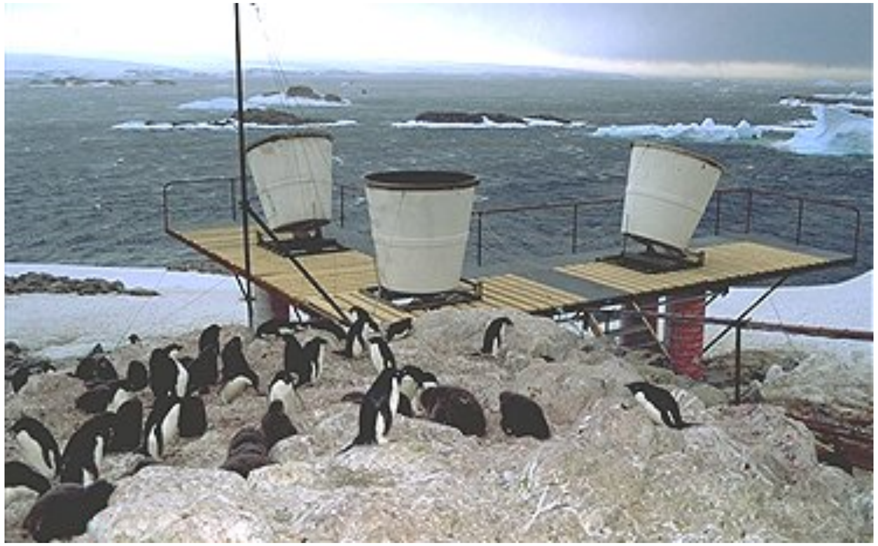
Turbulence Characterisation

(Ideal) Requirements for a Turbulence Profiler:

- Measure $C_n^2(h)$, + $V_w(h)$ if possible
- Measure all altitudes with high resolution
- Well calibrated (turbulence strength, altitude)
- Good time resolution (~1 minute)
- Real-time data
- Automated / robotic
- Portable (re-locatable) for site testing
- Cheap

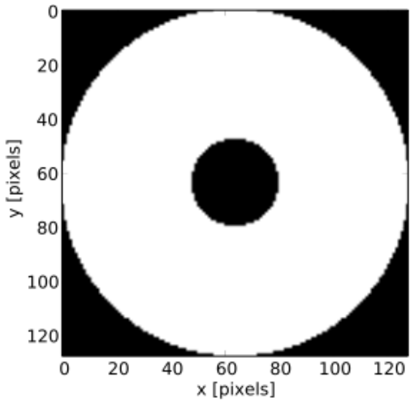
Turbulence Profiling: Methods

Micro-Thermal Balloon Probe
Measures $C^2_T(h)$

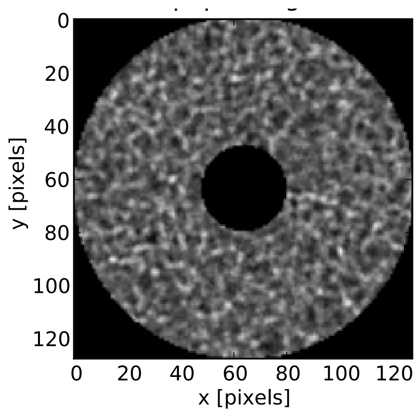


Acoustic Ranging (SODAR)

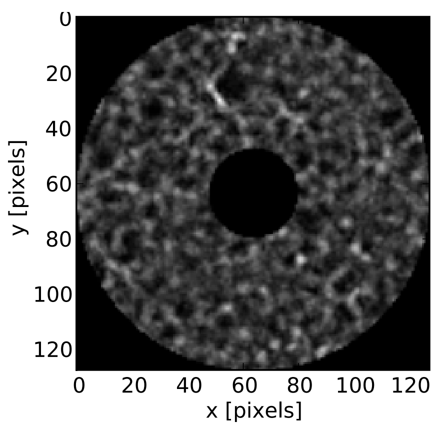
MASS: Scintillation Spatial Structure



0km



5km



10km

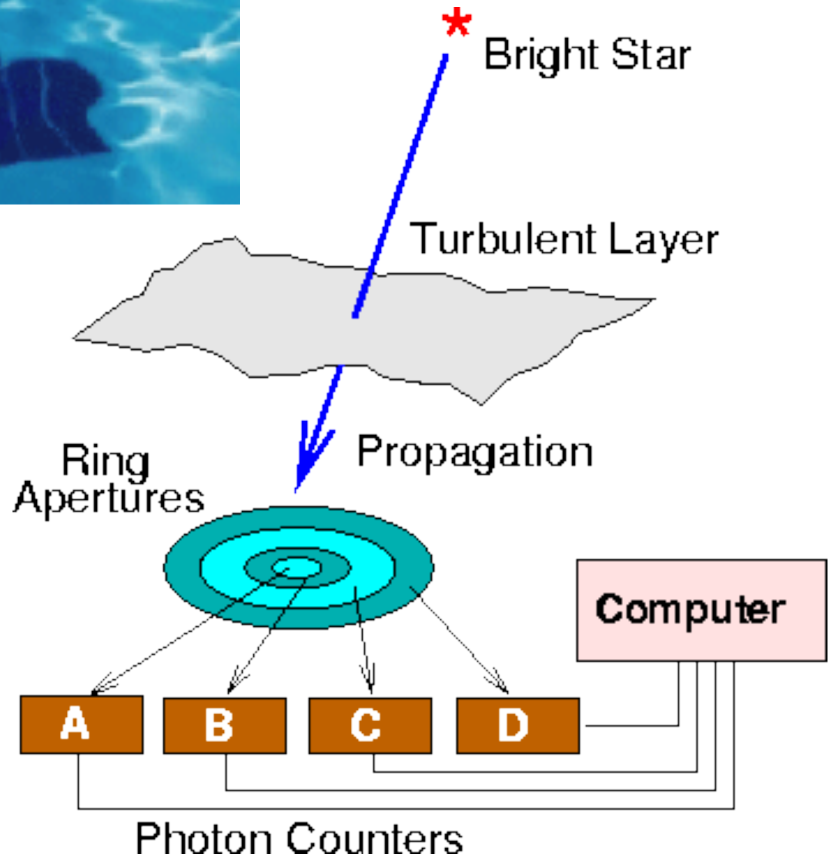


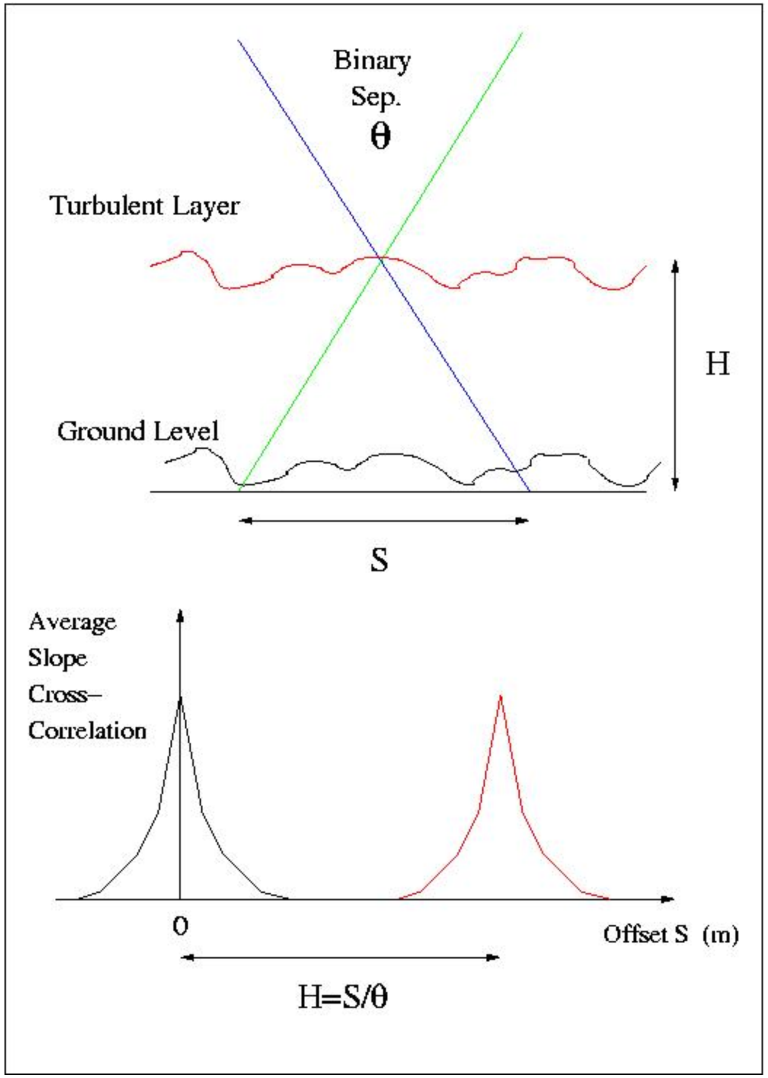
Image: http://www.ctio.noao.edu/~atokovin/profiler/index.html

Optical Crossed-Beams Methods

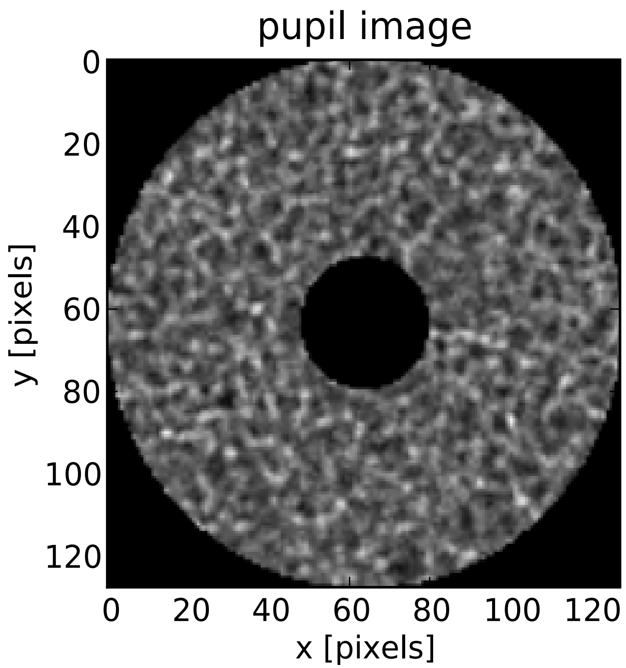
Recipe:

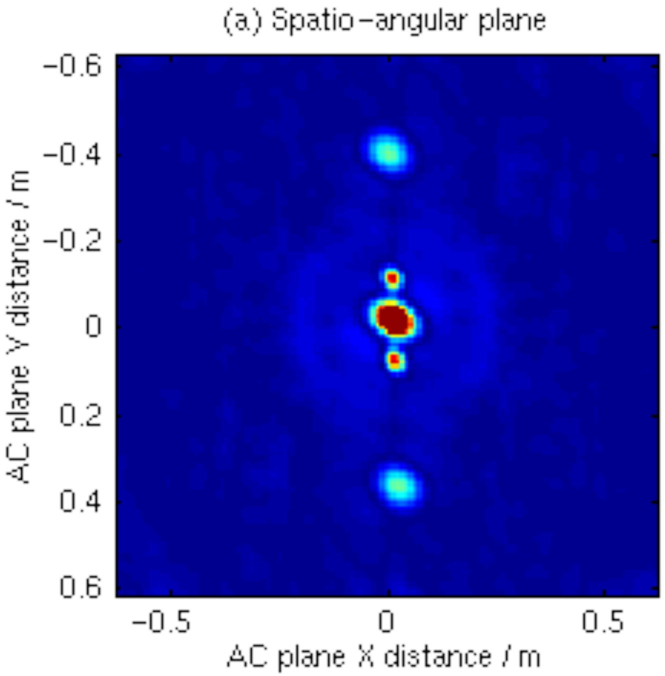
1. Observe a double star
2. Measure something at the ground… scintillation pattern, WFS centroids
3. Recover $C_n^2(h)$ from the **time-averaged cross-covariance** of the data

e.g. SCIDAR, LOLAS, SLODAR, Co-SLIDAR ….



SCIDAR (SCIntillation Detection And Ranging)





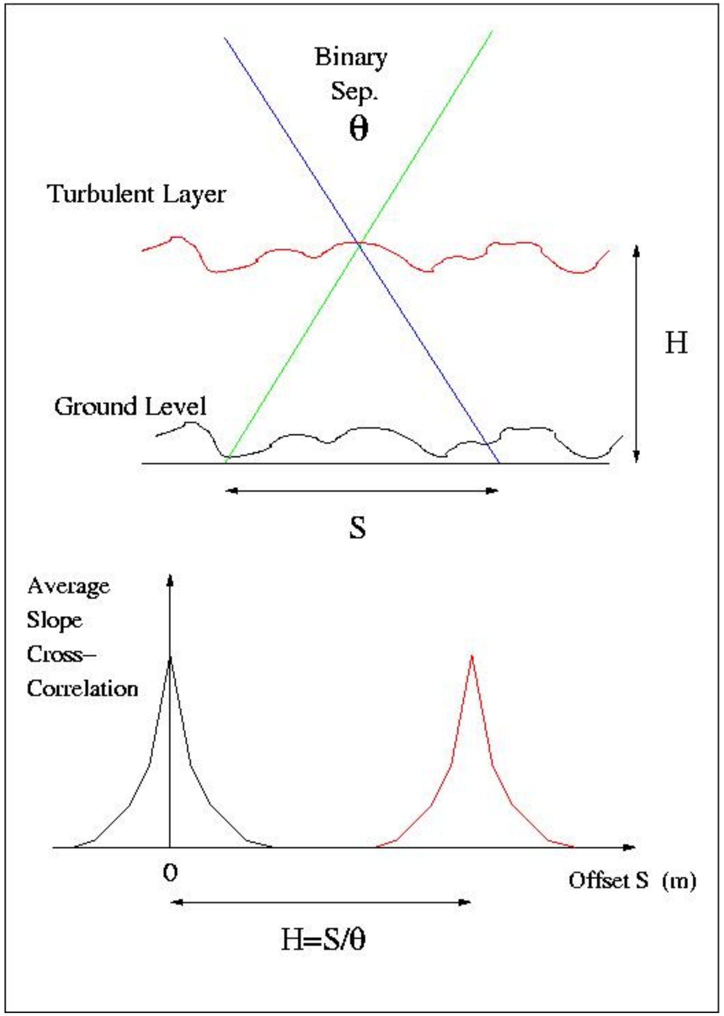
Double Star
Intensity Pattern

Intensity Auto-Correlation
(Time-Averaged)

Altitude resolution determined by double star separation and Fresnel zone size (roughly)

SLODAR (SLOpe Detection And Ranging)

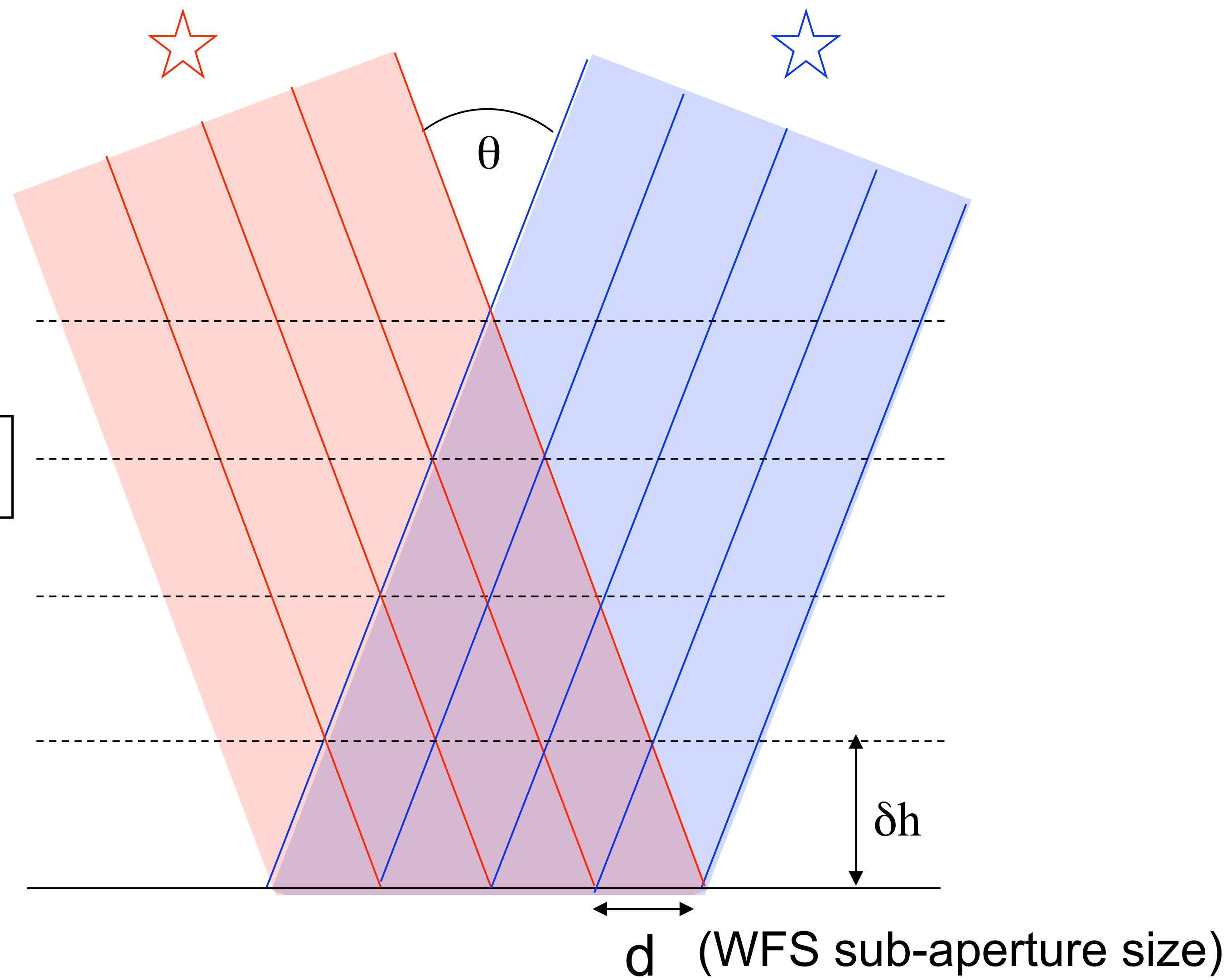
- Shack-Hartmann wavefront sensor
- Recover $C_n^2(h)$ from the time-averaged cross-covariance of the WFS data



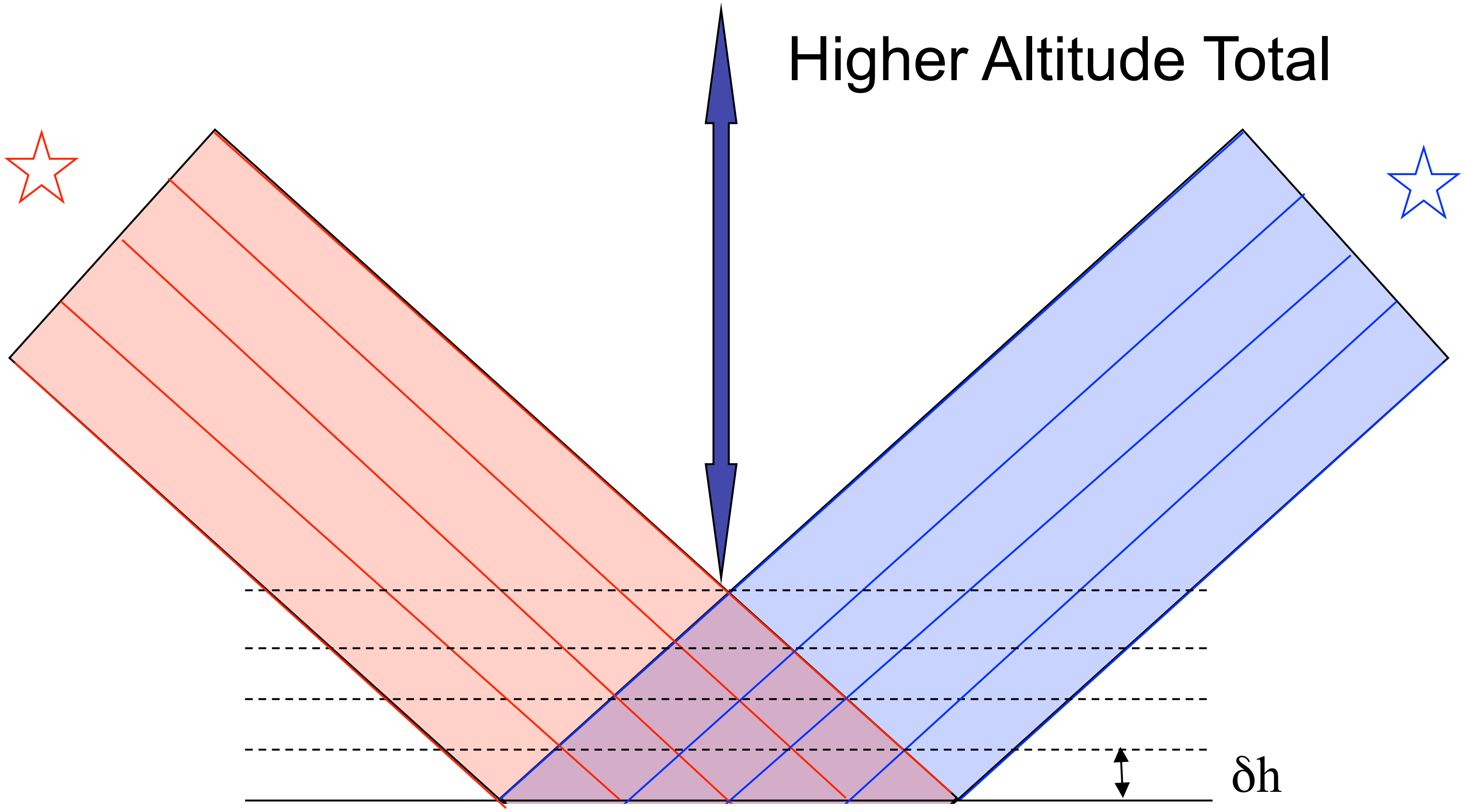
Altitude resolution determined by double star separation and Sub-apertures size (roughly)

SLODAR Altitude Sampling

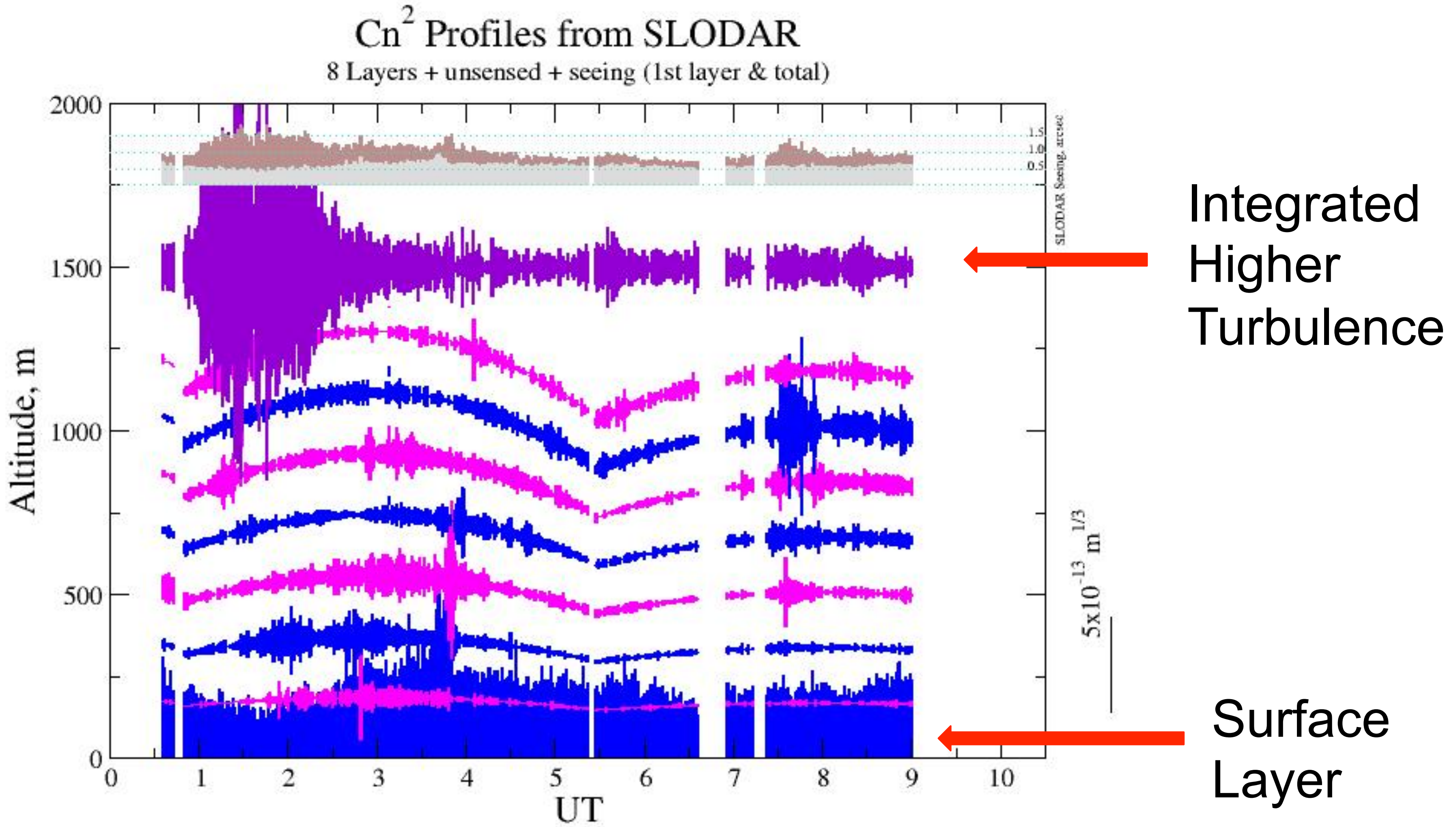
$$\delta h \propto d/\theta$$



SLODAR Altitude Sampling: Ground-Layer profiling



SLODAR Turbulence Profile Sequence (Paranal)

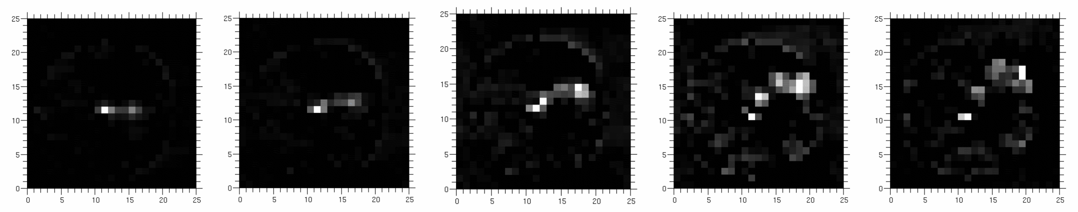


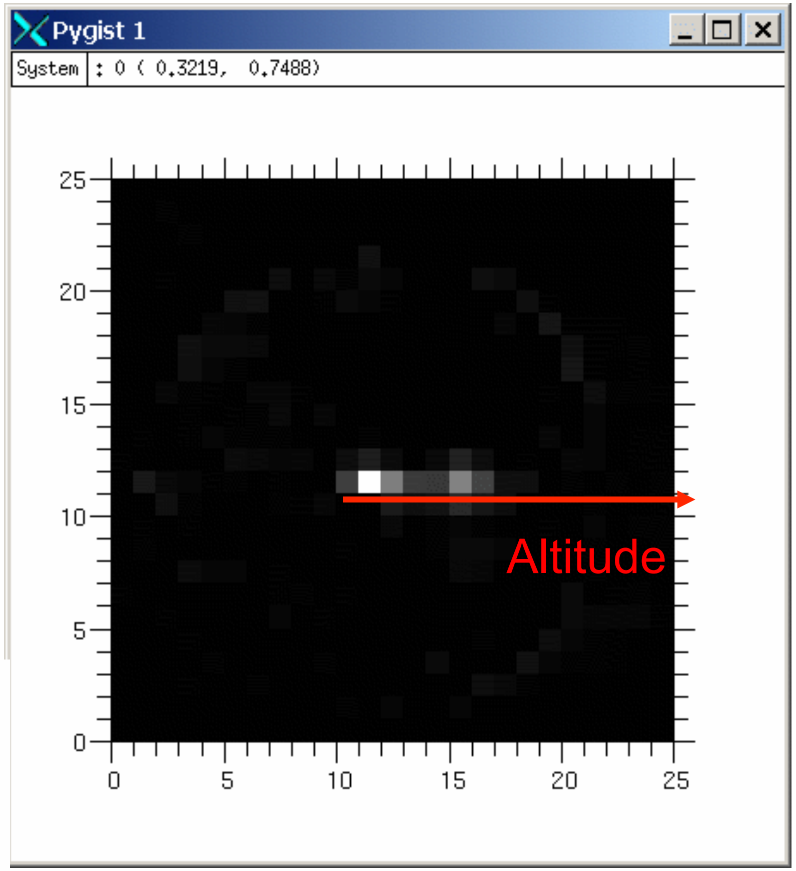
Altitude resolution varies with zenith angle

SLODAR: Turbulent Layer Velocities

- Movie shows the spatial cross-covariance with increasing time offset.

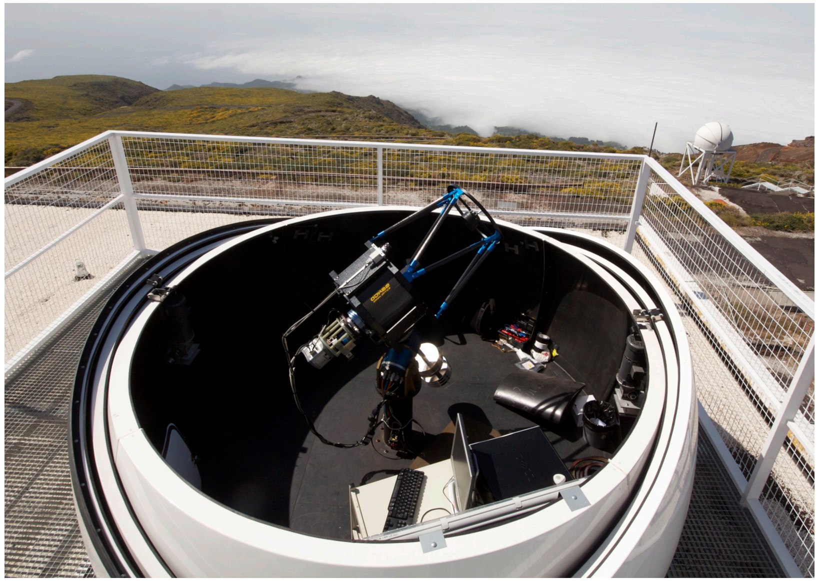
- Motion of peaks => layer velocity (with altitude).





SLODAR at La Palma

- Support CANARY MOAO demonstrator at WHT
- 0.5m telescope
- 'Whole' atmosphere profiling (up to ~10km)
- Fully automated



SLODAR Site Monitor, ESO Paranal, Chile

Surface-Layer SLODAR, Paranal

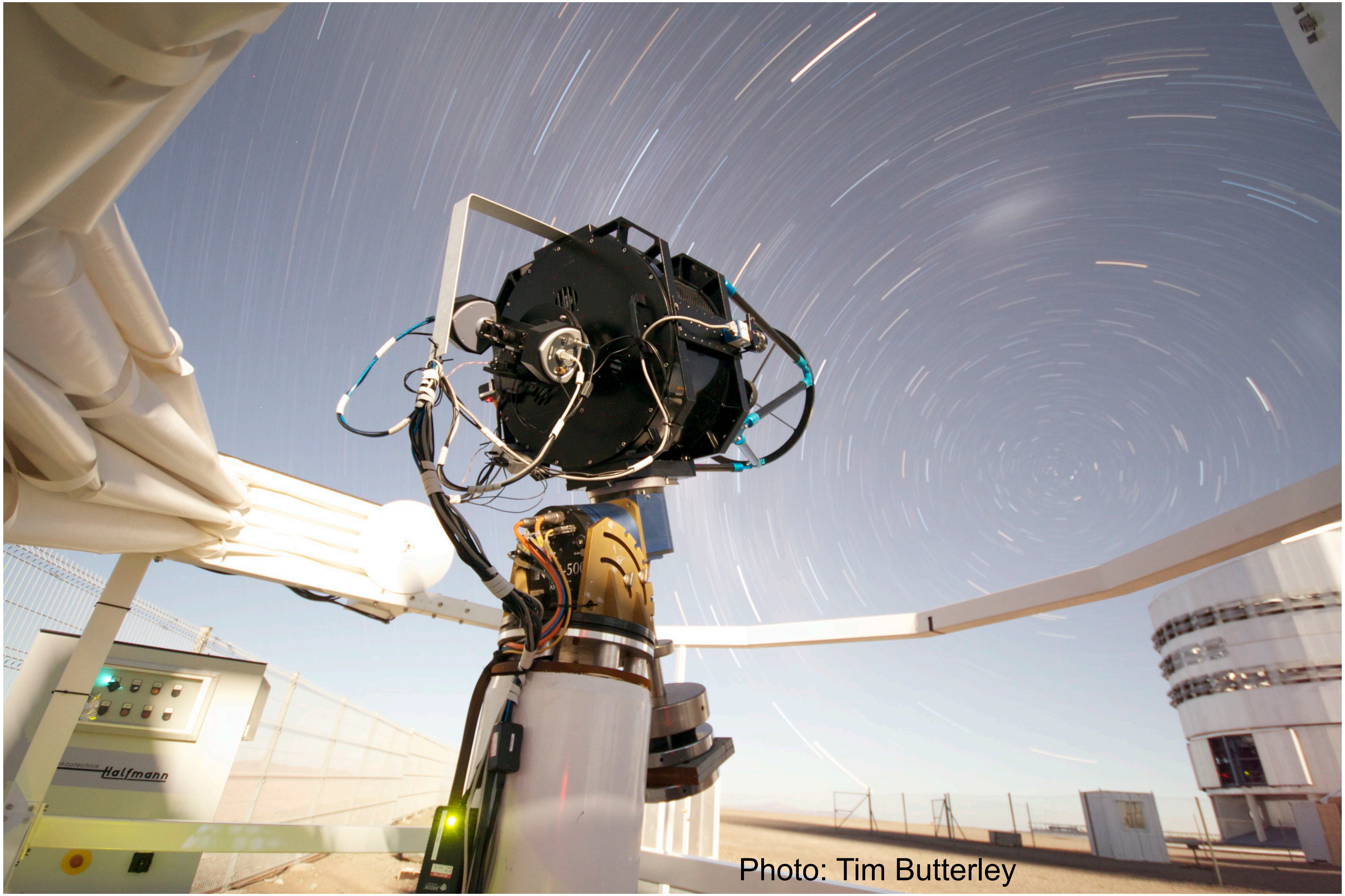
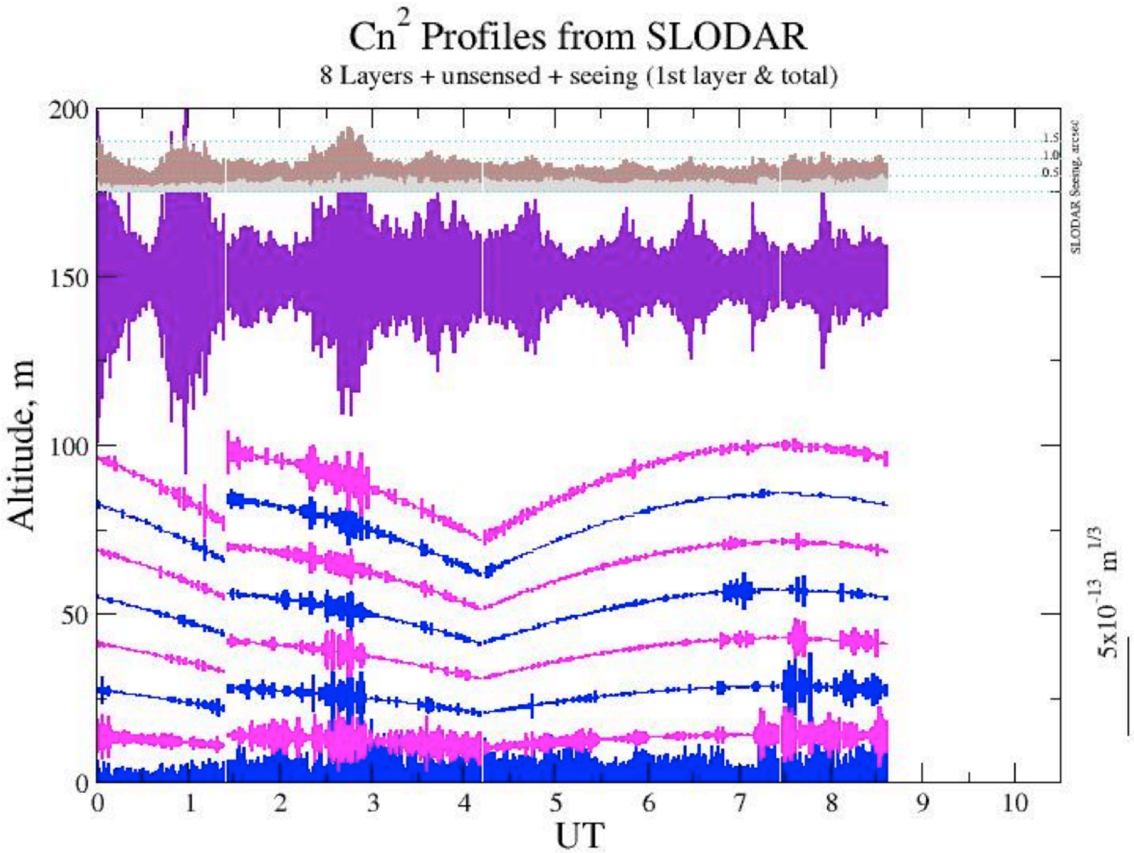


Photo: Tim Butterley

How Accurate are the Usual Assumptions ?

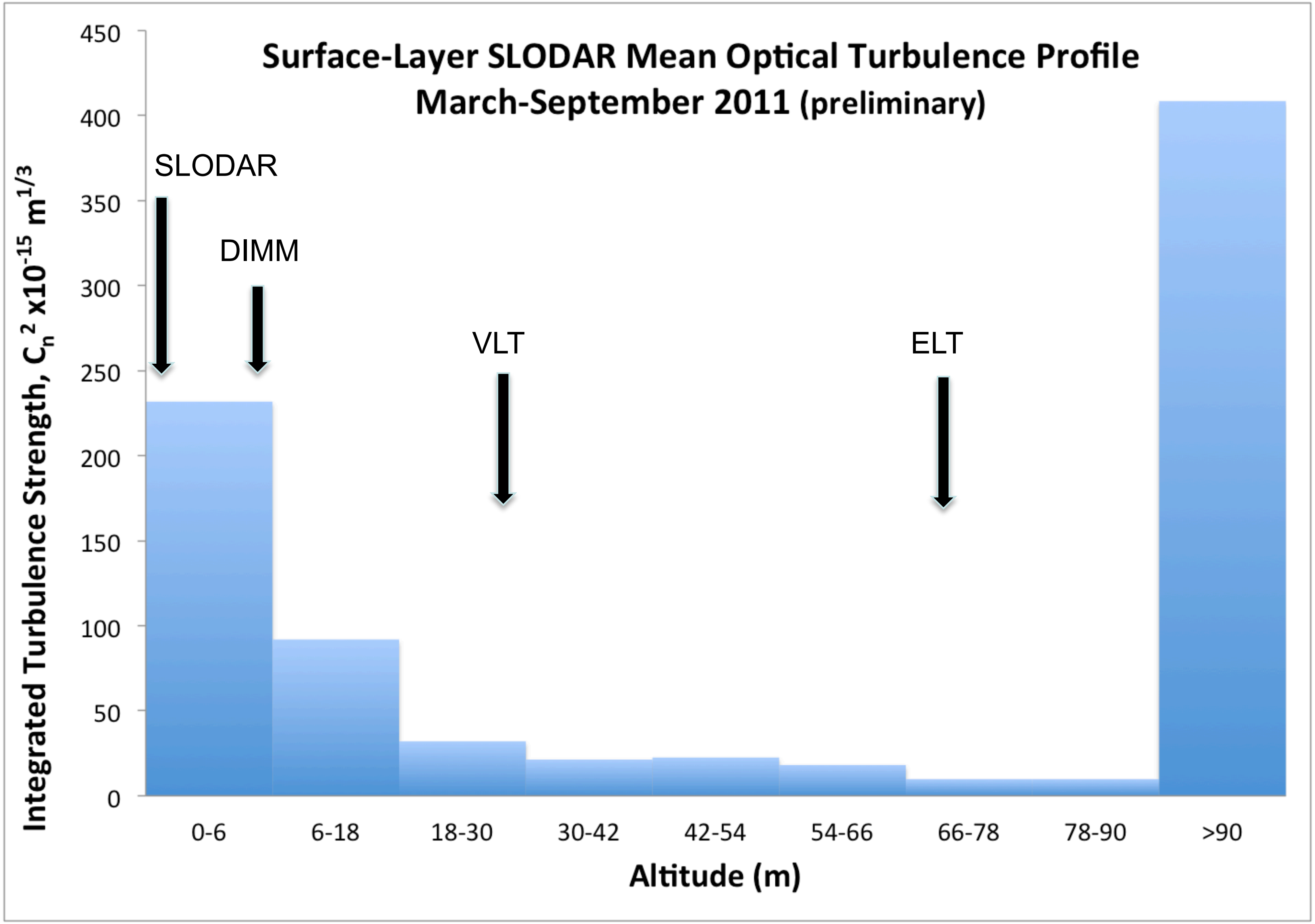
1. Thin Layers ?

Surface layer

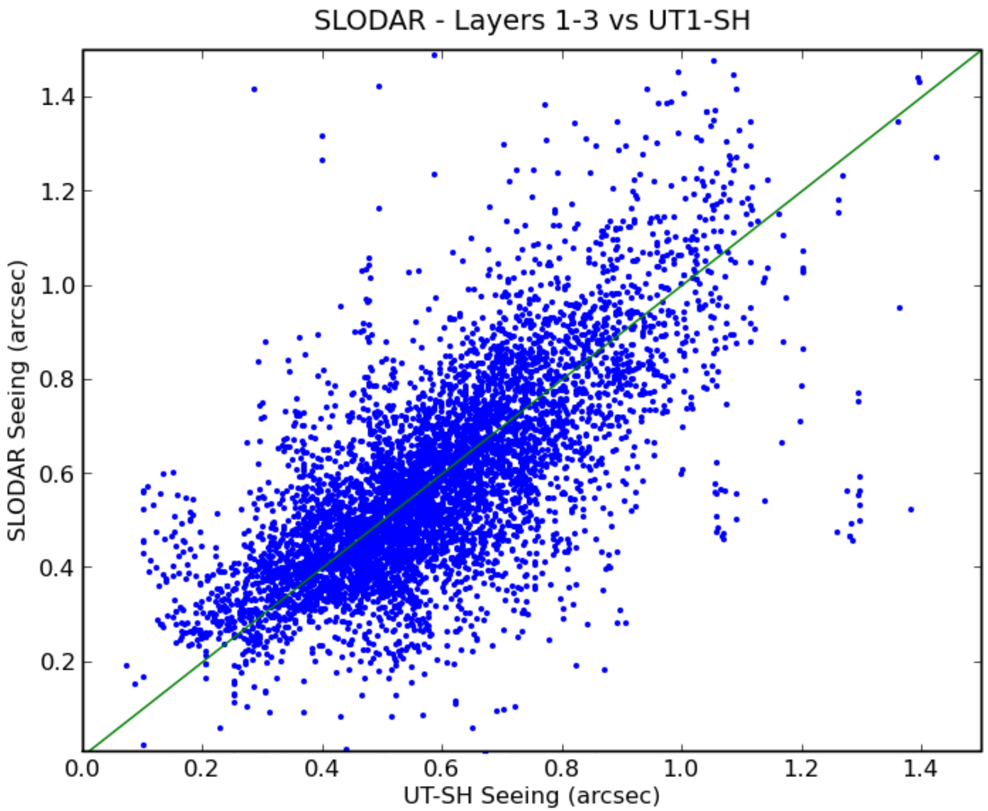


Turbulence profile sequence, Paranal

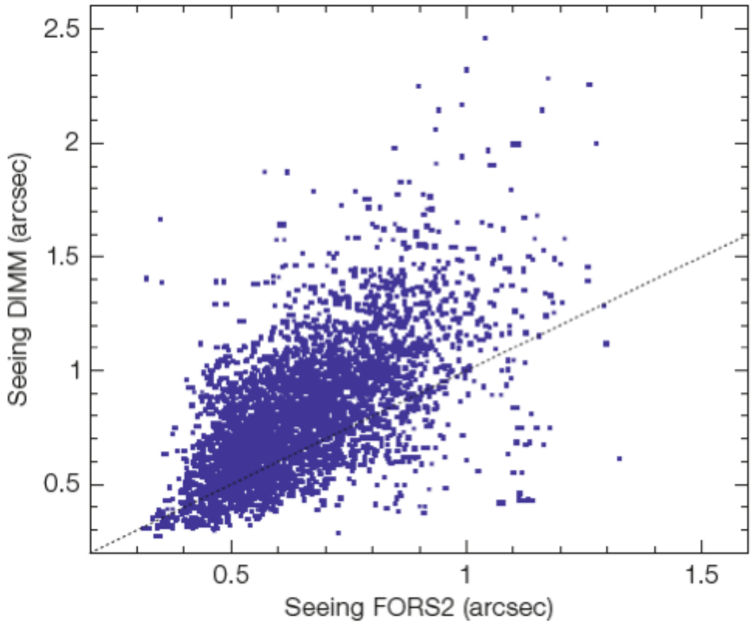
Paranal: Surface Layer Turbulence Profile



Understanding VLT (UT) Seeing



SLODAR total above 30m
versus UT shack-Hartmann seeing.



Paranal DIMM (at 5m)
versus UT seeing

Ground-Layer Turbulence: Does GLAO work ?

Thin surface layer –
no need for GLAO

Thicker surface layer –
GLAO is very effective and
has a huge field of view

How much turbulence does
the telescope create ?

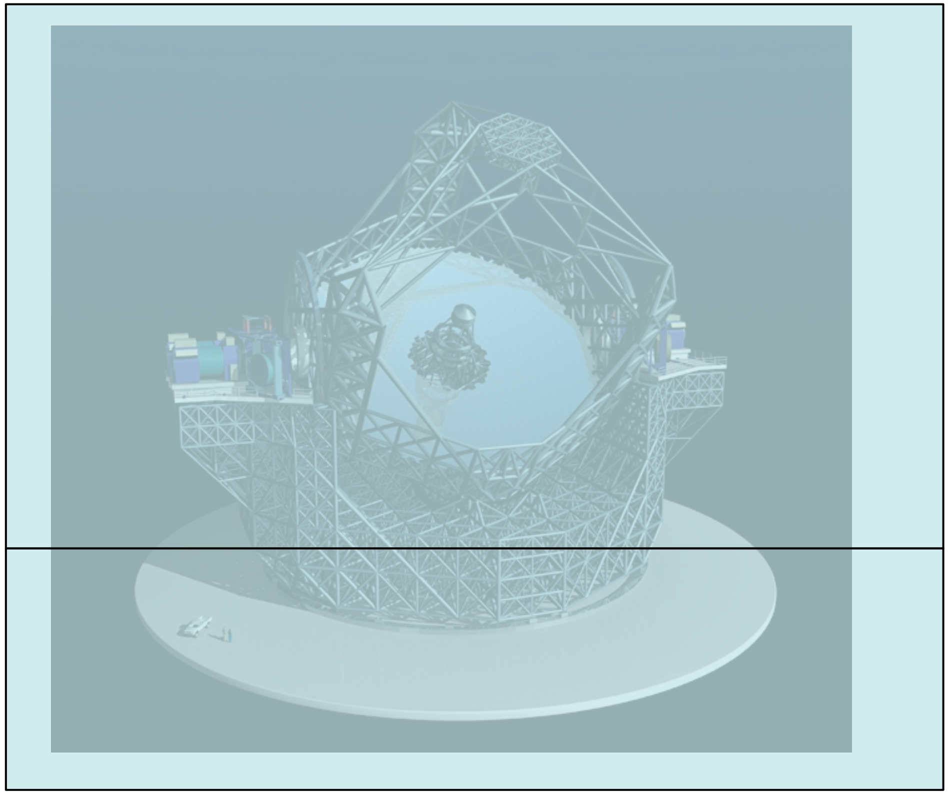
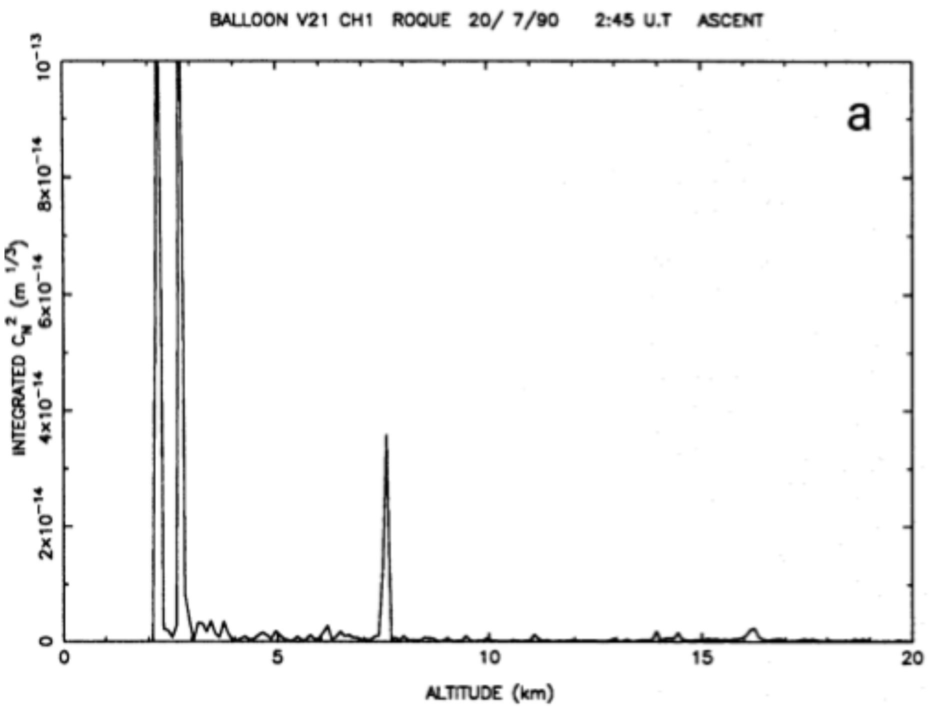


Image: www.eso.org

How Accurate are the Usual Assumptions ?

1. Thin Layers ? High layers

Very little high resolution profile data available (e.g. balloon soundings)



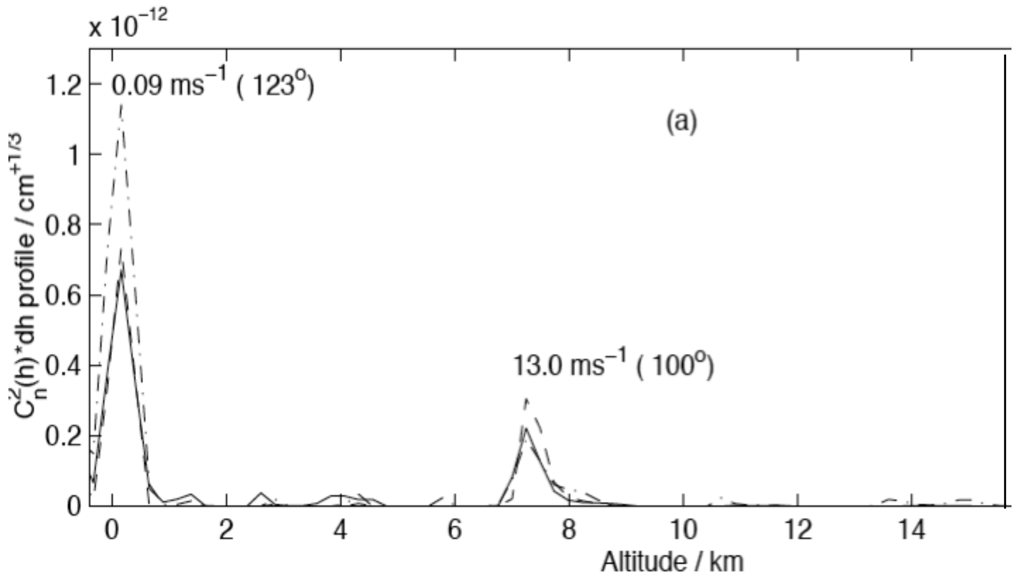
Balloon sounding turbulence profile, La Palma, Vertical resolution ~50m

Vernini et al, AA 204, 311, 1994

How Accurate are the Usual Assumptions ?

1. Thin Layers ? High layers

Lots of low resolution profile data available (e.g. SCIDAR)



SCIDAR turbulence profile, La Palma

Vertical resolution ~ 500m

Kluckers et al, A&AS 130, 141, 1998

How Accurate are the Usual Assumptions ?

1. Thin Layers ? High layers

- Implications: depends on the field of view…

- Individual layers are typically unresolved in low resolution data (δh ~ 500m). No implications for modeling AO with small field of view <1arcmin ?

- Higher resolution data, δh <100m, may be critical for larger FOV, e.g. MOAO / EAGLE (5 arcmin)

How Accurate are the Usual Assumptions ?

2. Kolmogorov statistics ?

Kolmogorov spatial spectrum:

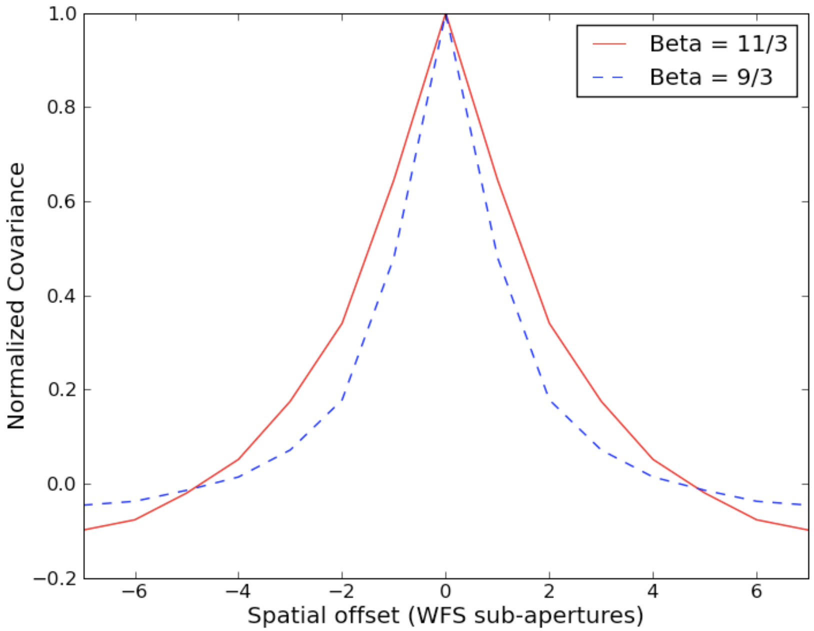
$$\Phi(\underline{k}) = 0.0229\, r_0^{5/3}\, \underline{k}^{-\beta}, \quad \beta = 11/3$$

Surface Layer / ‘local turbulence’:

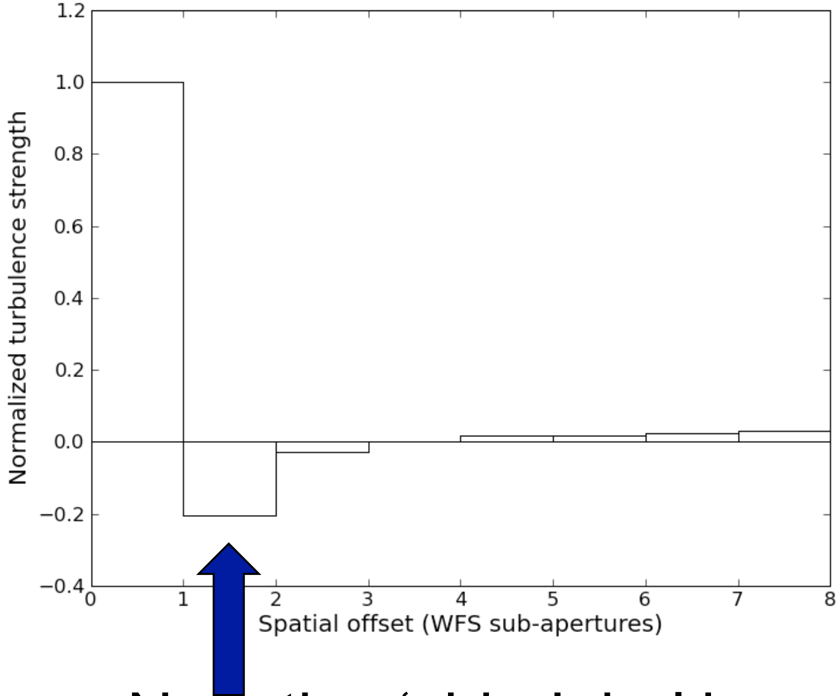
Often apparently measure $\beta < 11/3$, mainly in low wind speeds
(Can also model as a small ‘outer scale of turbulence’)

BUT: observed $\beta < 11/3$ results because, in light winds, larger spatial scales are not properly sampled (unless our sampling time is very long…)

Non-Kolmogorov Response



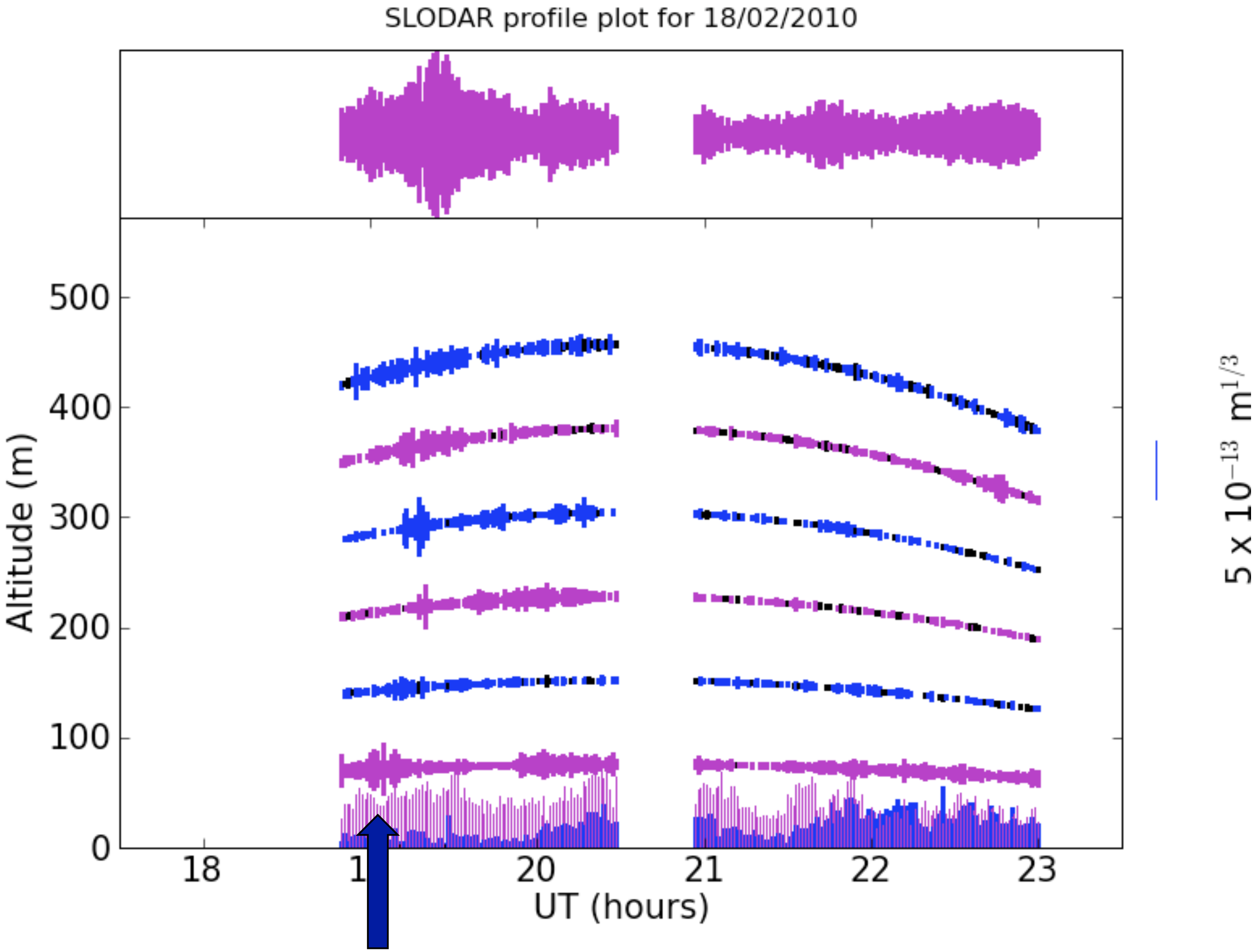
SLODAR response functions



Negative 'side-lobe' in restored turbulence profile

Beware of Enforcing Positivity !

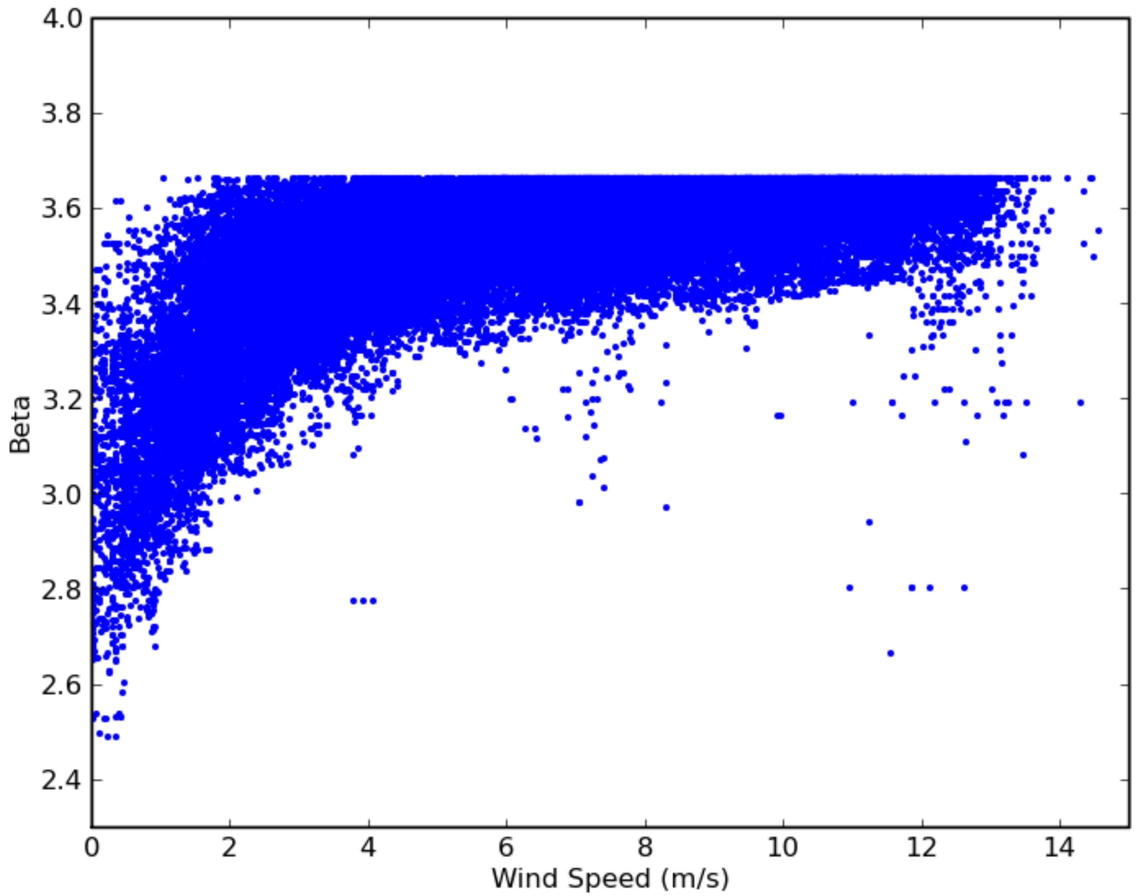
Non-Kolmogorov Response



'Fix': Include additional β <11/3 term at the ground

Non-Kolmogorov Response

Observed Spatial structure constant, β



Ground-level wind speed

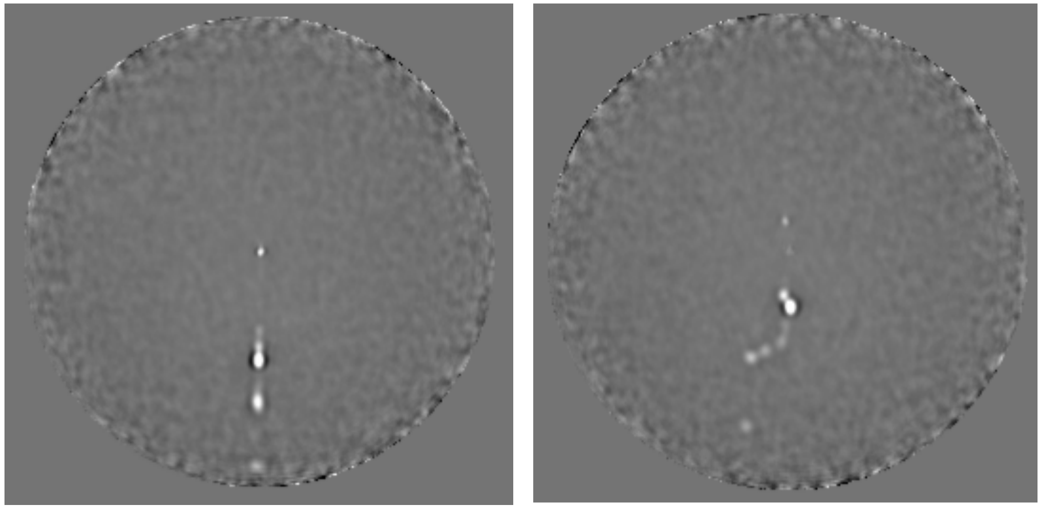
How Accurate are the Usual Assumptions ?

Taylor approximation

- Turbulence results from wind-shear => we should expect velocity dispersion
- High altitude- and time- resolution data needed…

High-resolution SCIDAR data, Nordic Optical Telescope, La Palma

Images: Harry Shepherd



Δt = 0ms Δt = 50ms

How Accurate are the Usual Assumptions ?

1. Thin Layers – incl. surface layer
   ✗ • Surface-Layer structure is critical
   ✓ (?) • High layers: may break down for very large field of view ?

2. Kolmogorov statistics (spatial structure)
   ✓ • Probably OK, but:
   • Need to model layer velocities correctly (e.g. range of surface wind-speeds)

3. Taylor approximation ?
   ✓ (?) • More high-resolution profile data needed

Key Issues for Profiling

- Surface-Layer Characterization
- Correct velocity structure
  - Effect of low winds (esp. surface layer)
  - Wind-shear
- Accurate Altitudes of (High) Layers:
  - Requirements for MCAO with ELT: <100m ?
  - How to do this (for the whole profile) ?