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Measuring, modelling and forecasting the dynamics of the Earth's optical turbulence

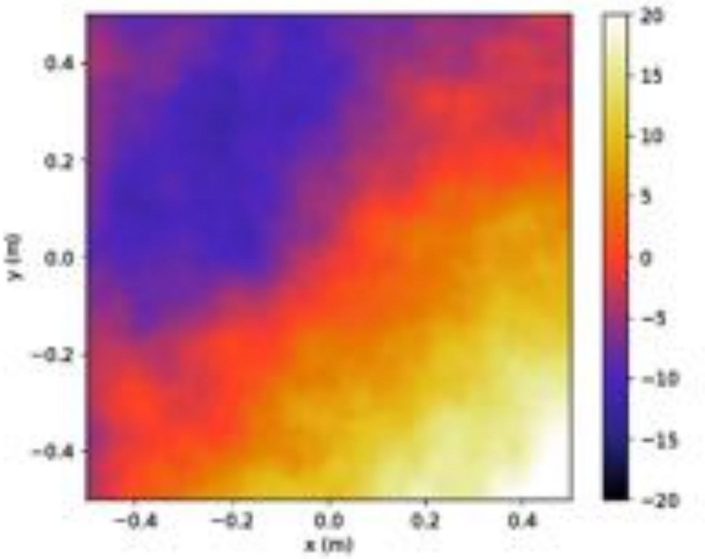
James Osborn

Matt Townson

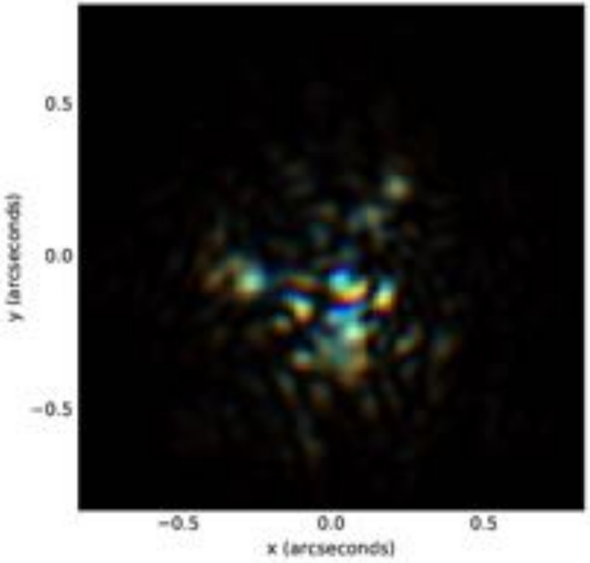
UK Research and Innovation

Science & Technology Facilities Council

Atmospheric Turbulence: Phase

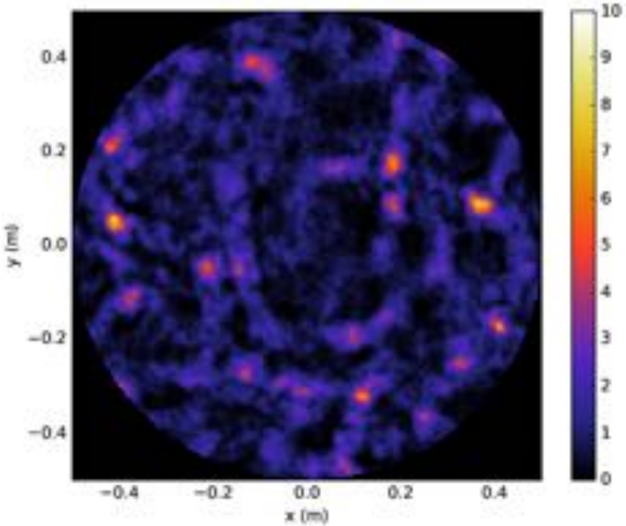


Phase

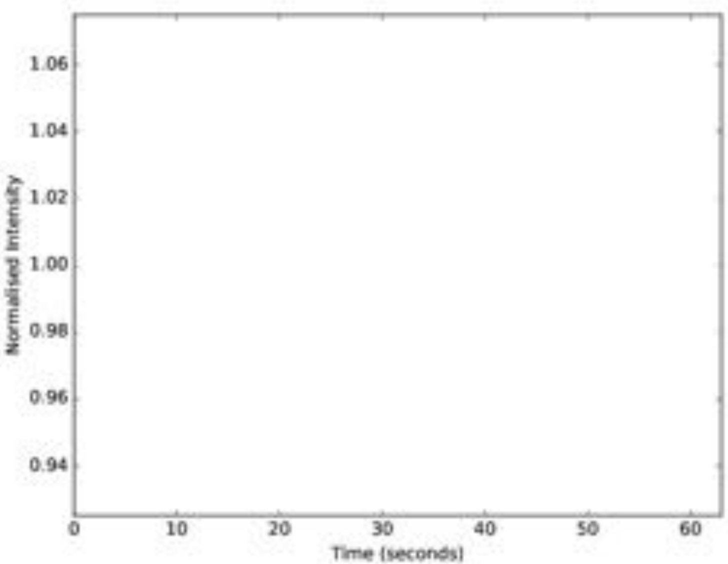


Image

Atmospheric Turbulence: Scintillation



Pupil image



Integrated intensity

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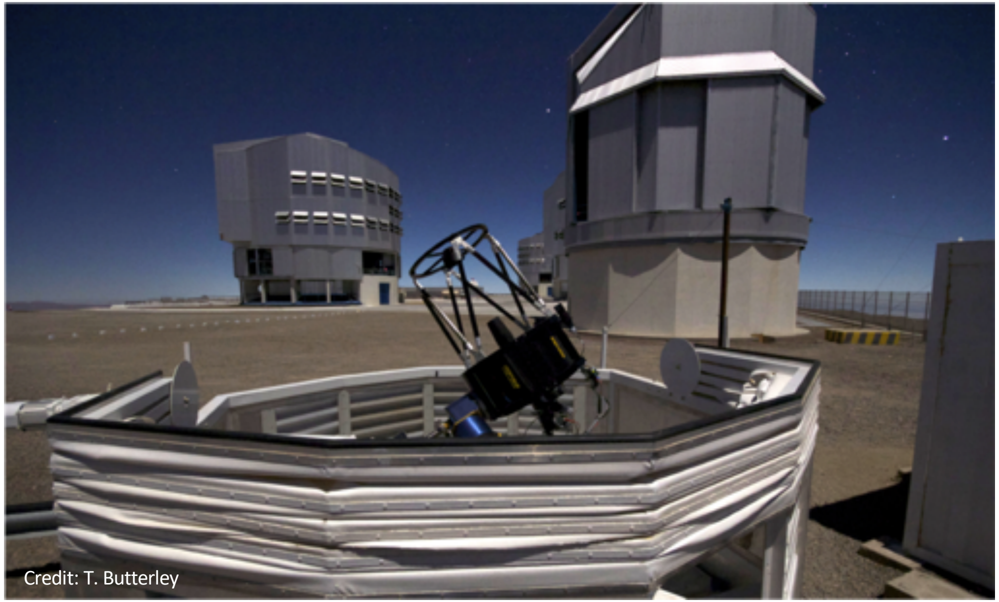
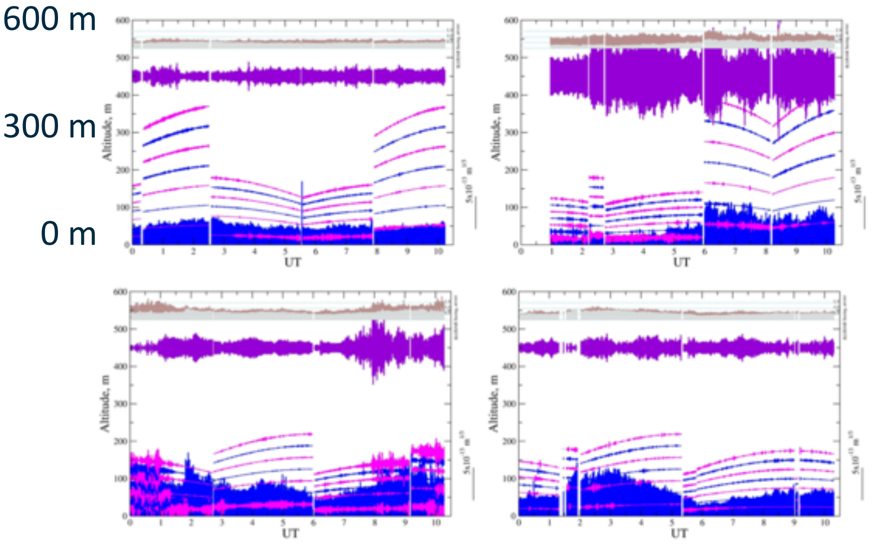
Instrumentation

Tim Butterley

Measuring Atmospheric Turbulence: SLODAR



Credit: T. Butterley



Osborn et al.,
MNRAS, 406, 1405-1408, 2010
Butterley et al.,
MNRAS, *submitted October 2019*

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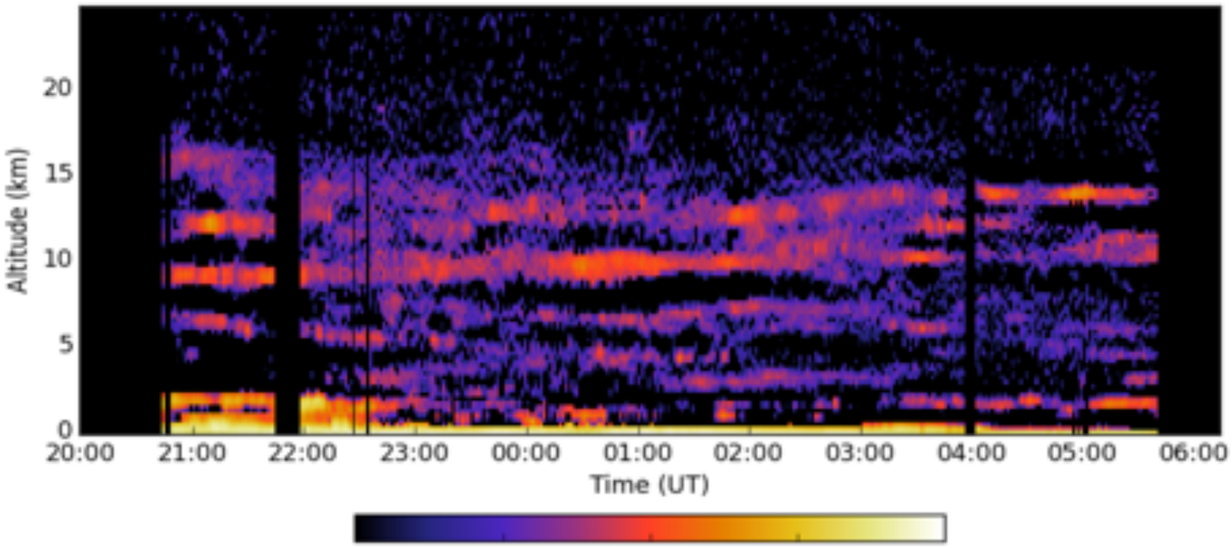
ESO

Measuring Atmospheric Turbulence: 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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Measuring Atmospheric Turbulence: SHIMM

- Shack-hartmann sensor looking at a single bright 'source'
- Turbulence strength, Coherence time
- Simple profile - ground / not ground - possible (not published)
- Isoplanatic angle possible

Perera, 2017

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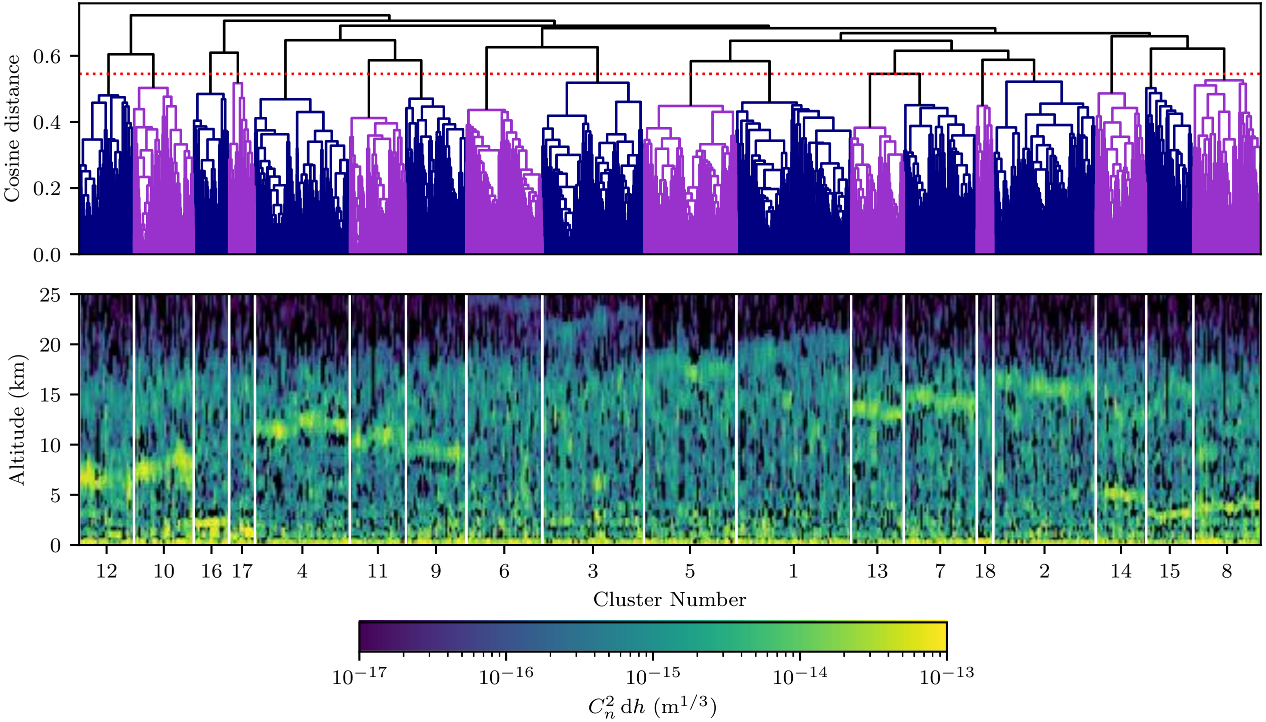
ESO

Measuring Atmospheric Turbulence: STEREO-SCIDAR

Farley et al., *MNRAS, 481, 2018*

- 10000+ profiles into 15
- Hierarchical clustering

Ollie Farley



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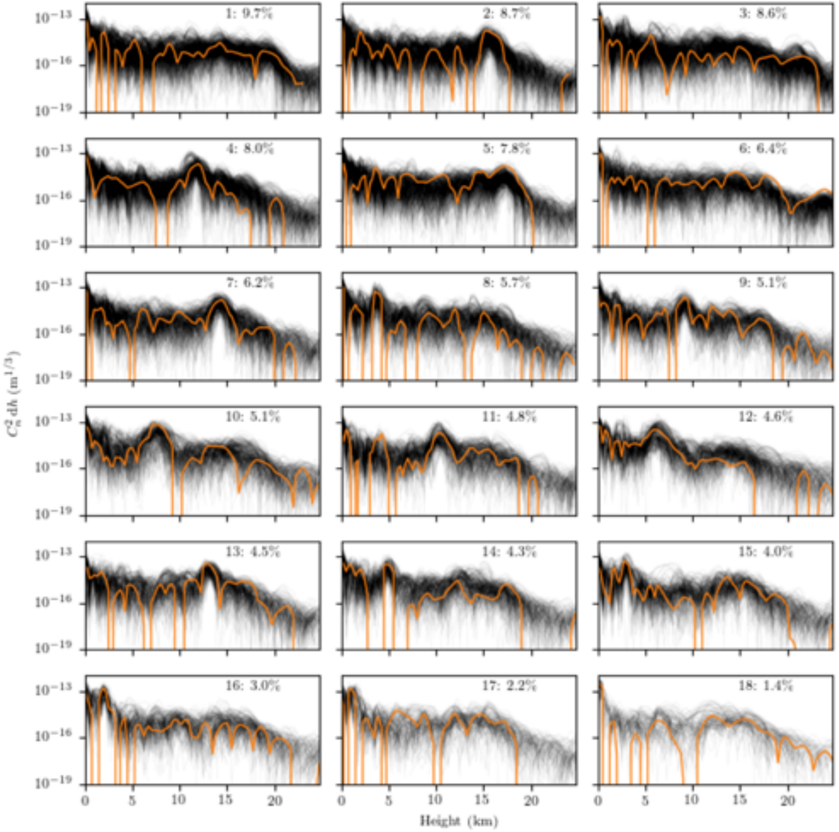
Measuring Atmospheric Turbulence: STEREO-SCIDAR

Farley et al., *MNRAS, 481, 2018*

- 10000+ profiles into 15
- Hierarchical clustering
- Reflects variability of atmospheric turbulence



Ollie Farley

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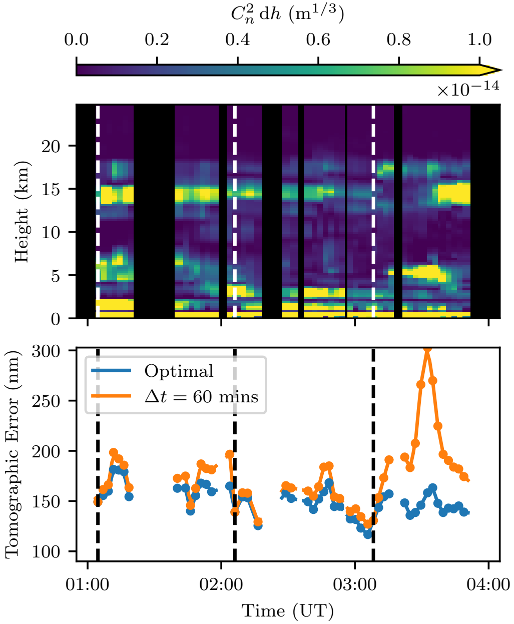
Measuring Atmospheric Turbulence: Modelling tomographic AO

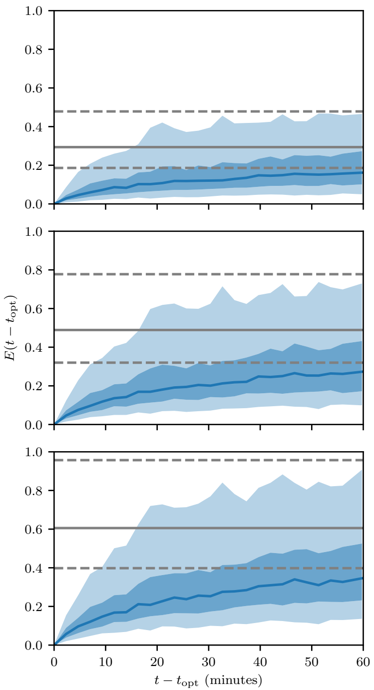
Farley et al., MNRAS, *in prep*

Ollie Farley

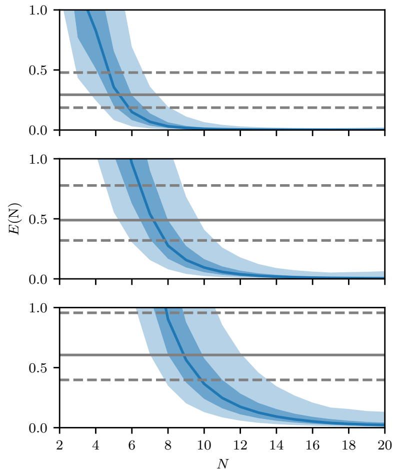
Expected tomographic error for various reconstruction architectures (temporal sampling of turbulence, number of layers, altitude of layers)

How often to update?





How many layers to reconstruct and where to put them?



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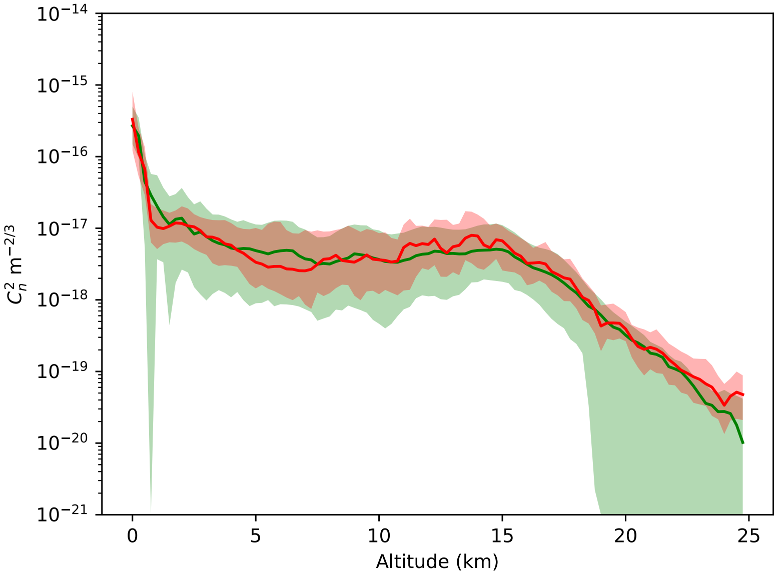
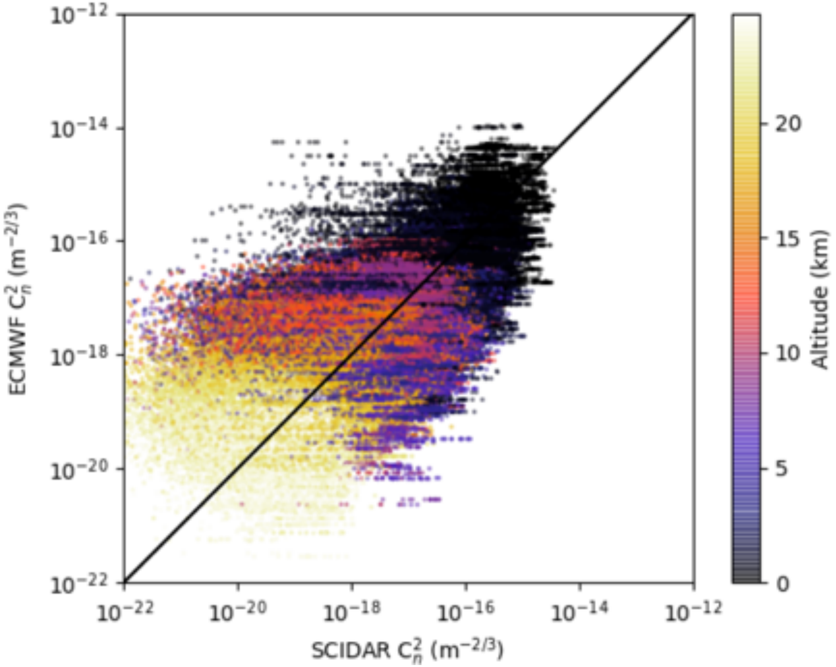
Turbulence Forecasts

Atmospheric Turbulence Modelling: Paranal

Osborn & Sarazin,
MNRAS, 480(1), 1278-1299, 2018





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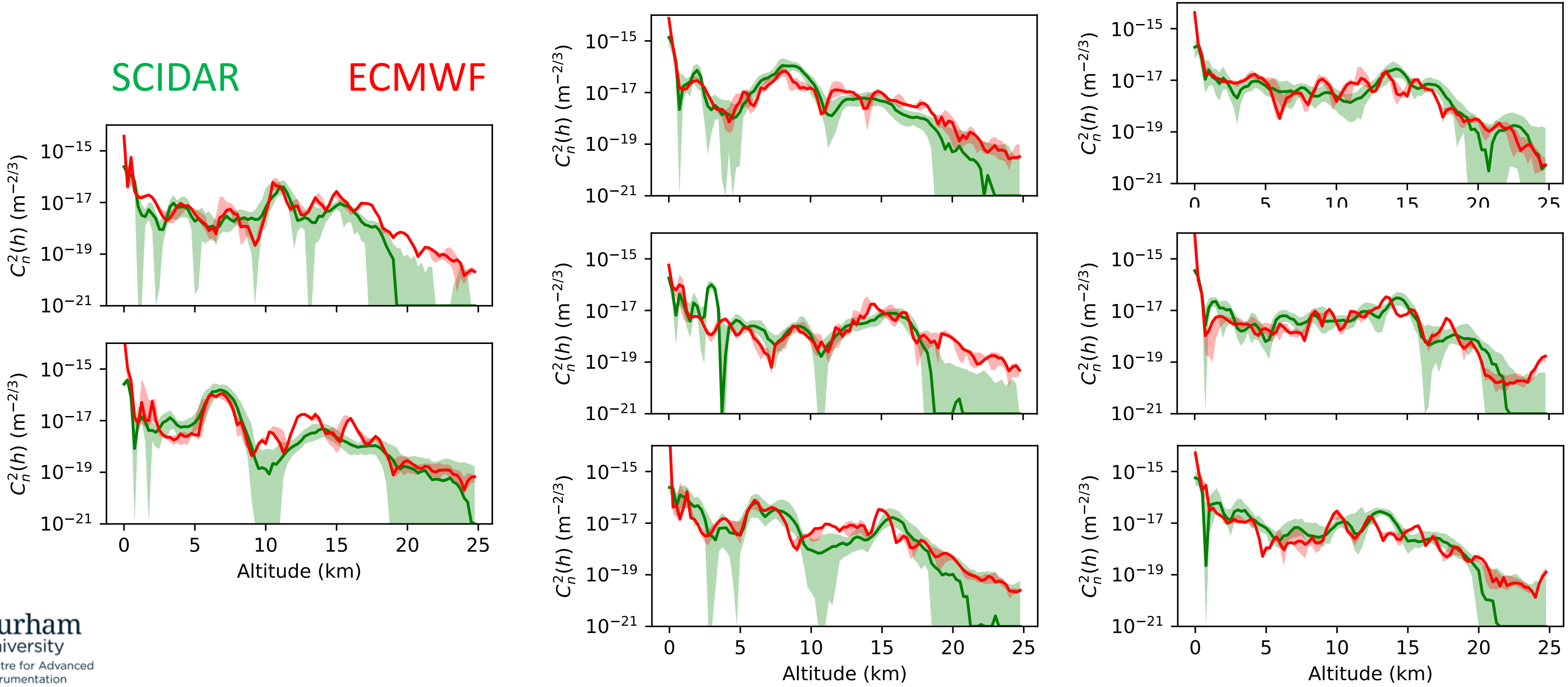
Osborn & Sarazin, MNRAS, 480(1), 1278-1299, 2018

Atmospheric Turbulence Modelling: Paranal



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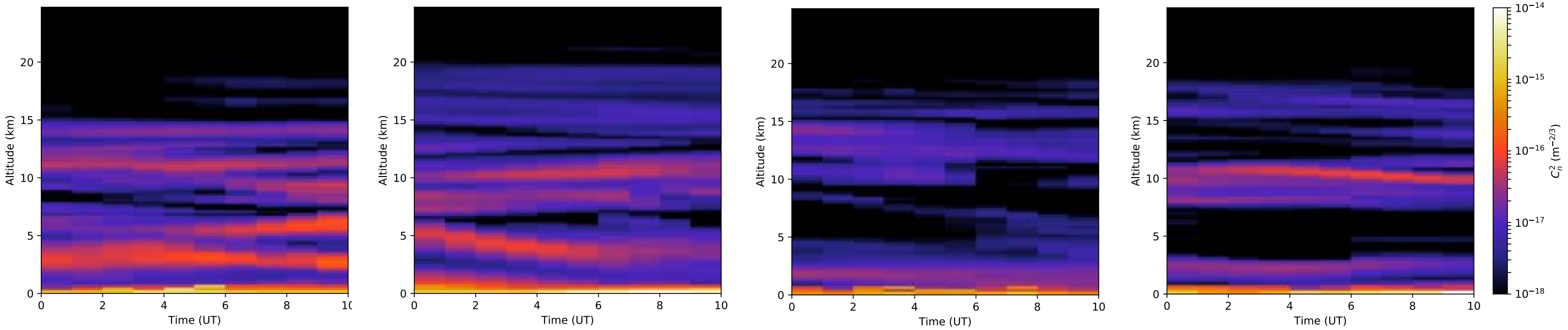
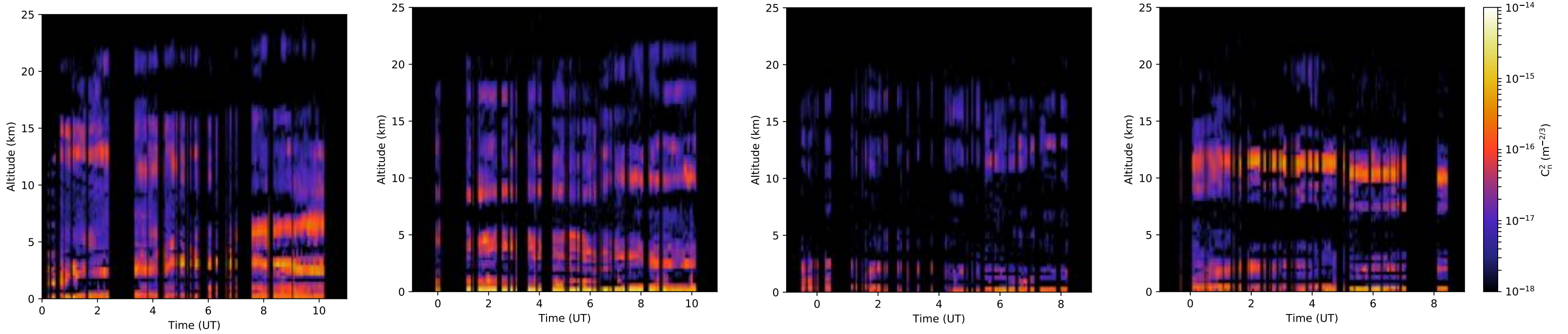
Osborn & Sarazin,
MNRAS, 480(1), 1278-1299, 2018

Atmospheric Turbulence Modelling: Paranal

ECMWF turbulence model



Stereo-SCIDAR



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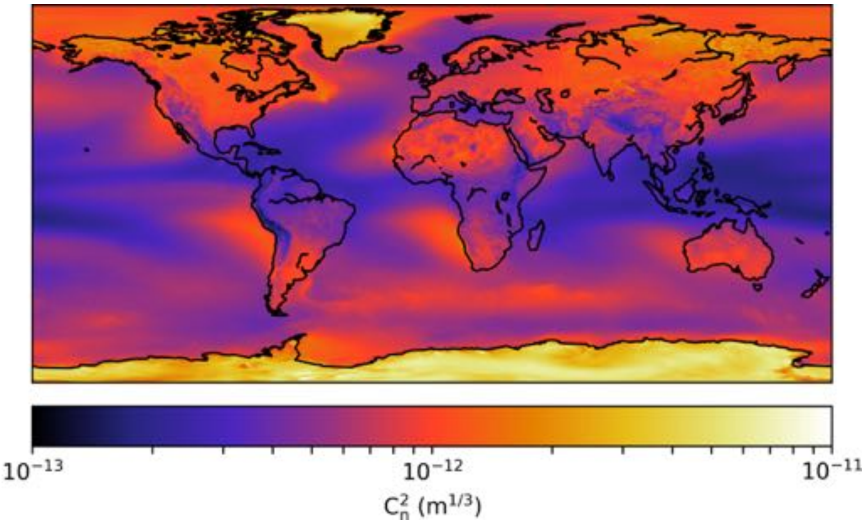
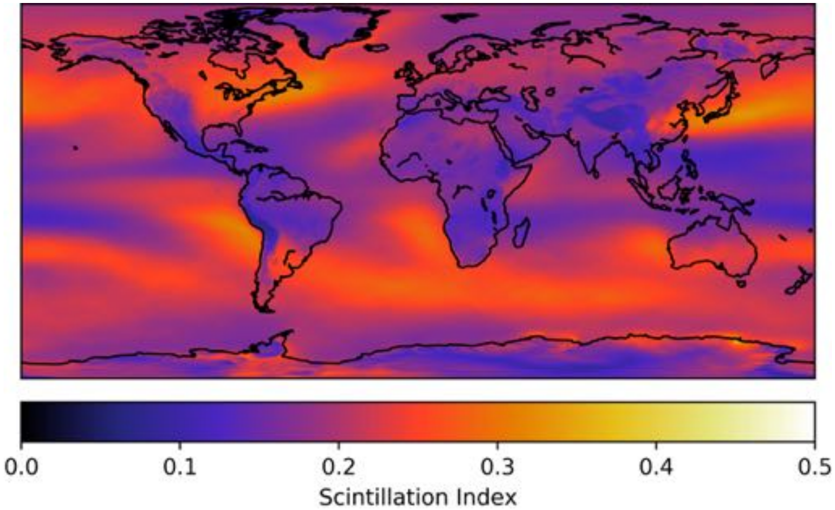
Atmospheric Turbulence Modelling: Global

Turbulence Strength



Scintillation



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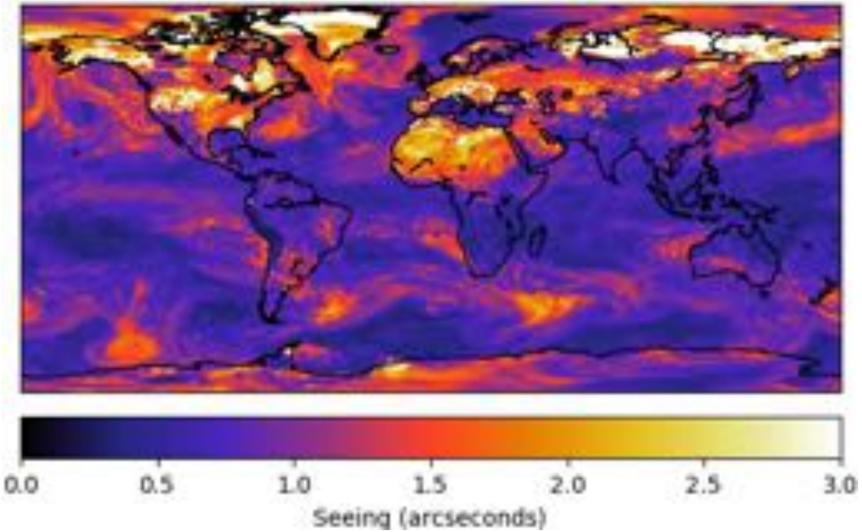
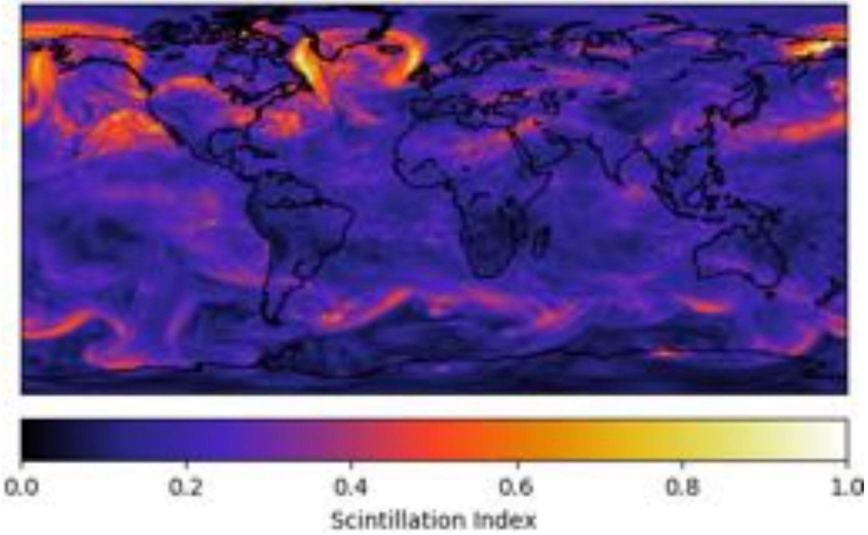
Atmospheric Turbulence Modelling: Global Models

Seeing

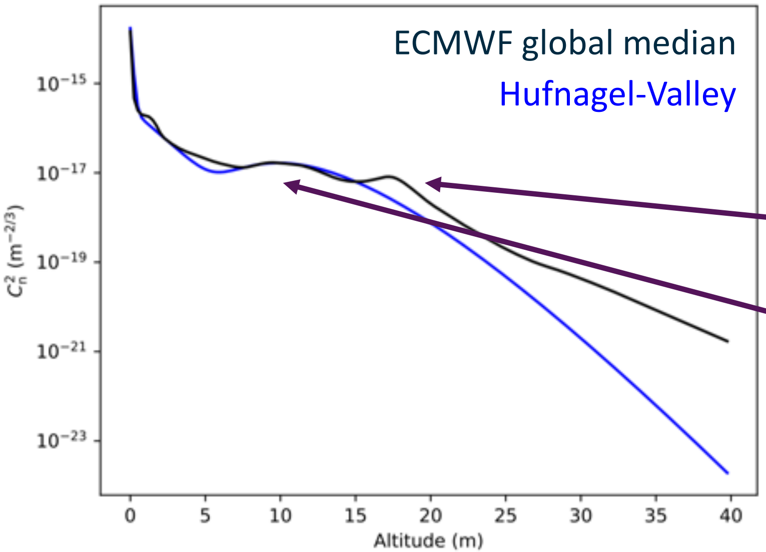


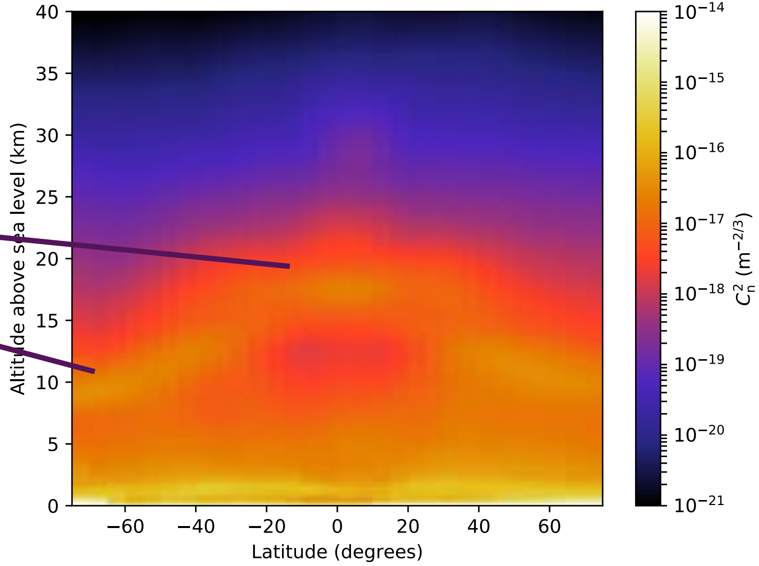
Scintillation



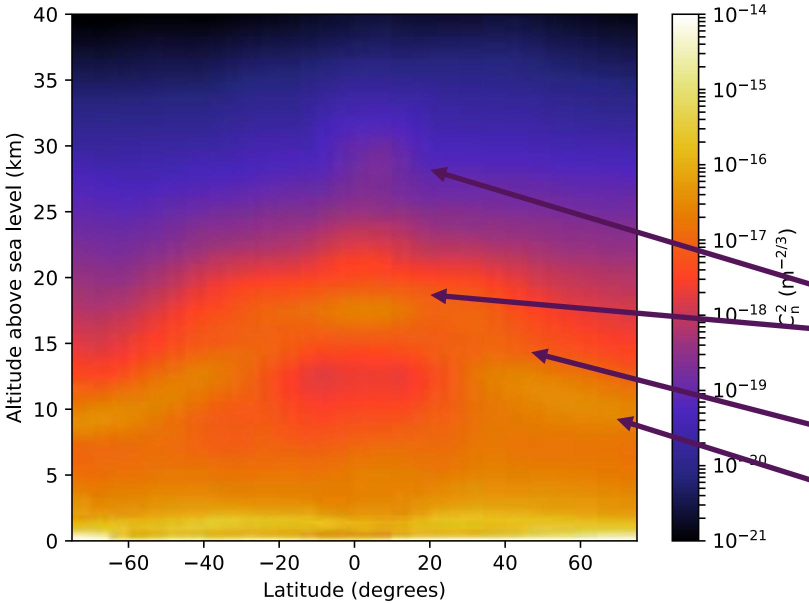
- Working with Sukanta Basu to improve meteorological models
- Best global data available?

Atmospheric Turbulence Modelling: Global Models





Atmospheric Turbulence Modelling: Global Models



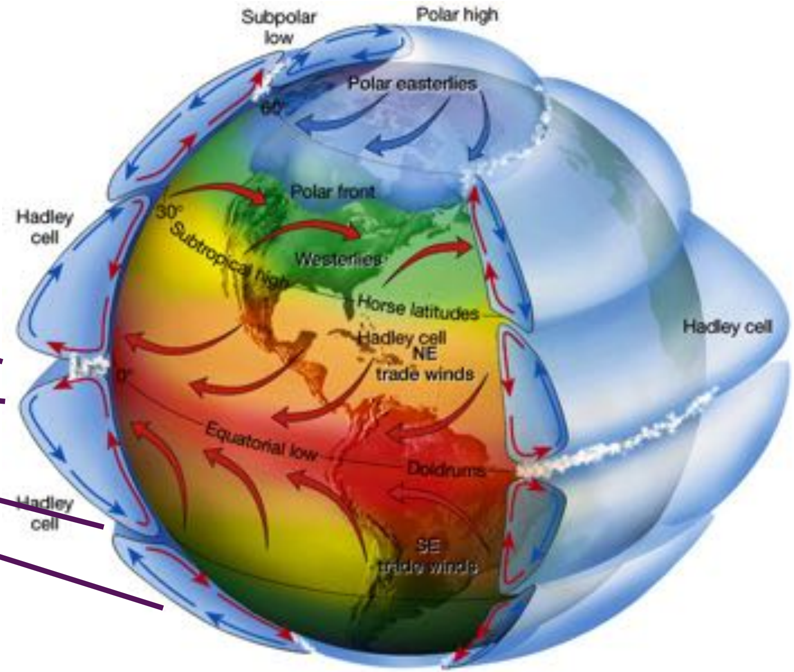
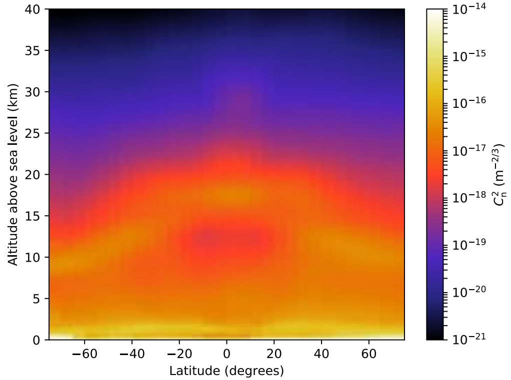


Image: NASA

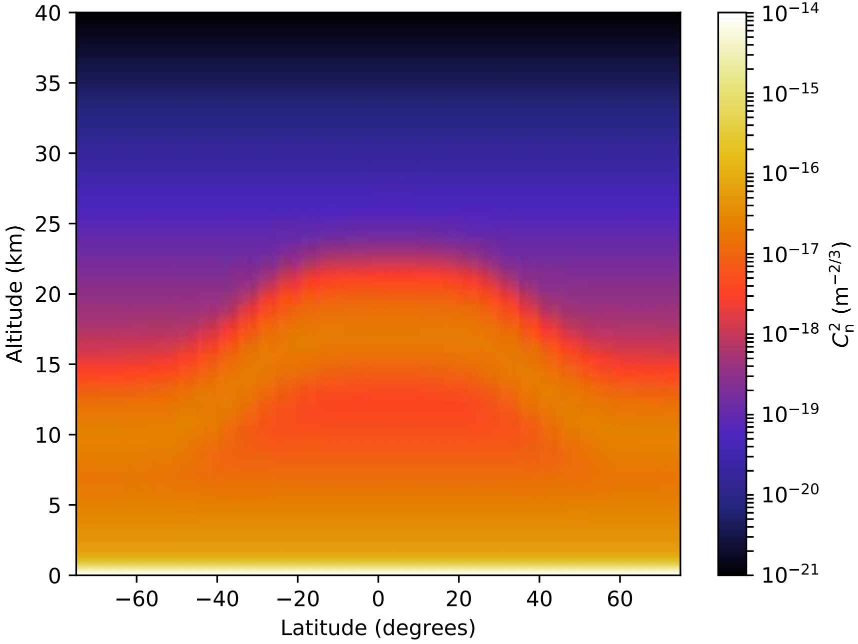
Atmospheric Turbulence Modelling: Latitude Models

- Simple parametric latitude model
- Laser communications studies
- Site characterisation
- Instrument design



ECMWF median

Parametric Latitude Model



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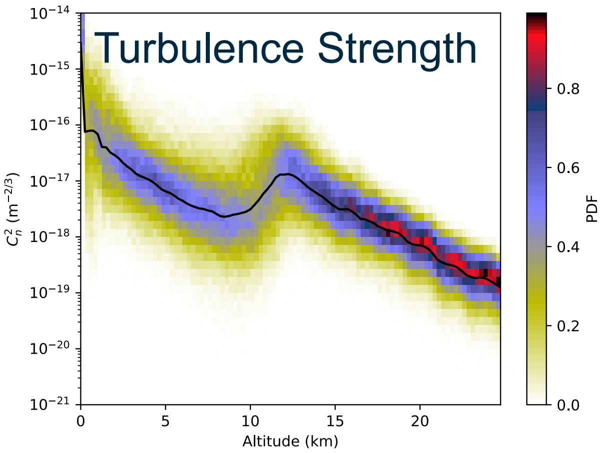
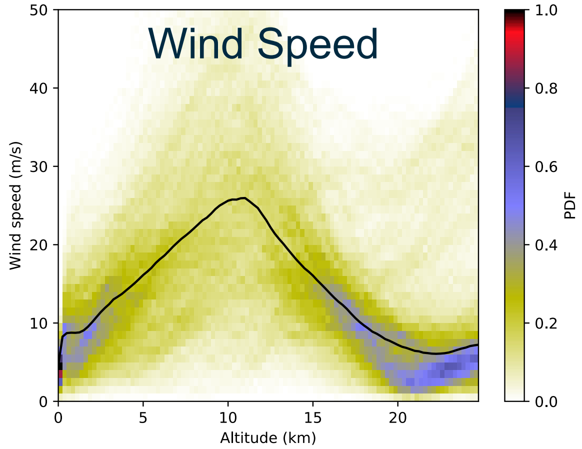
Case Study: Paris

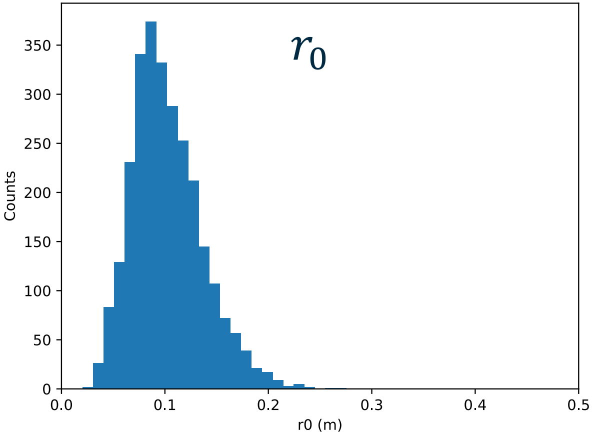


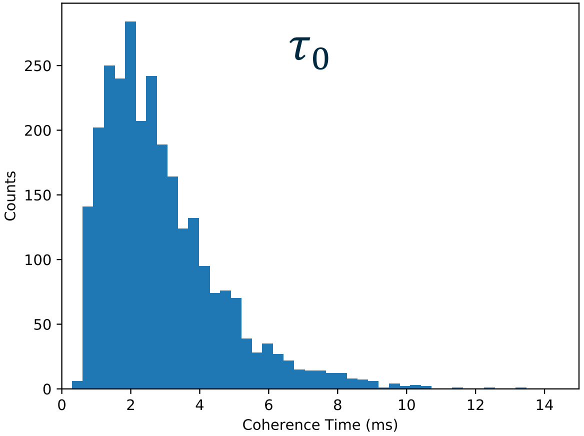


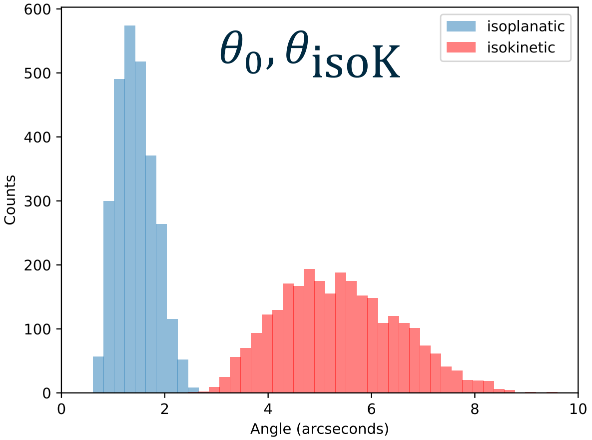
Case Study: Paris

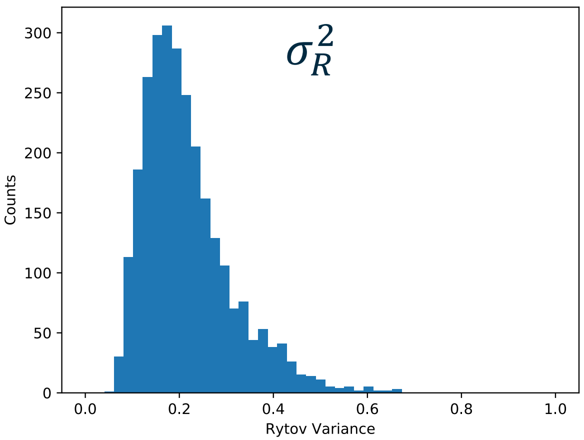
$r_0 = 0.1 \pm 0.03$ m
$\theta_0 = 1.44 \pm 0.37''$
$\theta_{\mathrm{isoK}} = 5.38 \pm 1.16''$
$\tau_0 = 2.88 \pm 1.7$ ms
$\sigma_R^2 = 0.22 \pm 0.09$

At 500nm









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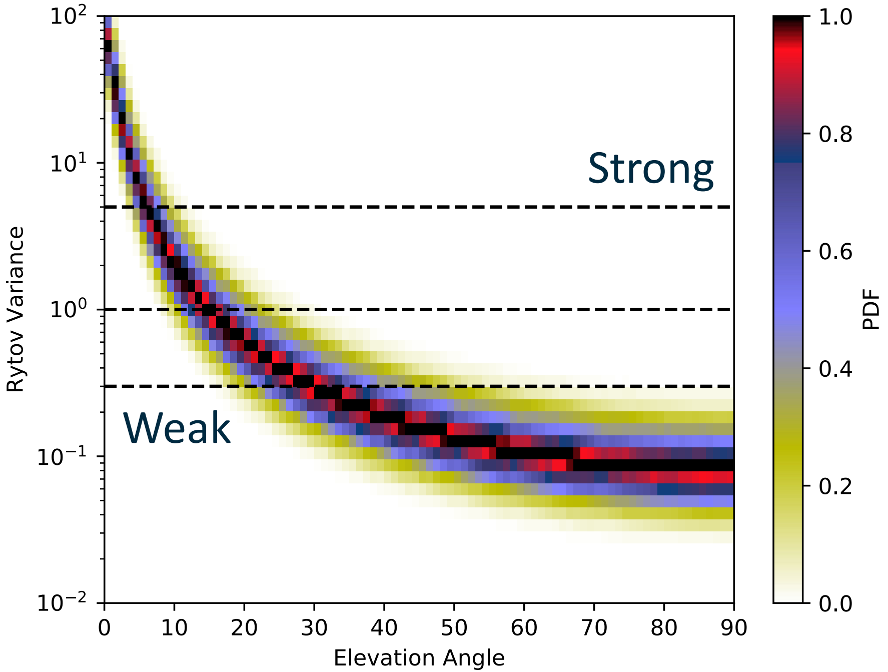
Case Study:
Paris: Rytov Variance

In this case we assume pointing to zenith, but results can be scaled



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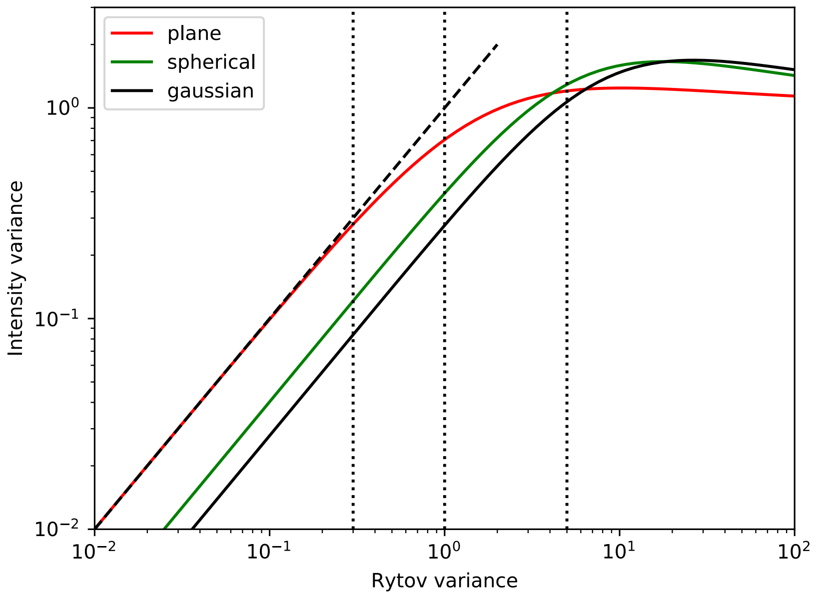
Atmospheric Parameters: Rytov Variance and Scintillation Index

Different model depending on beam shape (impacts propagation)

- Downlink
  - Assume plane at top of atmosphere
- Uplink
  - Assume spherical (simpler) as in Andrews & Phillips or gaussian (more complex)



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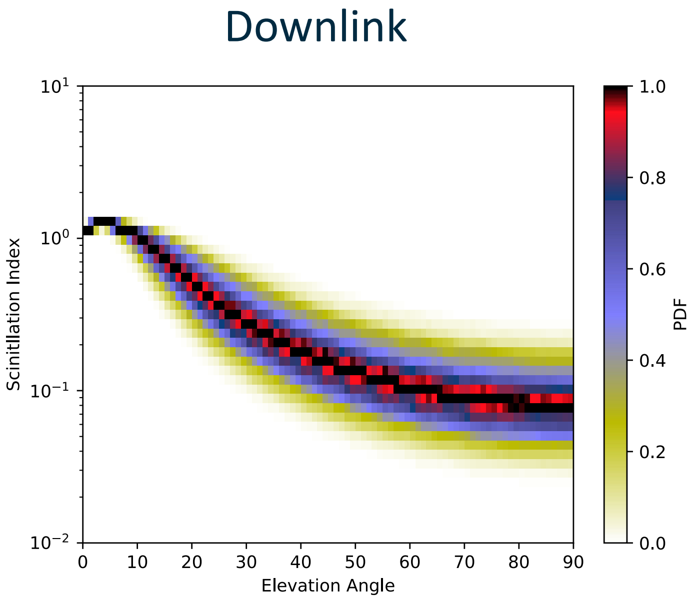
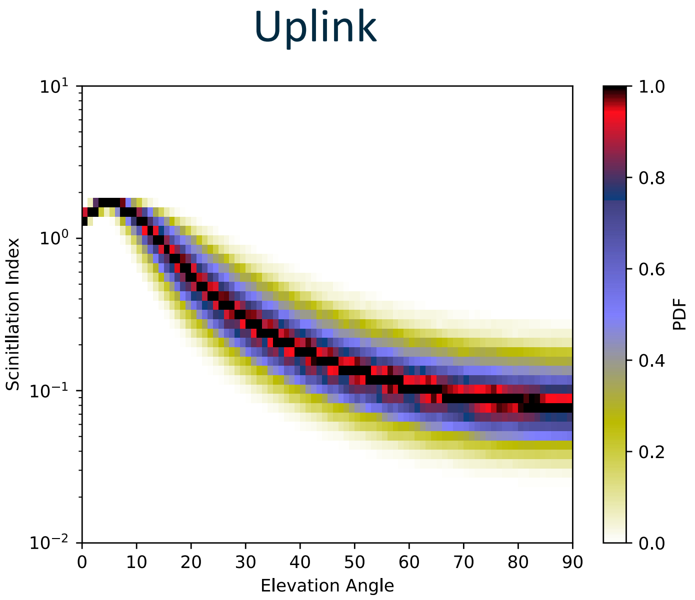
Case Study:
Paris Scintillation Index





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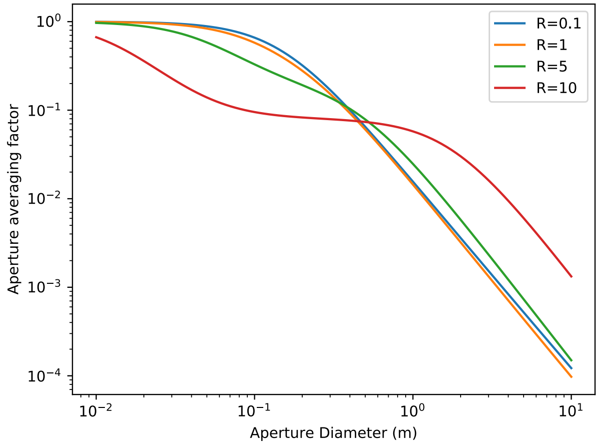
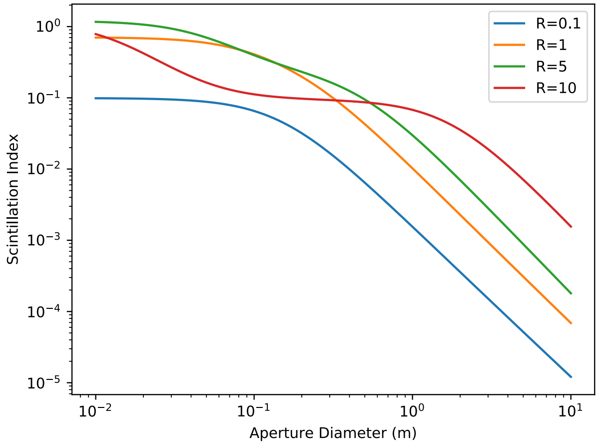
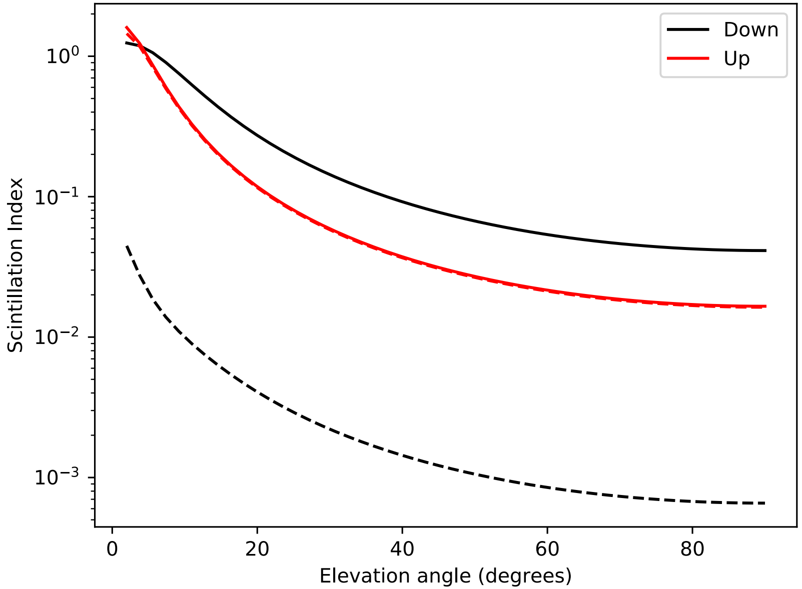
Atmospheric Parameters:
Aperture Averaging and Scintillation Index





- Scintillation Index as a function of receiver aperture size for a downlink plane wave in increasing Rytov variance conditions
- Aperture averaging is effective when the aperture is larger than the individual speckles

Case Study:
Paris Scintillation Index



No aperture averaging

With aperture averaging

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Numerical Modelling

Modelling – Monte-Carlo simulation: Overview

Problems:

- Theory for finite launch apertures
- Validation of performance using real turbulence profile and system parameters
- Understand architecture of potential AO systems

Features:

- Includes satellite motion (effective wind speed and variable zenith angle (propagation distance) during simulation)
- Physical propagation model of Gaussian and any other beamshapes
- Shack-Hartmann wavefront sensor or 'magicAO'
- Laser guide star
- Modal AO system
- Variable AO latency and frame rates
- Infinite phase screens
- Layer wind speed, direction and turbulence strength can vary during simulation
- Arbitrary transmitter and receiver geometries

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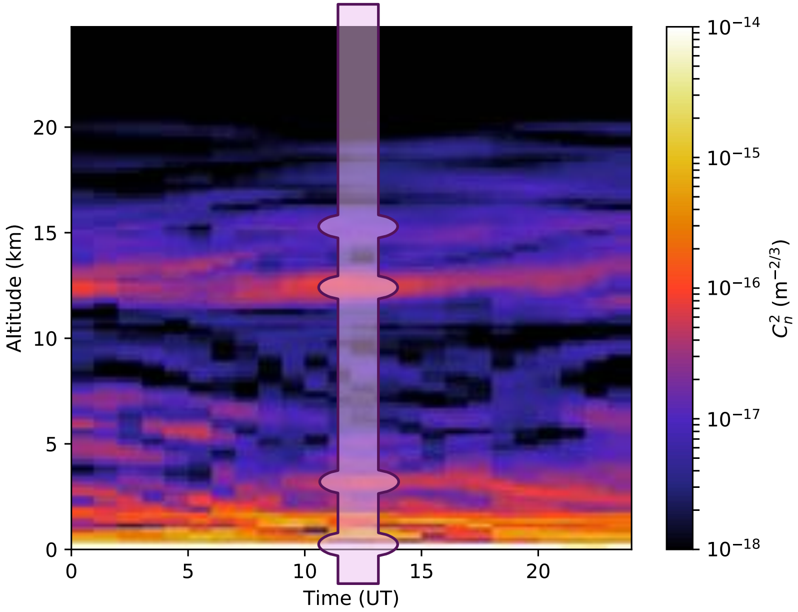
Case Study: Paris

Parameters used here:

- λ=1064nm
- Ground station receiver diameter = 1m
- Ground station transmitter = 1 m
- Satellite receiver diameter = 0.2 m
- Satellite altitude = 2000 km
- Paris turbulence profile (compressed to 4 layers, r_0, θ_{iso}, τ_0 and σ_I^2 are conserved)
- Frame rate = 1kHz
- 4000 frames (4 seconds simulation time), limited by available computational time
- Assume perfect pointing



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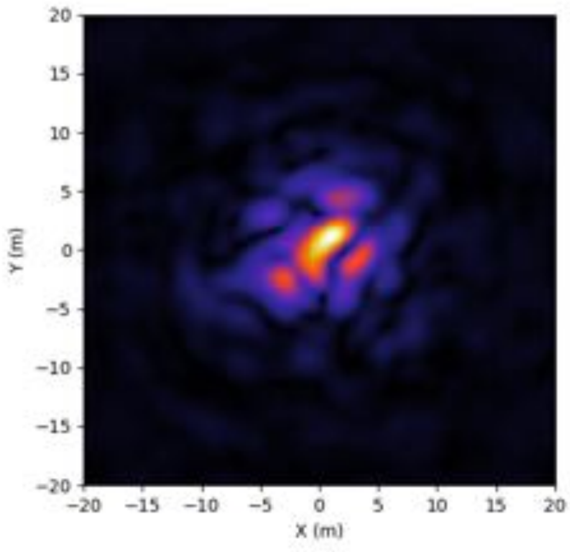
Modelling – Monte-Carlo simulation: Uplink - Uncorrected

Transmitter Diameter = 1 m

Ground to LEO (2000 km)

Elevation = 90 degrees

Wavelength = 1064×10^{-9} m



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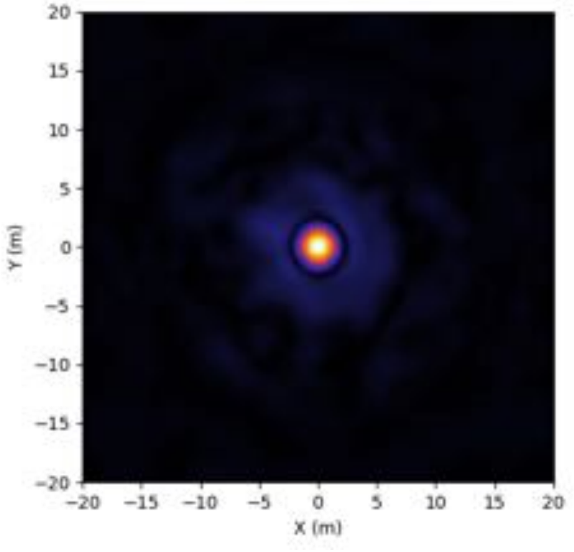
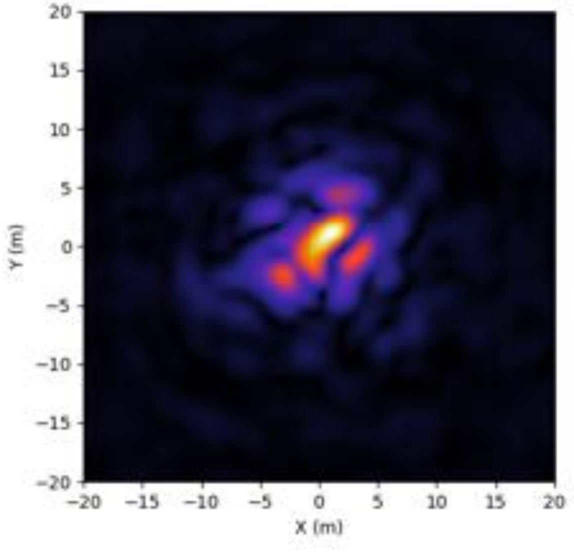
Modelling – Monte-Carlo simulation: Uplink - AO Corrected

AO corrected

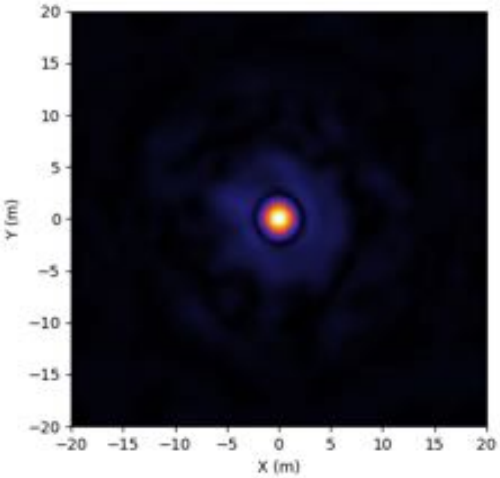


Uncorrected

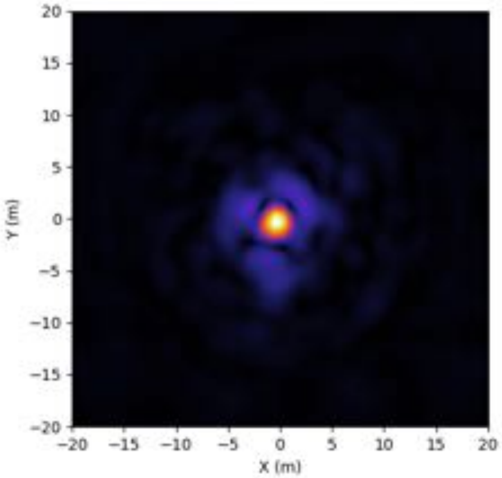


Modelling – Monte-Carlo simulation:
Uplink - AO Corrected: 10” point ahead angle

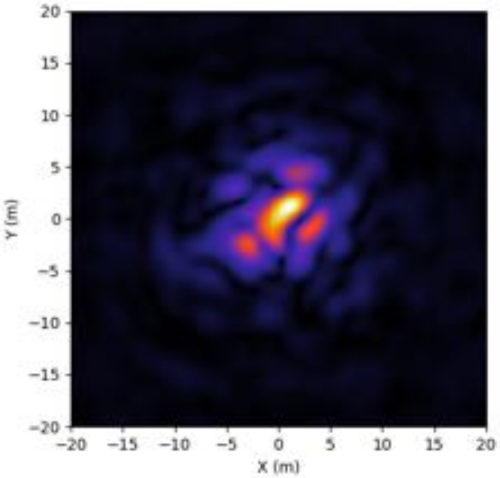
AO corrected



AO corrected
10” point-ahead

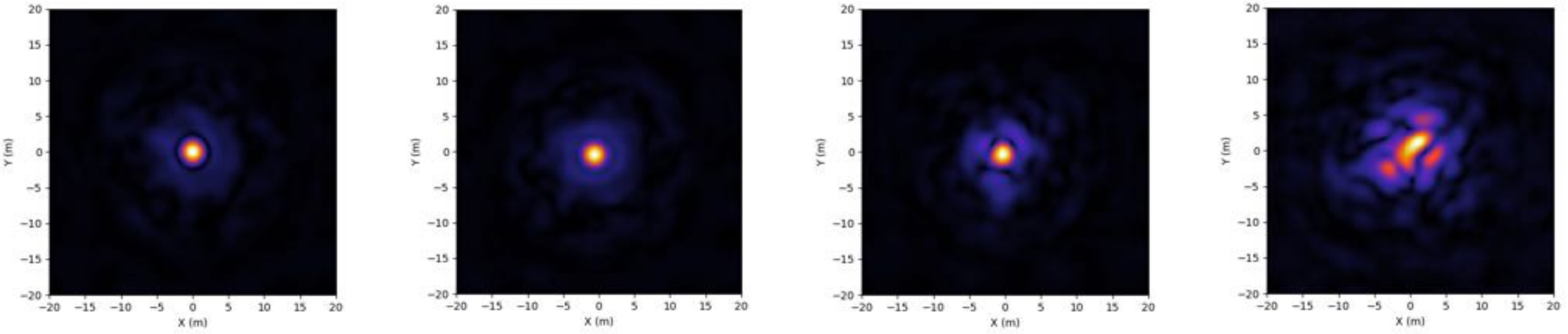


Uncorrected



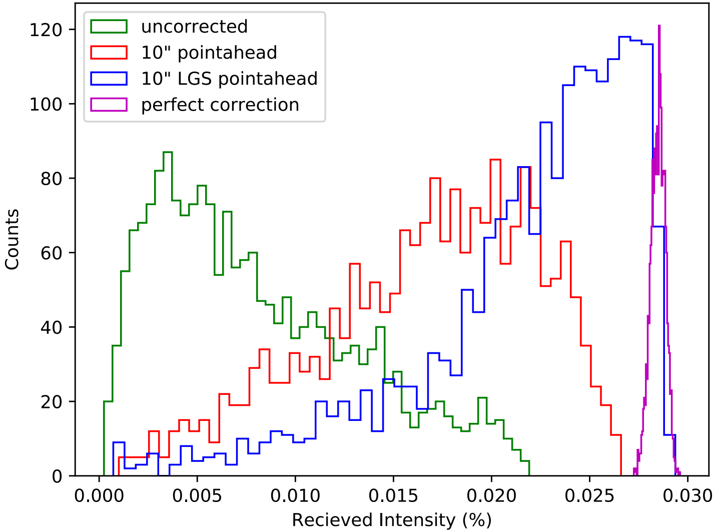
Modelling – Monte-Carlo simulation: Uplink – LGS corrected: 10” point ahead angle

AO corrected | LGS corrected uplink | AO corrected 10” point-ahead | Uncorrected

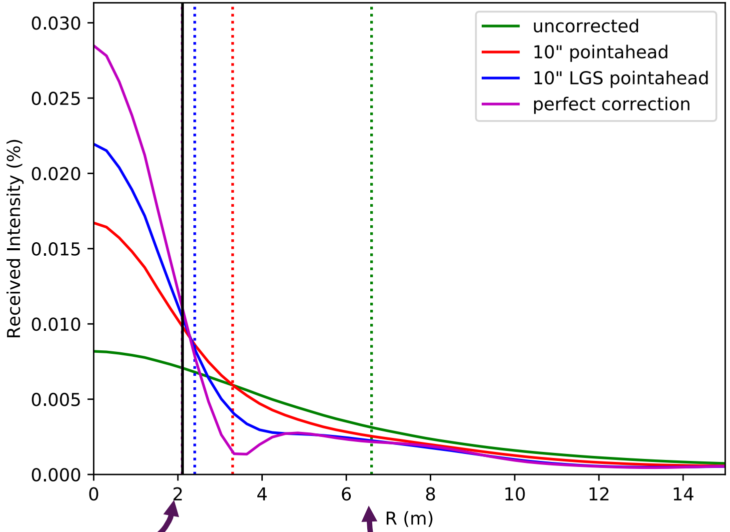


Modelling – Monte-Carlo simulation: Results

Received intensity distributions



Radial average long exposure PSF



Diffraction

Turbulence induced beam spread

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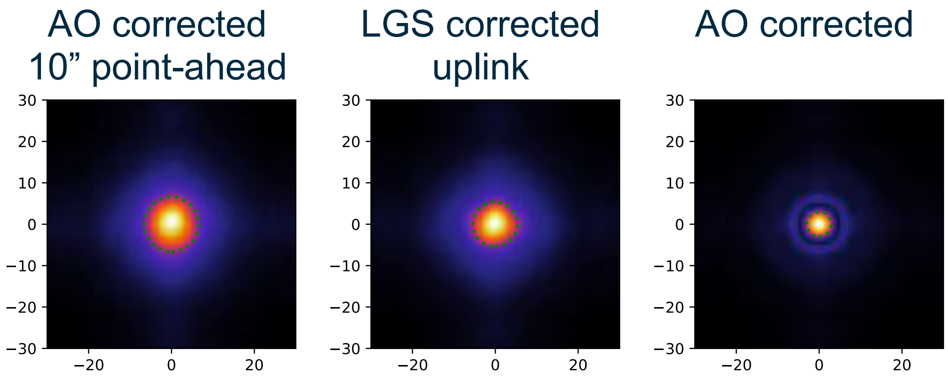
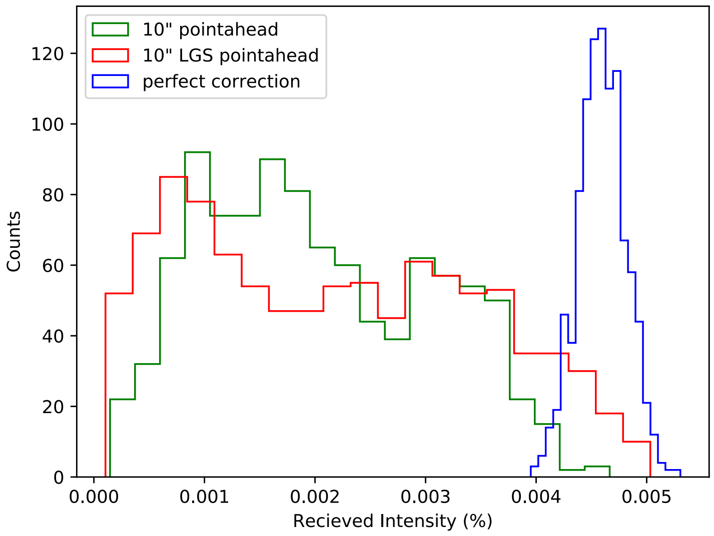
Monte-Carlo Simulation: Elevation angle

Elevation angle = 10 degrees





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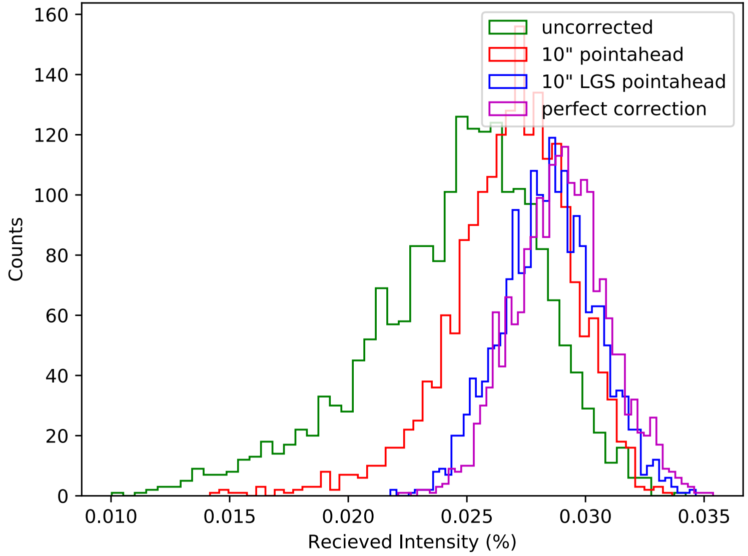
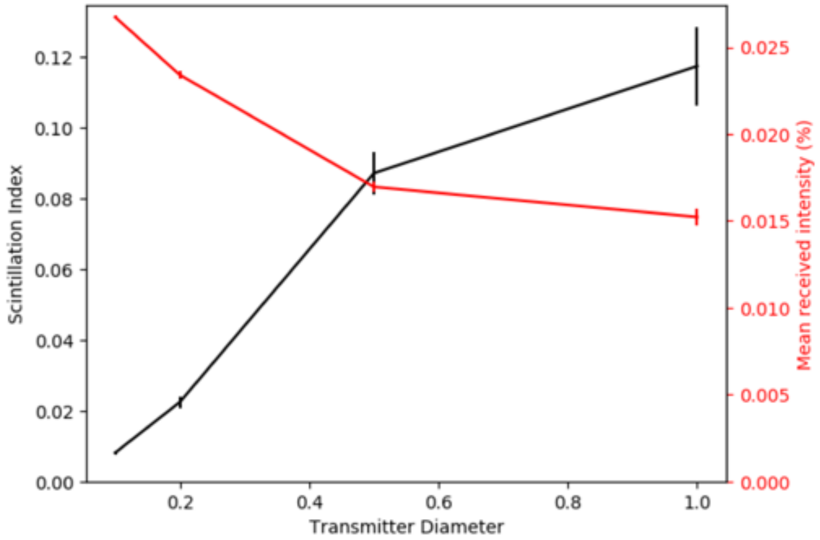
Monte-Carlo Simulation: Transmitter Diameter

Transmitter Diameter
= 0.2m





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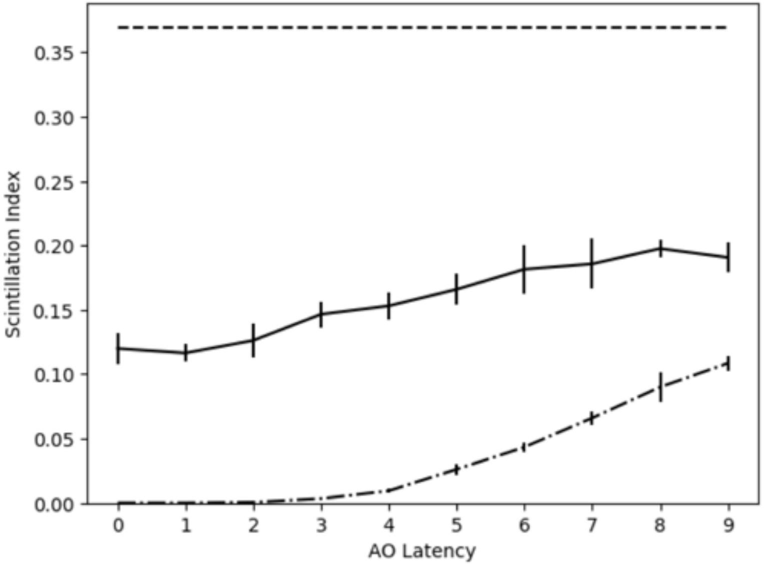
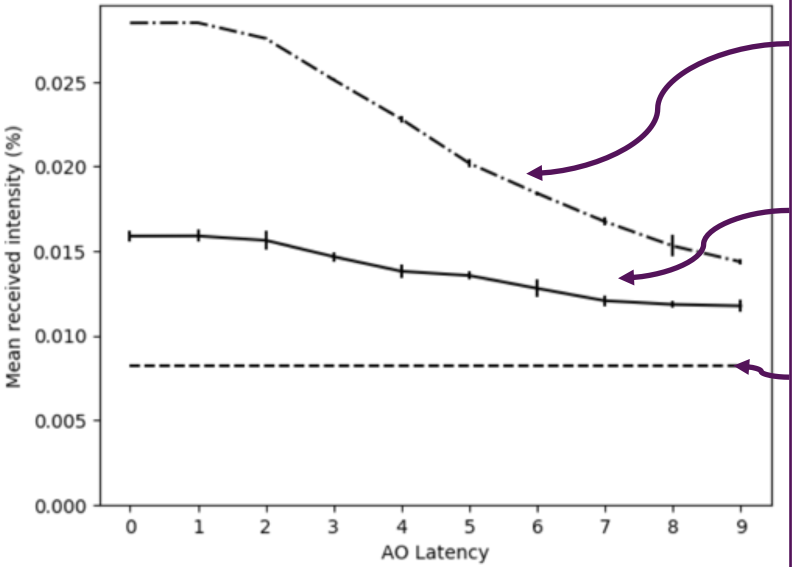
Monte-Carlo Simulation: AO latency

Scintillation Index



Received Intensity



Perfect AO

10” point-ahead

Uncorrected

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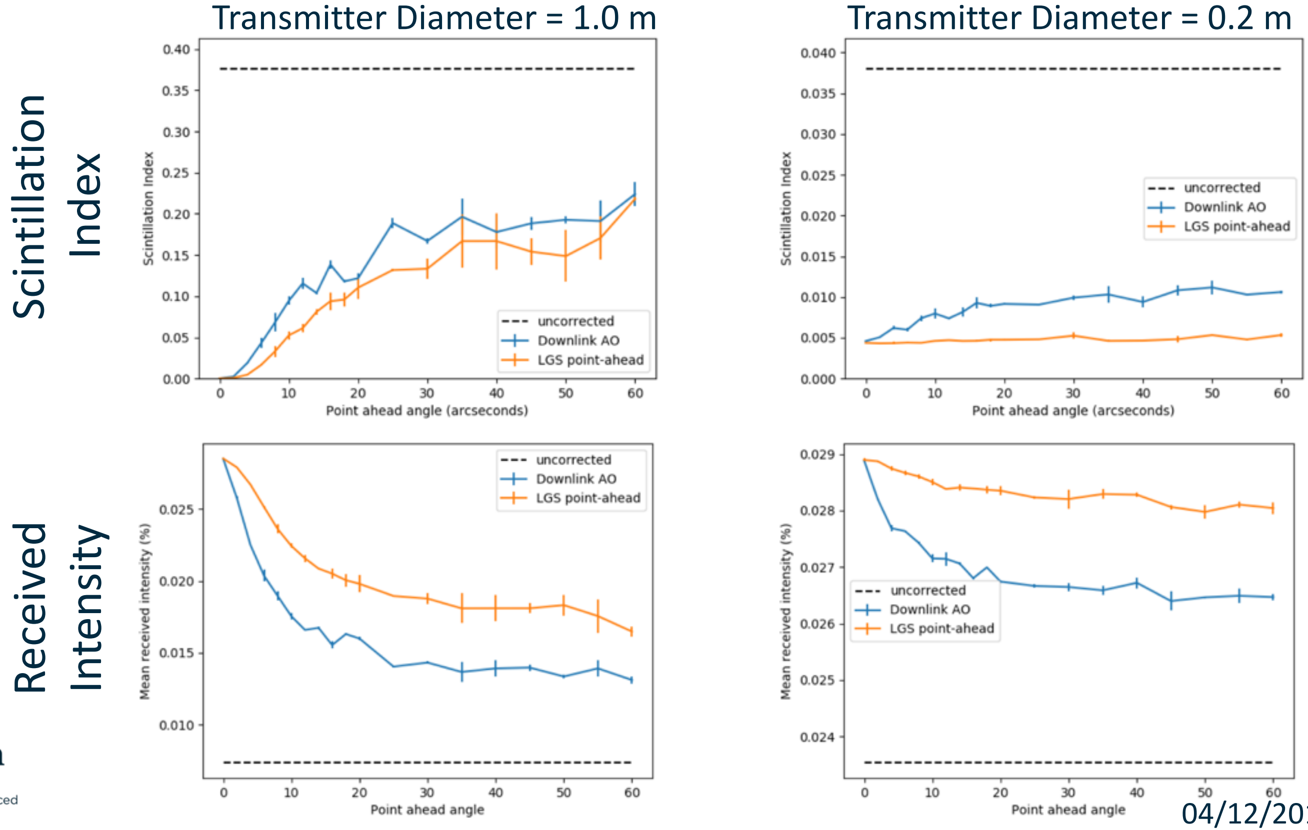
Monte-Carlo Simulation: Point-ahead angles



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Conclusions:

Ongoing activities

- Working with meteorologists to improve global forecasts
- Developing instrumentation for strong turbulence and strong scintillation conditions
- Implementing / Developing theoretical models for optical propagation
- Using Monte-Carlo simulations to probe effect of atmosphere on optical links
- Experimenting with novel mitigation technology, for example laser guide star tip/tilt correction (see Matt Townson) and photonics

Linked Presentations:

Matthew Townson et al.:

"Retrieving Tip/Tilt from Laser Guide Stars with the LATTE Experiment"

Sukanta Basu:

"Mesoscale Modelling of Optical Turbulence in the Atmosphere: Quantifying the Impact of Ultra-High Vertical Resolution"

Baptiste Sinquin et al.:

"Data-based modelling of low-order modes for AO control: what do on-sky experiments tell us?"

Advertisements: Opportunities

Assistant Professor in Advanced Instrumentation and Data Analysis:

(https://www.dur.ac.uk/jobs/recruitment/vacancies/phys20-4/)

Closing date 13th December 2019

Assistant Professor in Advanced Instrumentation (Fixed Term):

Closing date 20th January 2020

PhD Ground to space laser communications through atmospheric turbulence:

(https://www.findaphd.com/phds/project/ground-to-space-laser-communications-through-atmospheric-turbulence/?p116214)

Closing date 31st January 2020