Site Characterisation

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Turbulence Characterisation for Astronomical Adaptive Optics

Site selection

Instrument design

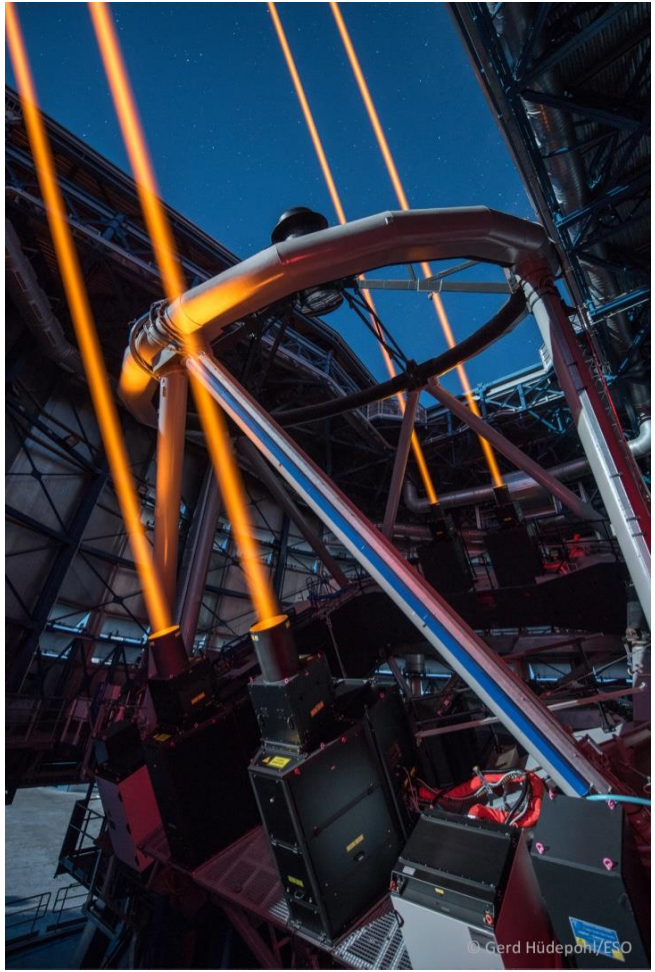
Real-time performance optimisation

- Tomographic reconstruction
- Predictive controllers
- Artificial Neural Networks

Performance monitoring

PSF reconstruction

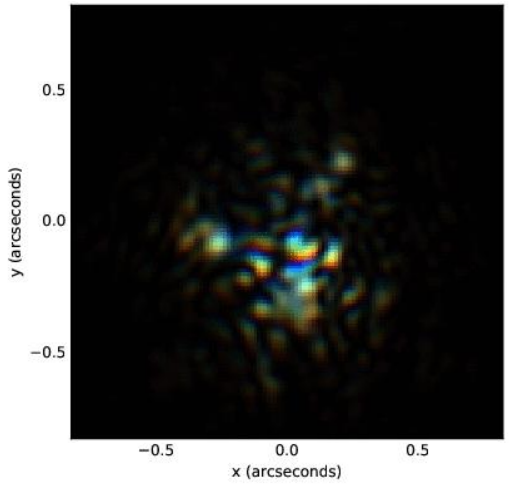
Smart scheduling



Free-Space Optics

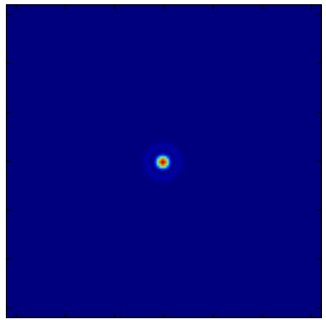
- When light travels through the Earth's atmosphere it becomes distorted
- This is a problem for:
  - Astronomy
    - Limits precision of measurements
  - Free-space optical communications
    - Limits data bandwidth
  - Satellite Surveillance
    - Limits precision of imaging, astrometry and photometry measurements
- **Free-Space Optics Research: To develop the technology and techniques to measure, model and mitigate this effect.**

Computer simulation of star imaged through the Earth's atmosphere

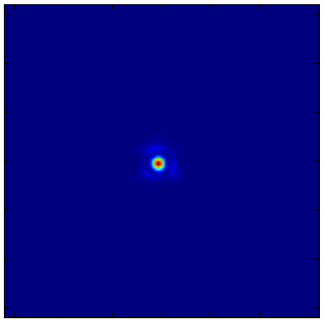


Free-Space Optics: Phase

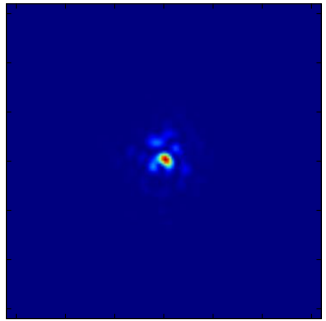
Ratio of D/r0 is critical



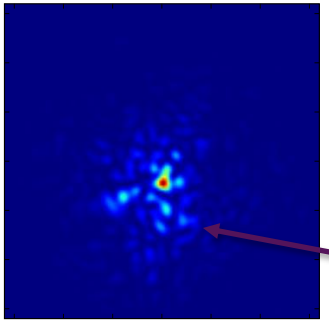
Diffraction limited, FWHM ~ λ/D



D/r0 = 1



D/r0 = 4

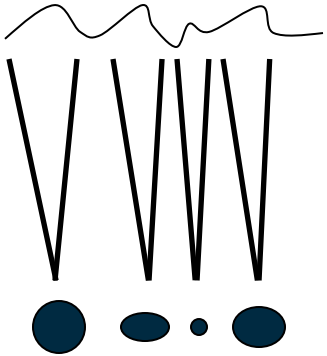


D/r0 = 10

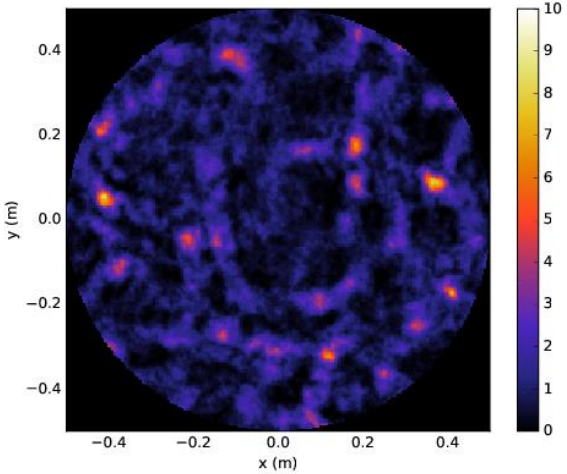
Each speckle of size $\sim\lambda/D$

The size of the image is $\sim\lambda/r_0$

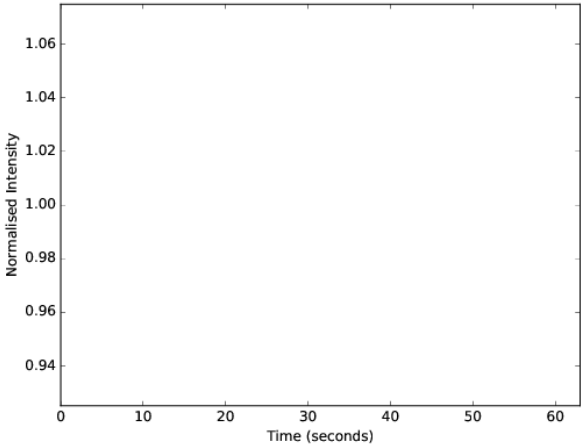
Free-Space Optics: Atmospheric Scintillation



Focusing from high-altitude turbulence



Pupil image



Integrated intensity

Local wavefront curvature propagates into intensity fluctuations

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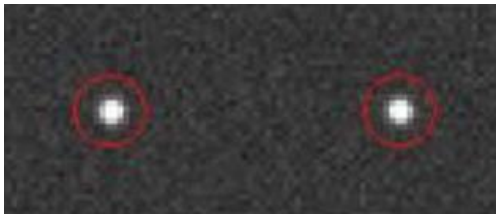
Turbulence Strength
Differential image motion

- Measure differential motion on short exposures

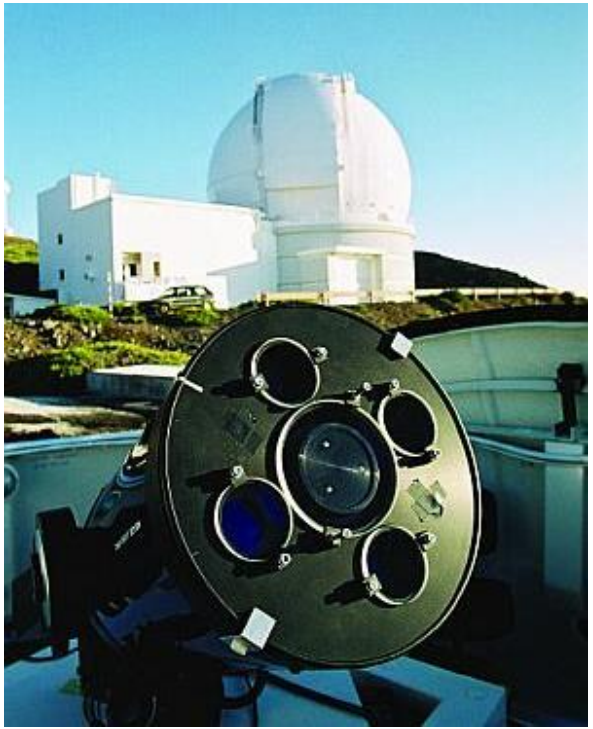
$$\sigma^2_{diff} \propto f(d,s)\, r_0^{-5/3}$$

f(d,s) is fixed for a given aperture mask configuration, d = sub-aperture diameter, s = aub-aperture separation.

- Insensitive to vibrations
- Standard at astronomical observatories



Durham DIMM



DIMM Seeing Monitor
La Palma observatory

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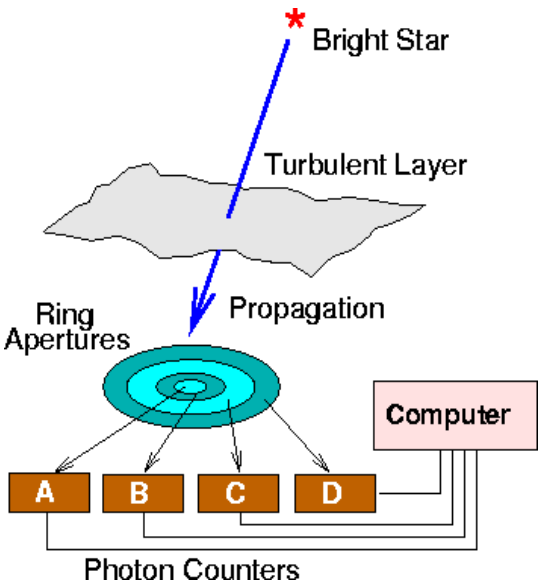
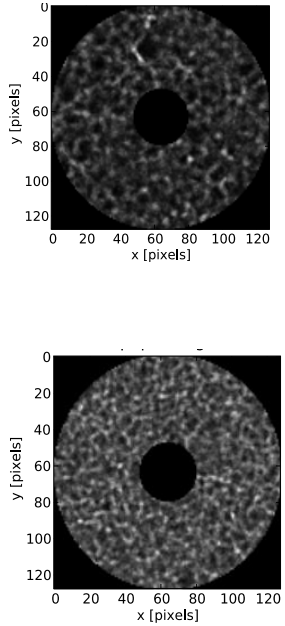
http://www.ctio.noao.edu/~atokovin/profiler/index.html

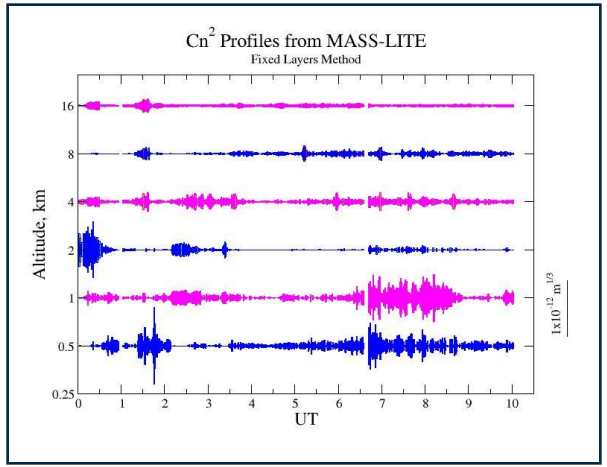
Turbulence Profiling: MASS

Usually implement on a small telescope alongside a DIMM seeing monitor.



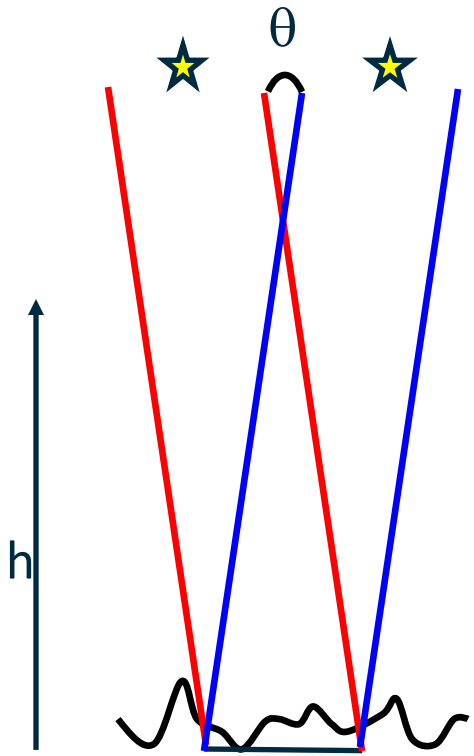
Schematic of the MASS profiler.





Example MASS $C_n^2(h)$ profile for a night at the ESO Paranal observatory.

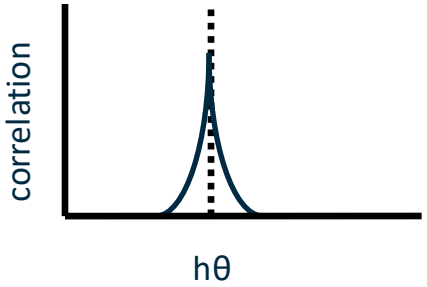
Turbulence Profiling: Cross-beams techniques



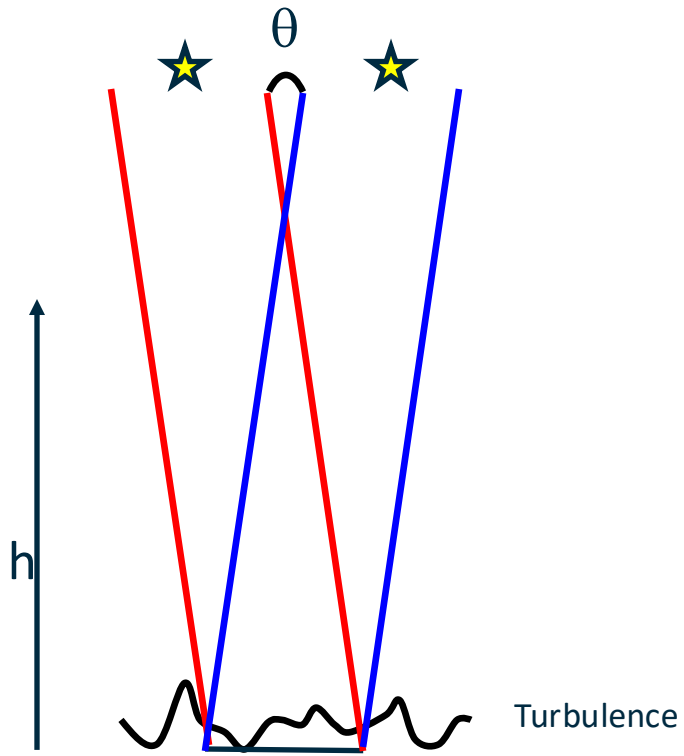
Turbulence

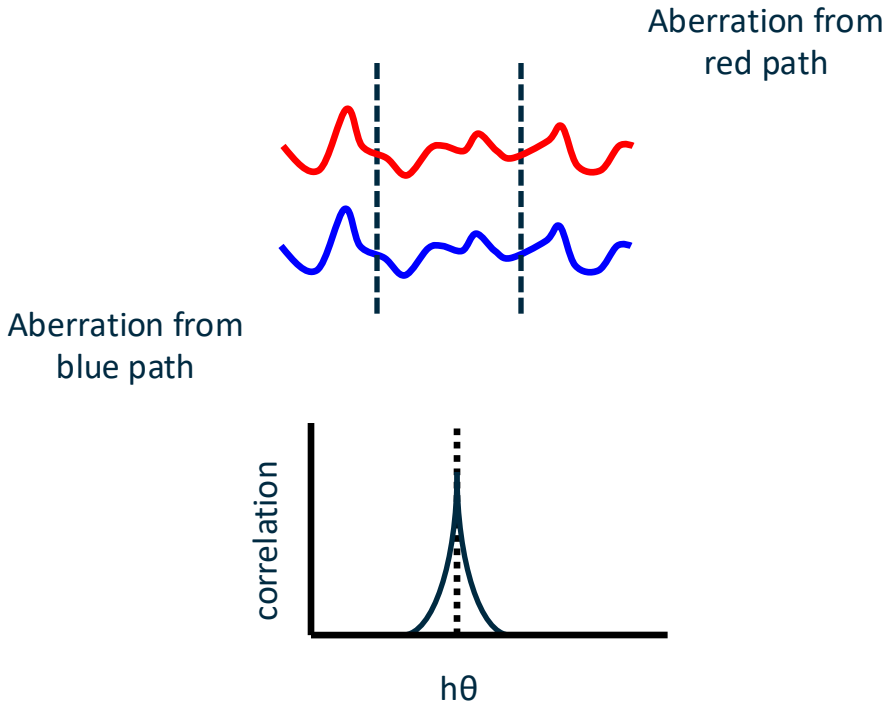
Aberration from red path

Aberration from blue path

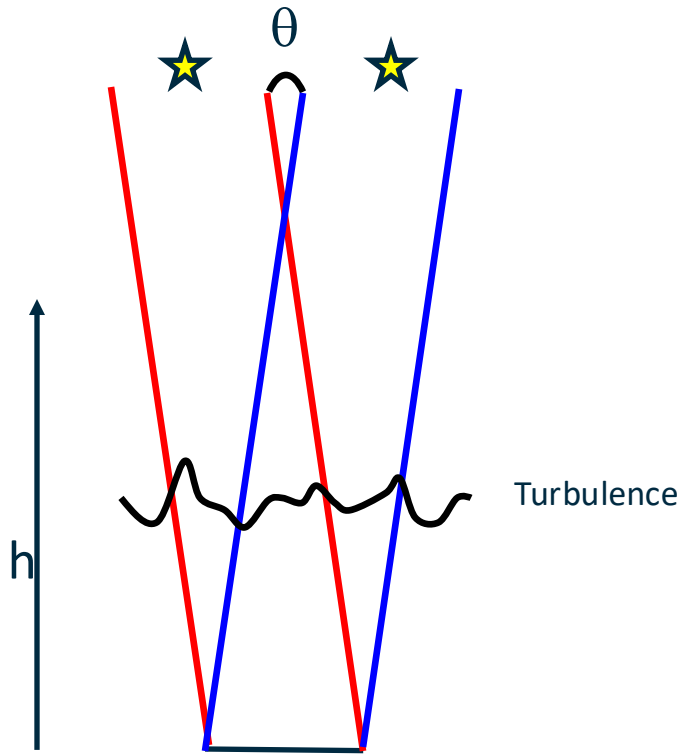


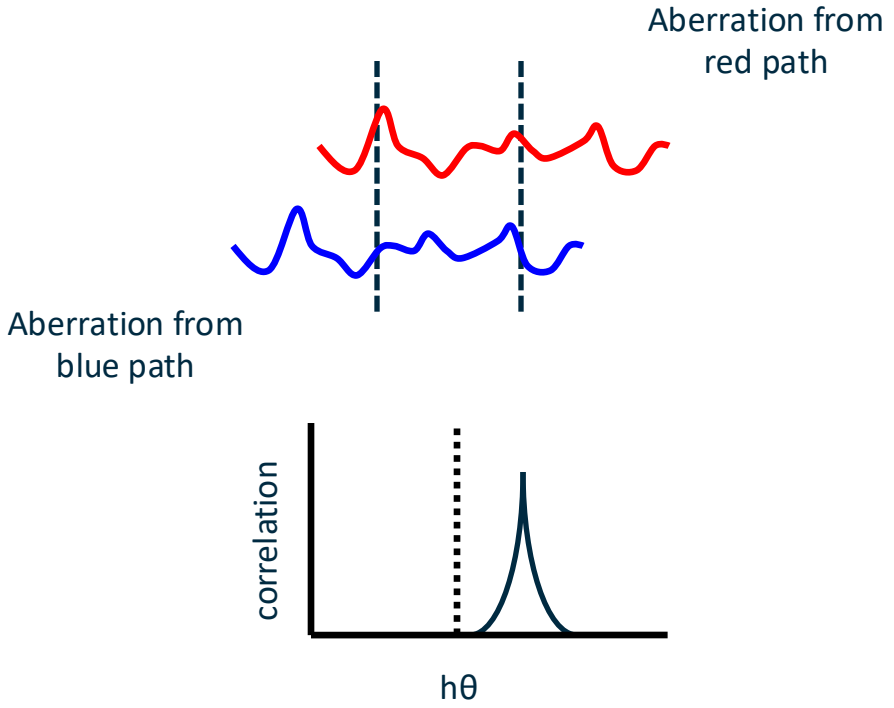
Turbulence Profiling: Cross-beams techniques





Turbulence Profiling: Cross-beams techniques

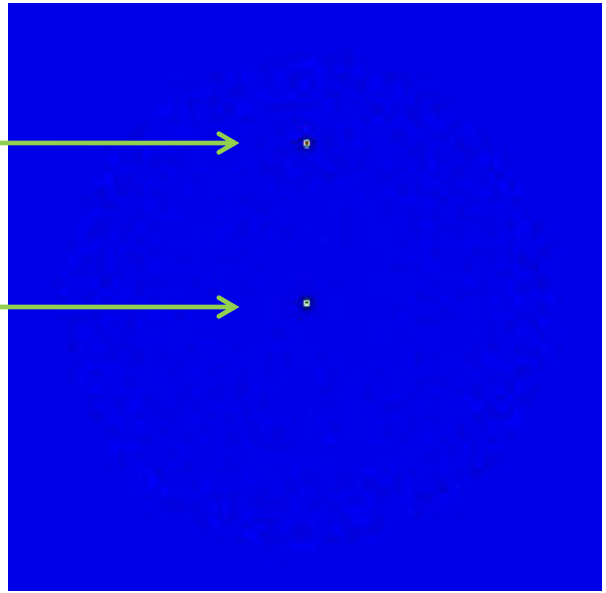


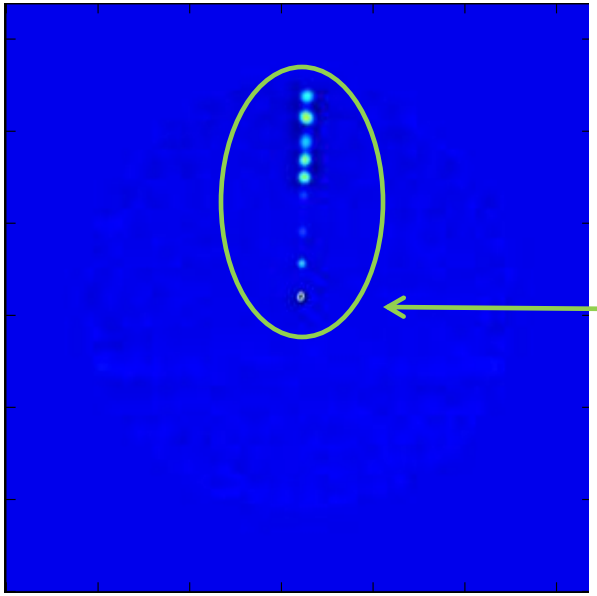


Cross-covariance functions

Simulation

Measured





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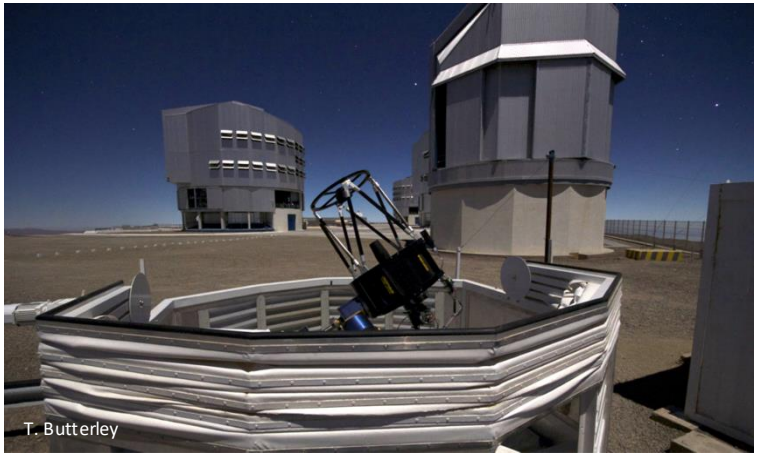
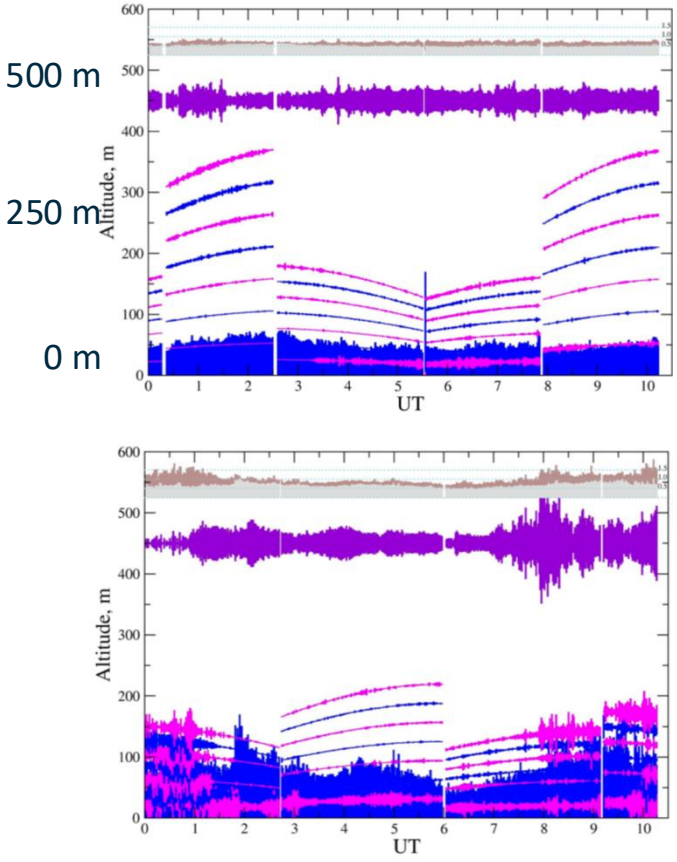
Measuring Atmospheric Turbulence: SLODAR

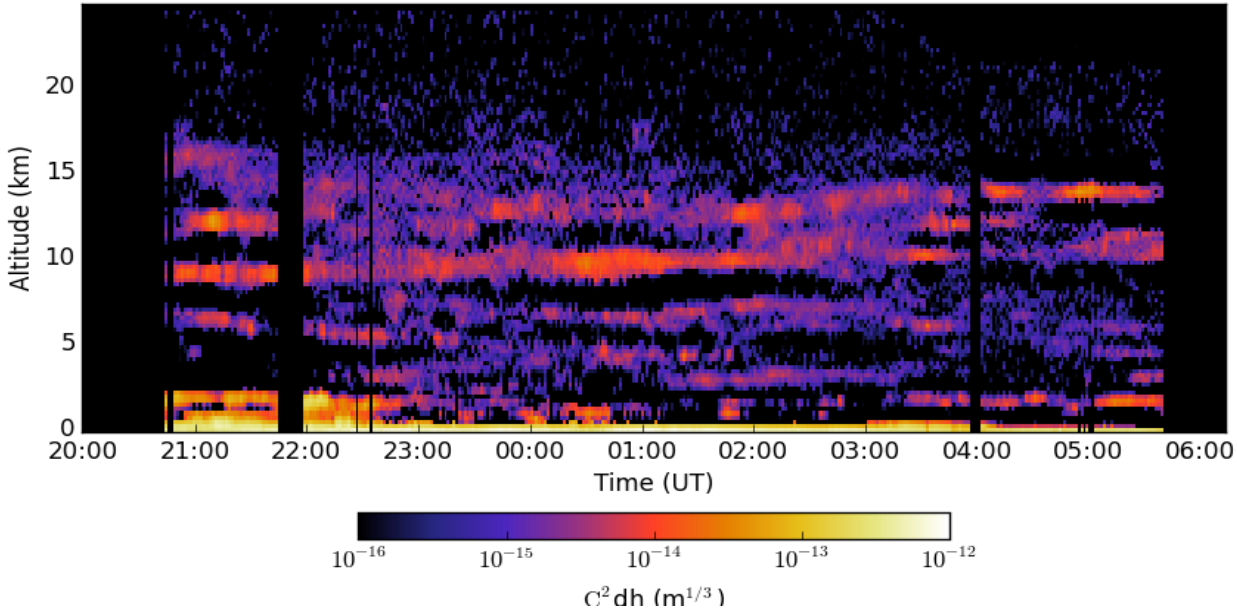


Osborn et al., MNRAS, 406, 1405-1408, 2010
Butterley et al., MNRAS, 492, 934-949, *2019*



Stereo-SCIDAR

Osborn et al.,
MNRAS, 478(1), 825–834, 2018
Shepherd et al.
MNRAS, 437(4), 3568-3577, 2013
Osborn et al.
MNRAS, 464 (4), 3998 - 4007, 2016
Derie et al.
ESO Messenger, 166, 41-66, 2017
Osborn et al.
MNRAS, 478 (1), 825 - 834, 2018
Osborn et al.
MNRAS, 406(2), 1405-1408, 2010



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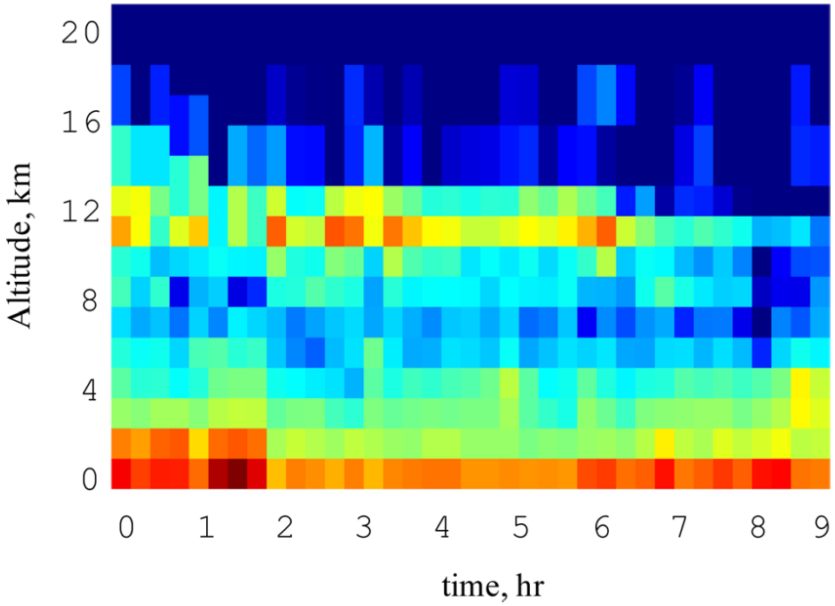
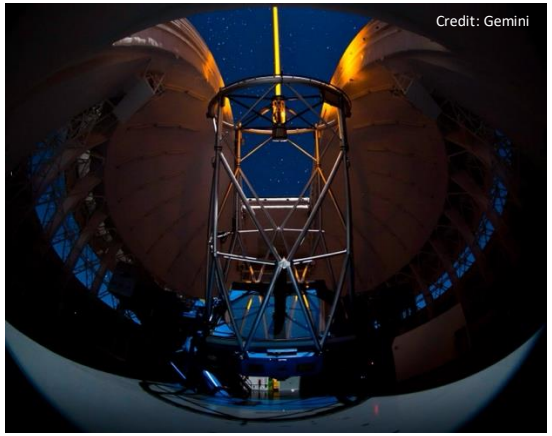
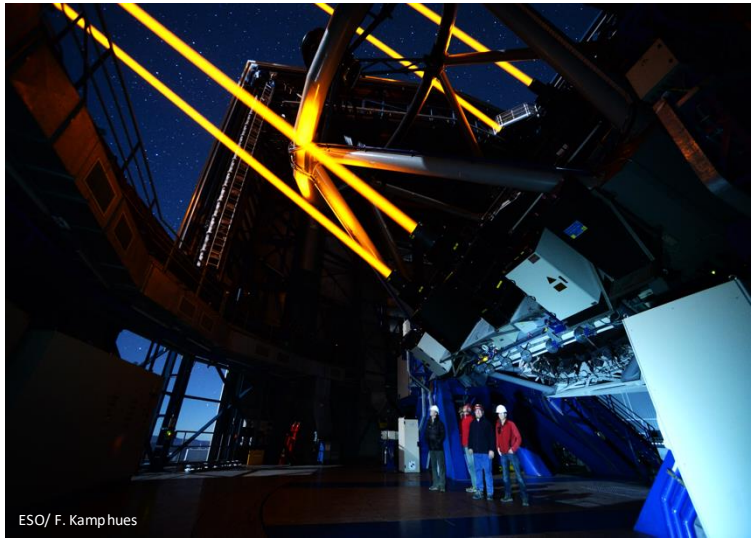
Guesalaga, Neichel, Correia, Butterley, Osborn, MNRAS, 465(2): 1984–1994, 2016
Cortes, Neichel, Guesalaga, Osborn, Rigaut and Guzman, MNRAS, 427(3), 2089-2099, 2012

Measuring Atmospheric Turbulence: AO telemetry







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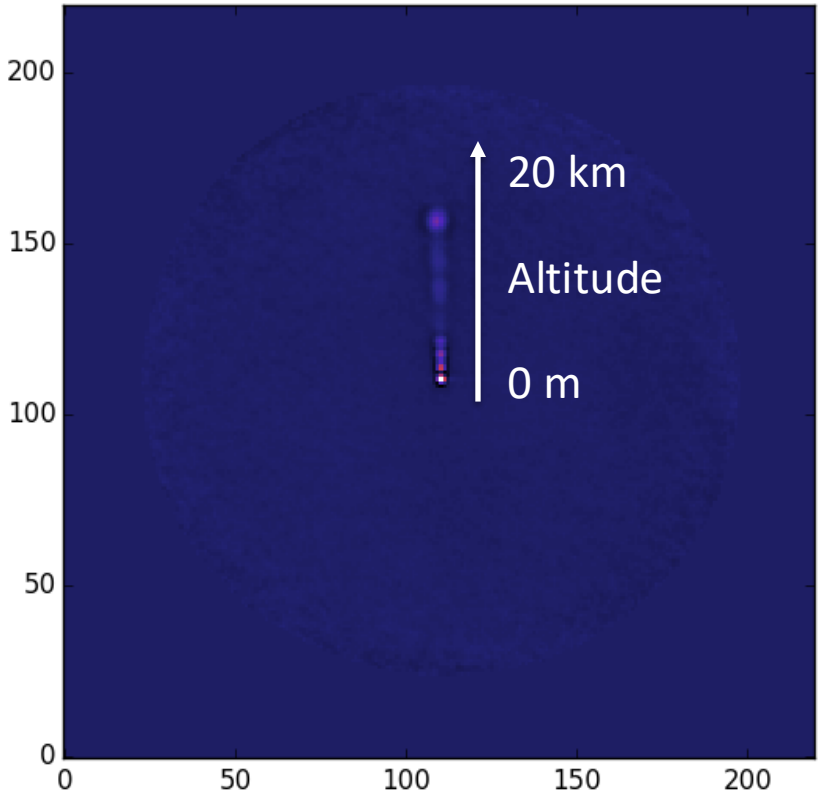
GEMINI OBSERVATORY

Stereo-SCIDAR

Raw data:

- Each peak indicates a turbulence layer



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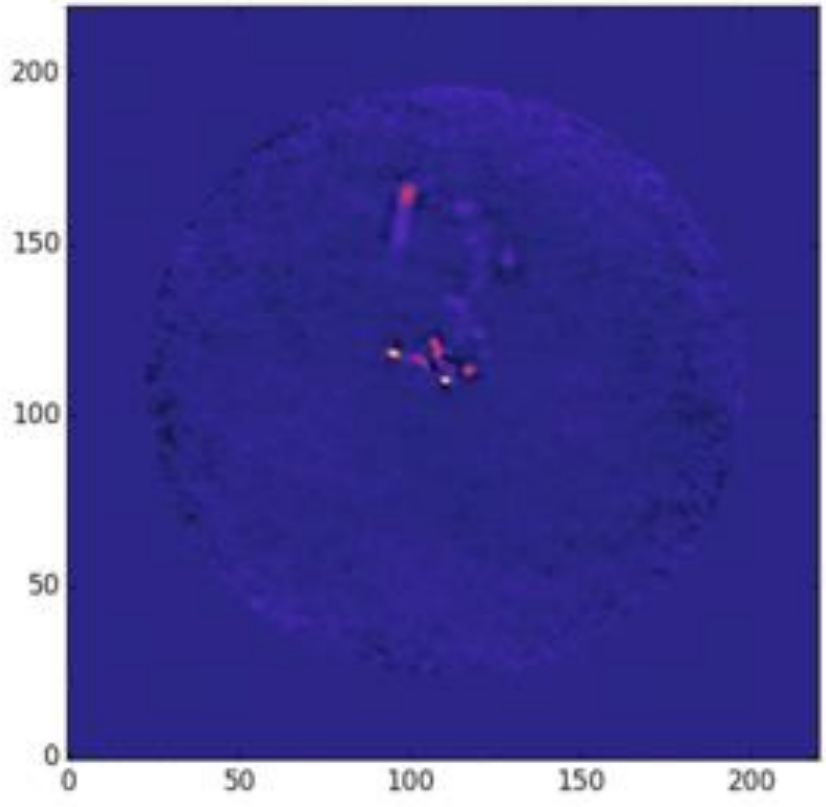
Stereo-SCIDAR

Raw data:

- Each peak indicates a turbulence layer
- Temporal offsets gives us turbulence velocity
- Open question: how to extract, formalize and use this information



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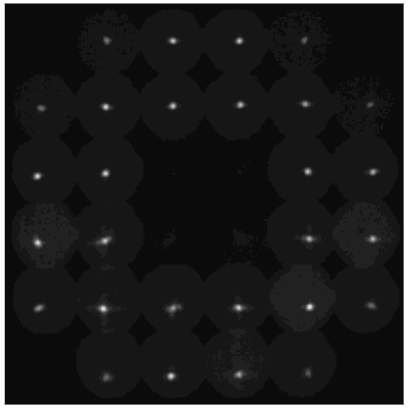
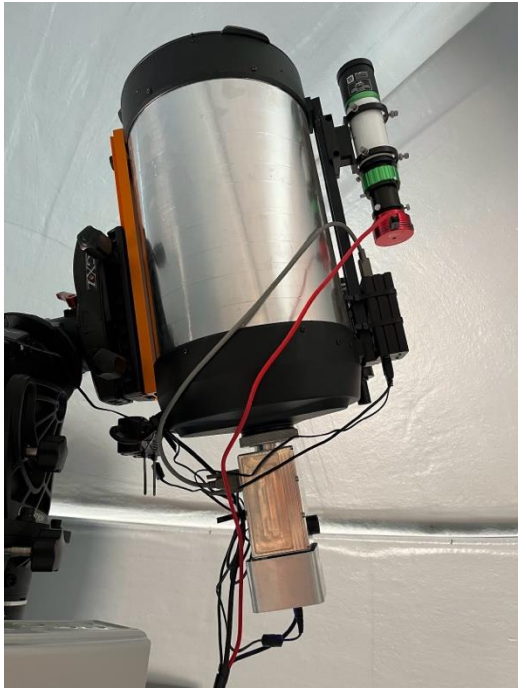
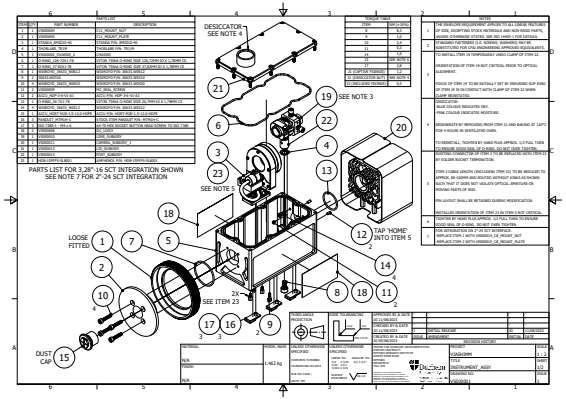
Shack-Hartman Image Motion Monitor

- Fried parameter r_0
- Coherence angle θ_0
- Rytov variance σ_R^2
- Coherence time τ_0
- 4-layer vertical profile
- Dome turbulence
- (outer scale)





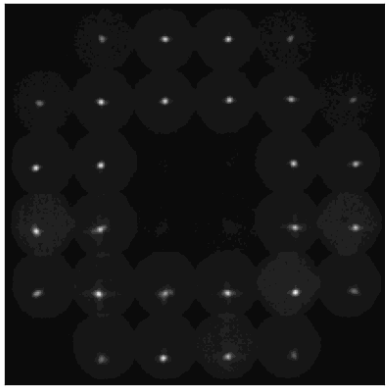


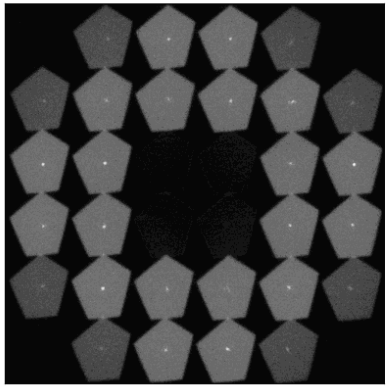
Griffiths et al., Opt. Exp. 31, 2023

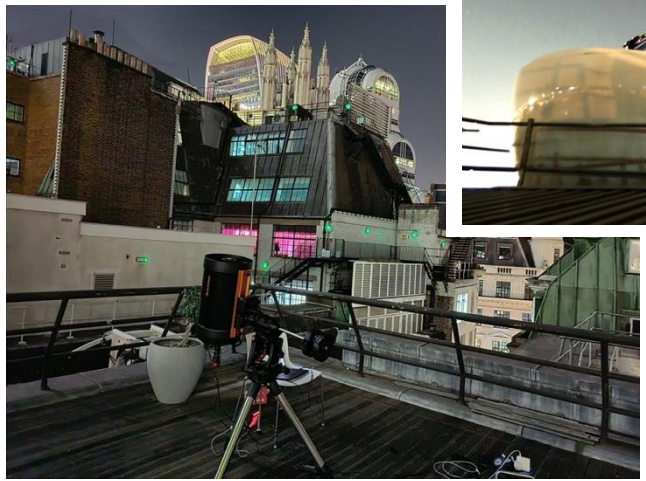
SHIMM

Observes bright stars near zenith during the day and night:

- SWIR (900-1700nm), **sky glow fainter**
- **Turbulence weaker** in SWIR
- Developing robotic facility in Barcelona







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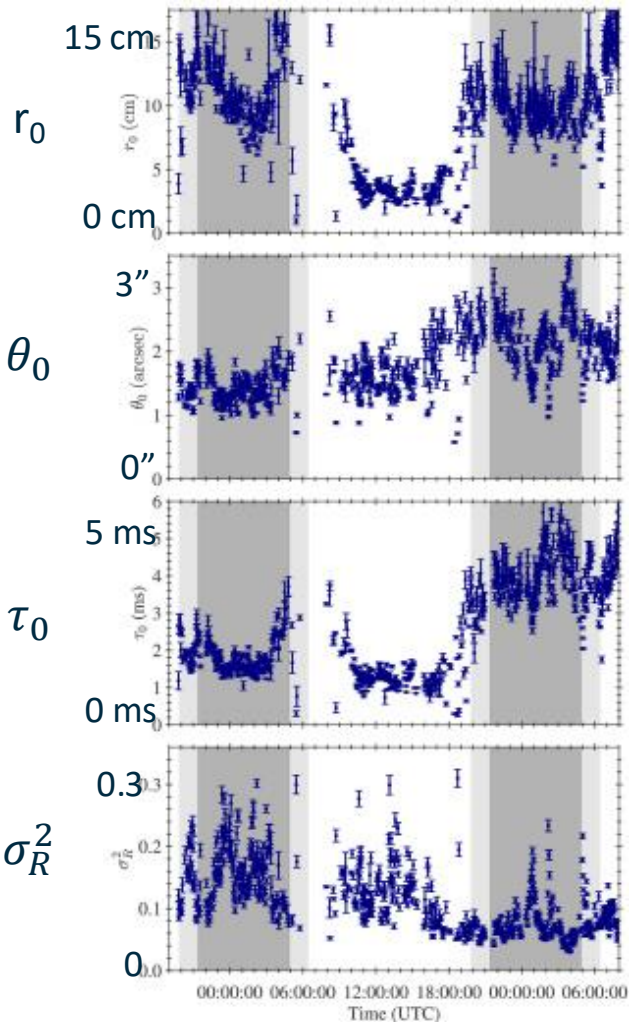
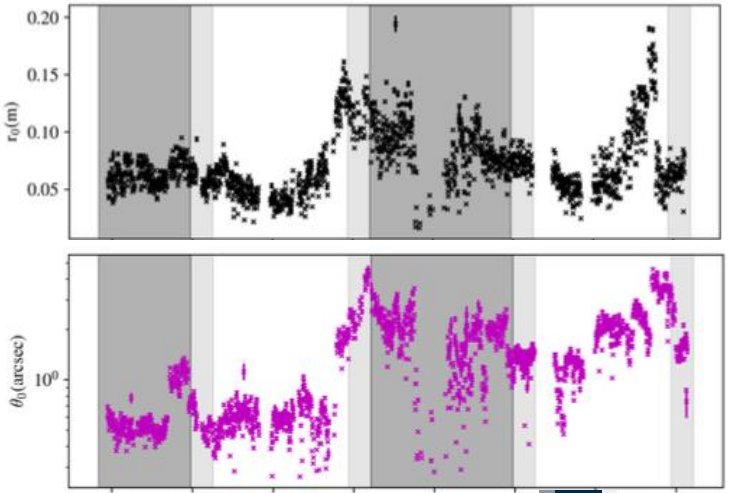
SHIMM data

La Palma

Barcelona





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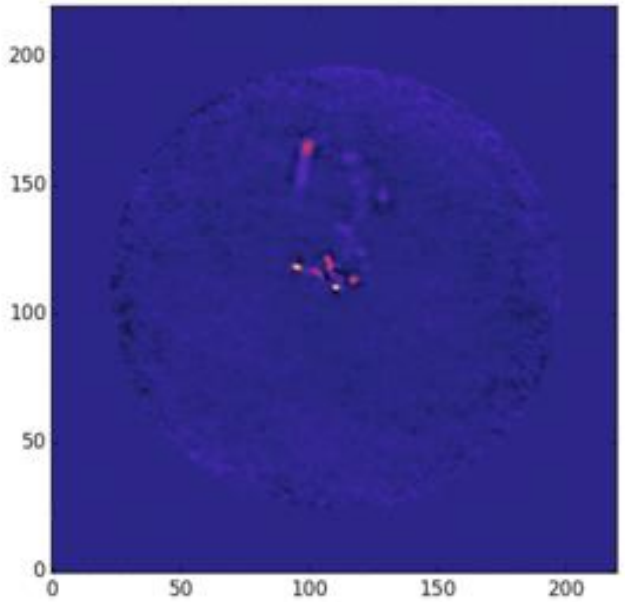
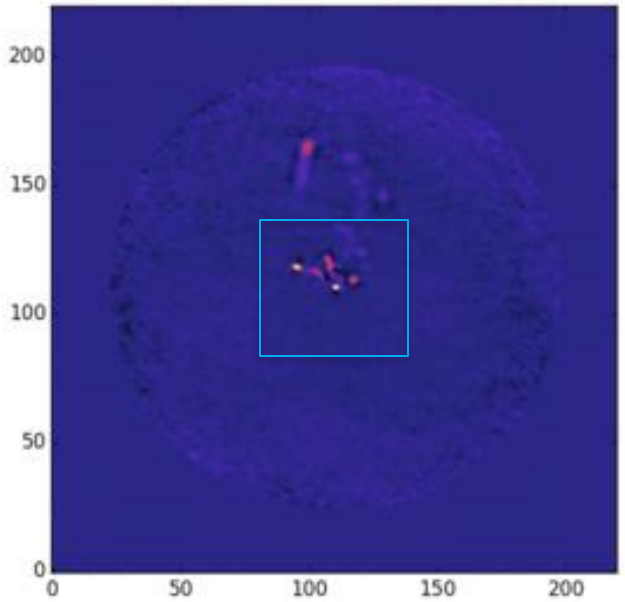
Dome Turbulence

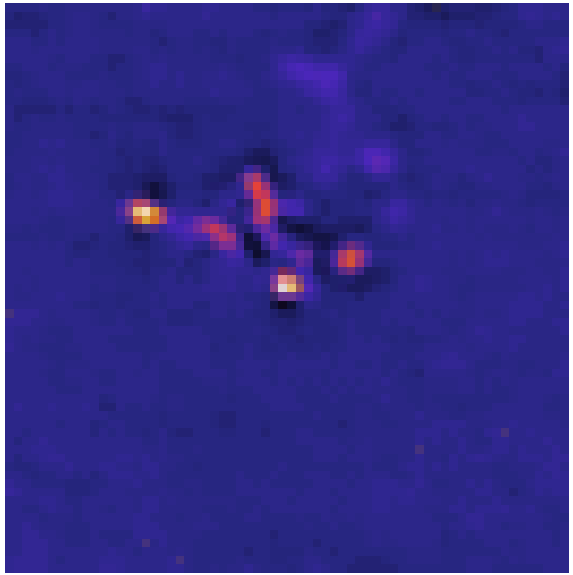


Dome Turbulence



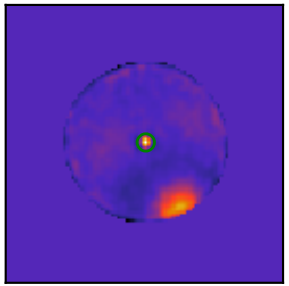
Dome Turbulence

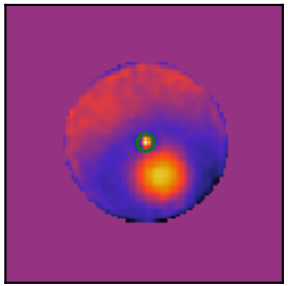
- Assume low translational velocity
- Slow temporal decorrelation
- Extrapolate temporal-covariance to t=0 (overlap of dome and surface layer)
- Can be done with SCIDAR, SLODAR, SHIMM, or dedicated monitor

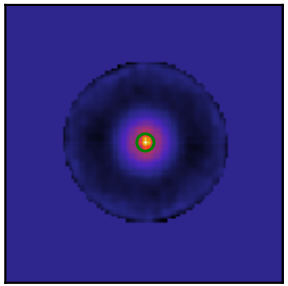


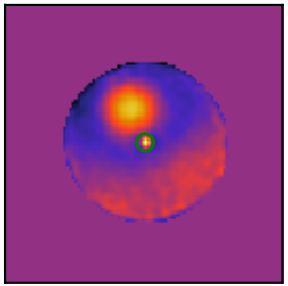
Dome turbulence monitor

Defocused pupil image (cf single-star SCIDAR)


d*t*=-10.0 ms


d*t*=-5.0 ms


d*t*=0.0 ms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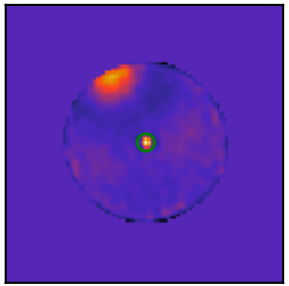
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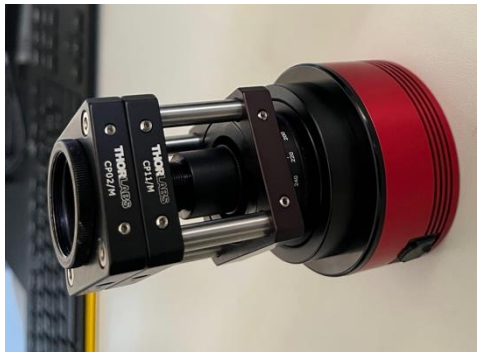
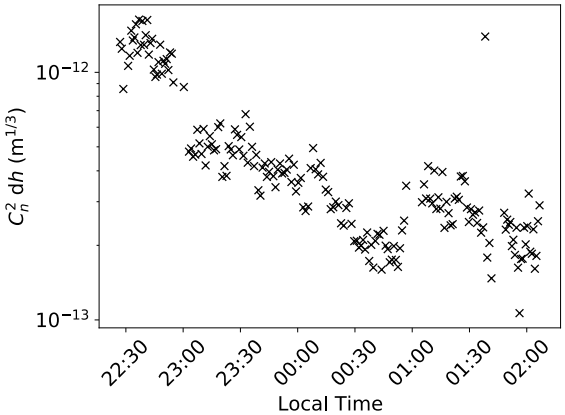
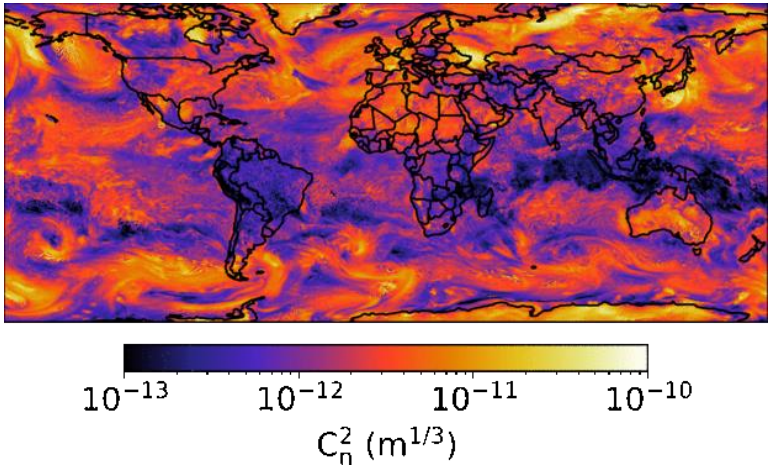




Turbulence Forecasting

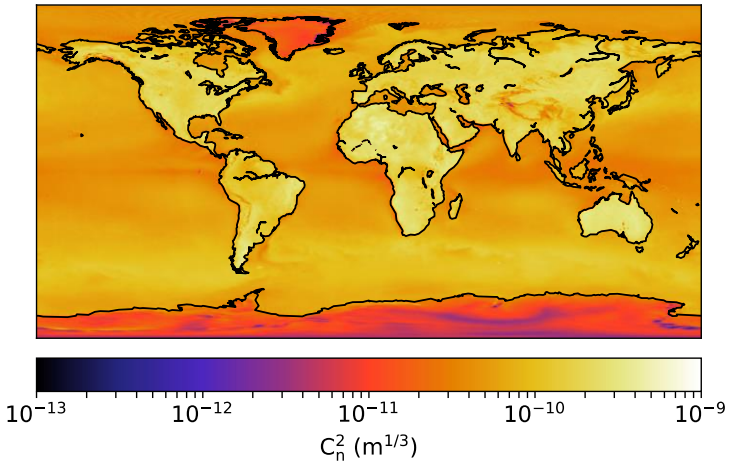
- Forecasting atmospheric turbulence
  - Queueing astronomical observations to make sure the most sensitive measurements are performed at the optimal time
  - Network routing to optimal ground station depending on conditions
  - Use archived data to get statistics of sites for site selection and instrument development



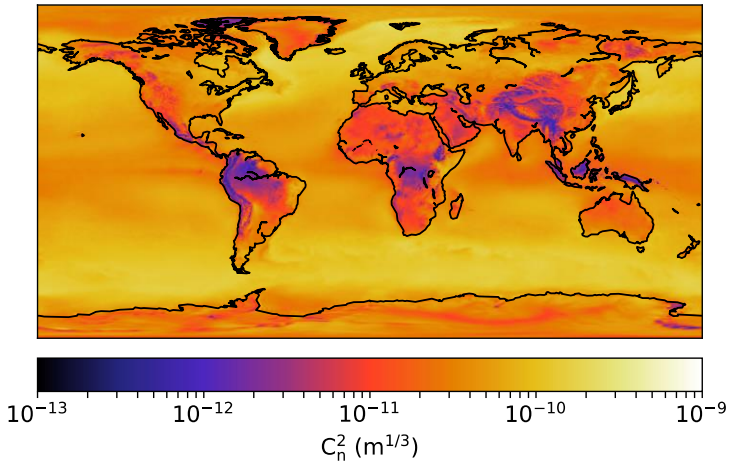
Global turbulence forecasting

Global maps of turbulence strength: Day and night

Median day

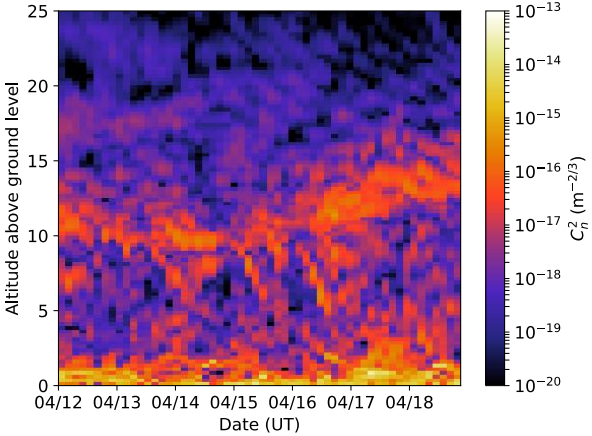


Median night

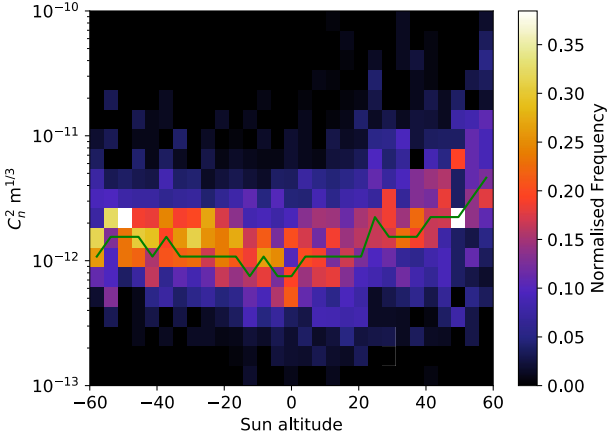


Atmospheric Modelling Durham

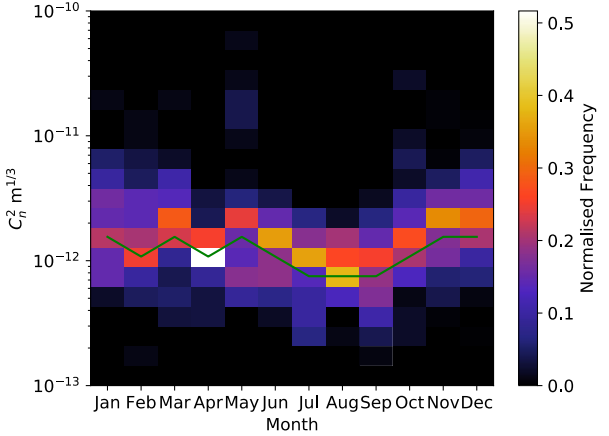
Example 1 week sequence



Turbulence strength and sun elevation



Night time turbulence strength and month



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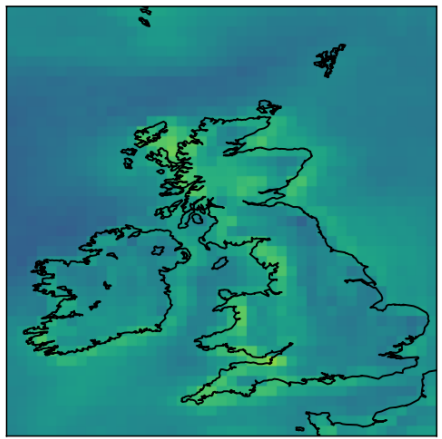
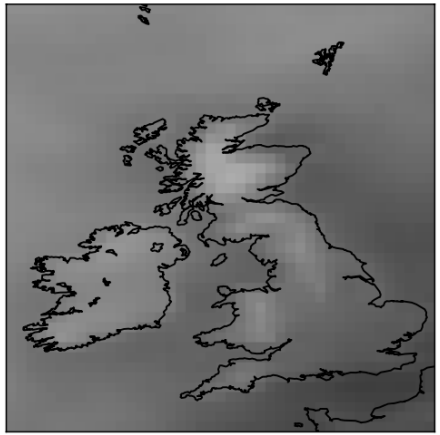
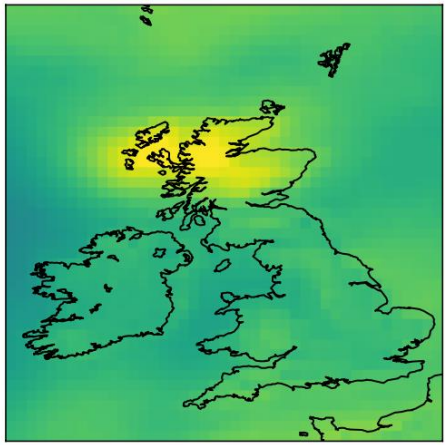
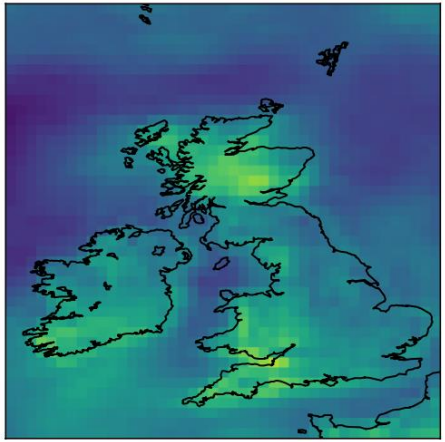
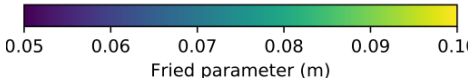
Atmospheric optical turbulence parameters UK

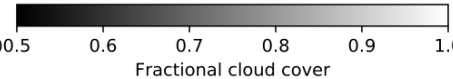


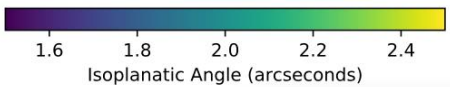












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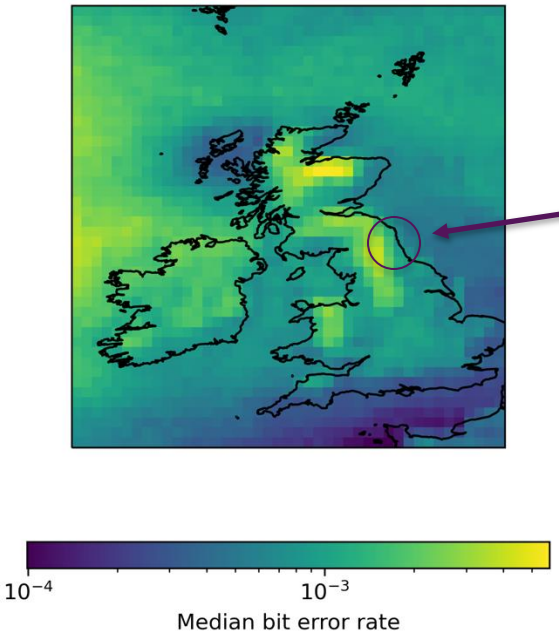
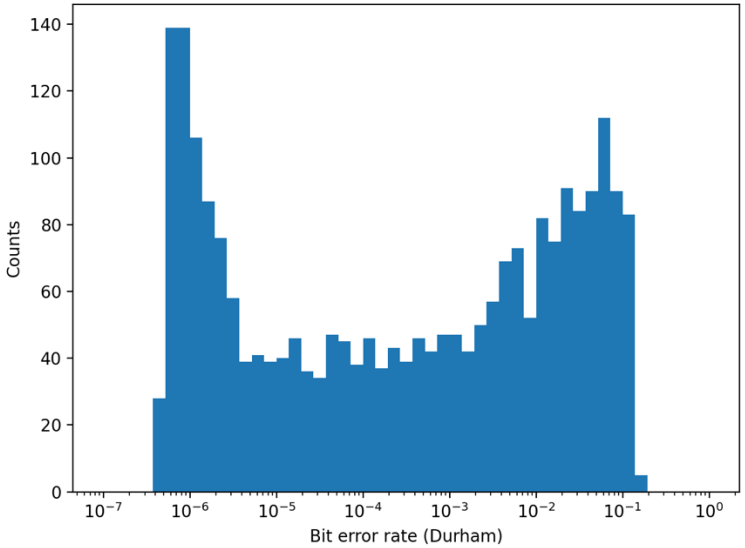
Site Characterisation for Free-space optical communications - Bit-error rate





Each element has a full relative density profile – the median is not good enough

Site Chracterisation

Site characterisation for astronomy is well developed

New challenges have recently emerged to support Free-Space Optical Communications and Space Situational Awareness

Technology and techniques originally developed for astronomy is being adapted for these new applications

OPTICON was critical to the development process of many of these techniques

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OPTICON