Impact of Atmospheric Turbulence on SLR system

NESC Meeting

Julien Chabé

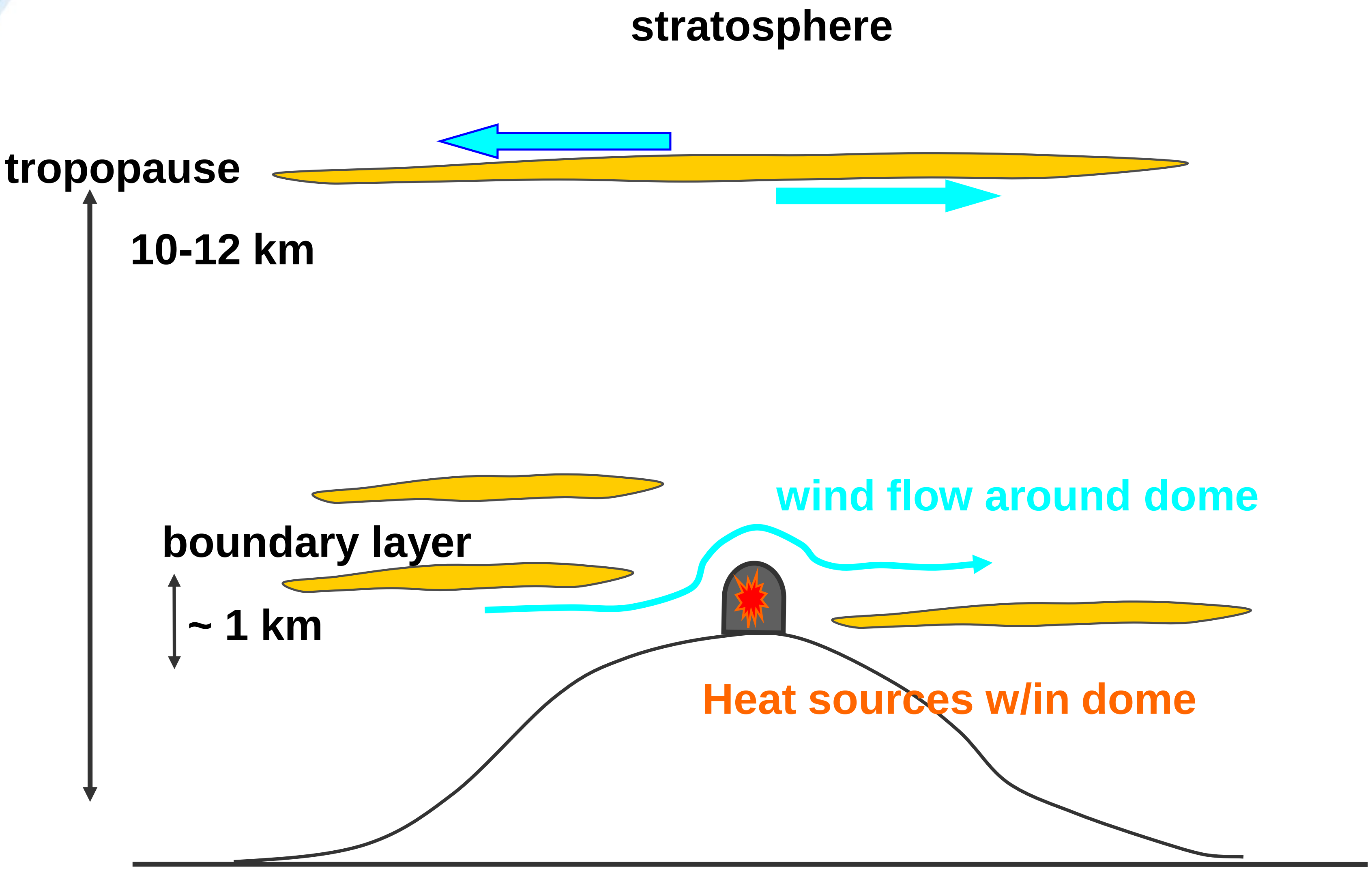
With contributions from my colleagues : Duy Hà Phung, Clément Courde, Aziz Ziad, Eric Aristidi.

Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, IRD, Géoazur, 2130 Route de l’Observatoire, 06460 Caussols, France;

What I will talk about

- What is atmospheric turbulence and how to measure it ?
- What is the effect for SLR systems ?
- Upcoming challenges regarding turbulence
- Conclusion

Turbulence everywhere



How to quantify turbulence ?

- Atmosphere is stratified in turbulent layers which are in constant evolution…
- A local parameter to quantify the <u>turbulence</u> « strength » : $\boldsymbol{C_n^2}$ in $m^{-2/3}$
- By computing the refractive index structure function:

Refraction index at 2 positions :

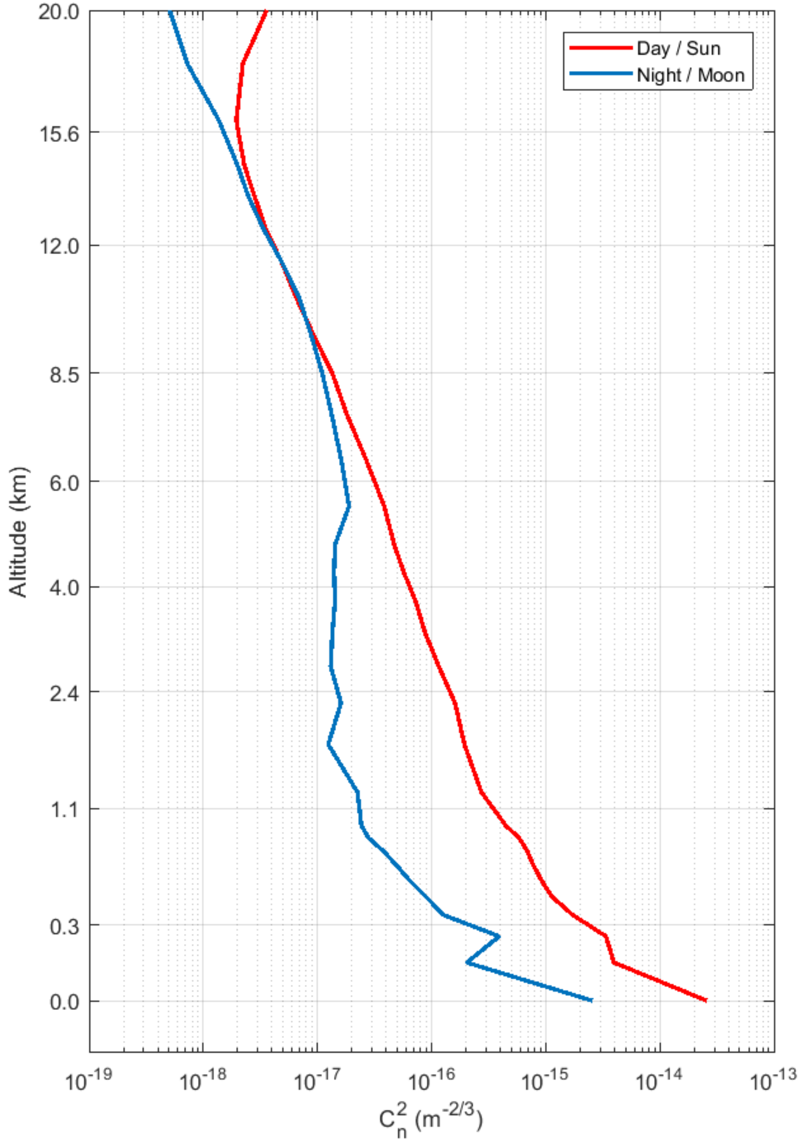
ρ

$n\,(r)$ $\quad\quad$ $n\,(r+\rho)$

- one can found:

$$D_n(\vec{\rho}) = \left\langle [\delta n(\vec{r}) - \delta n(\vec{r} + \vec{\rho})]^2 \right\rangle = C_n^2 \rho^{2/3}$$

- C_n^2 is the Refraction index structure constant (If no turbulence : δn(r)- δn(r+ρ) constant : $C_n^2=0$

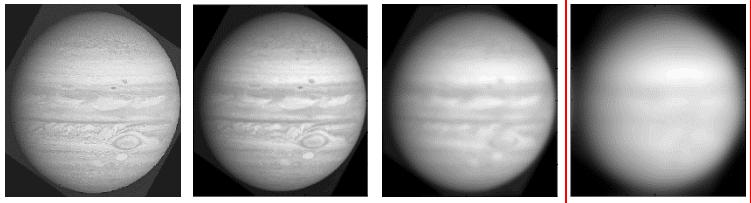


Grasse Observatory (Moon Limb profiler)

How to quantify turbulence ?

- And the Fried Parameter (r_0) and astronomical Seeing (ε)

$$r_0 = \left[0.42k^2 \int_0^L C_n^2(z)\,dz\right]^{-3/5}$$



$$\epsilon = 0.98\frac{\lambda}{r_0}$$

- The isoplanetic angle θ_0 is the angular coherence of the turbulence:

$$\theta_0 = \left[2.91k^2 \int_0^L C_n^2(z) z^{5/3}\,dz\right]^{-3/5}$$

  – Typical values for θ_0 at wavelength λ=500nm are roughly **7–10 µrad** for a near vertical path

- The coherence time related to wind speed (V) :

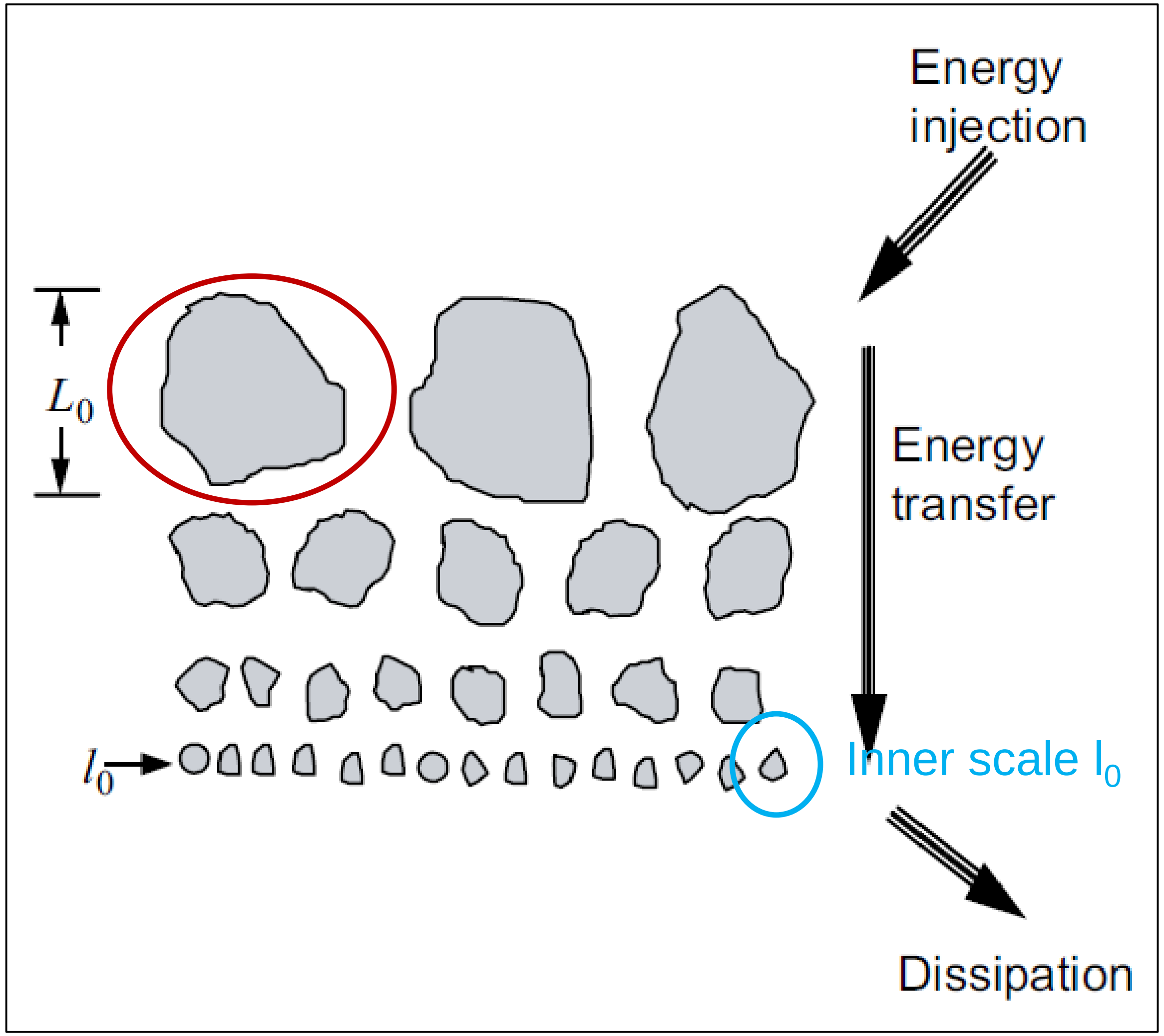
$$\tau_0 = \left[2.91k^2 \int_0^L C_n^2(z) V^{5/3}(z)\,dz\right]^{-3/5}$$

$$\tau_0 = \frac{0.32 r_0}{V_\perp}.$$

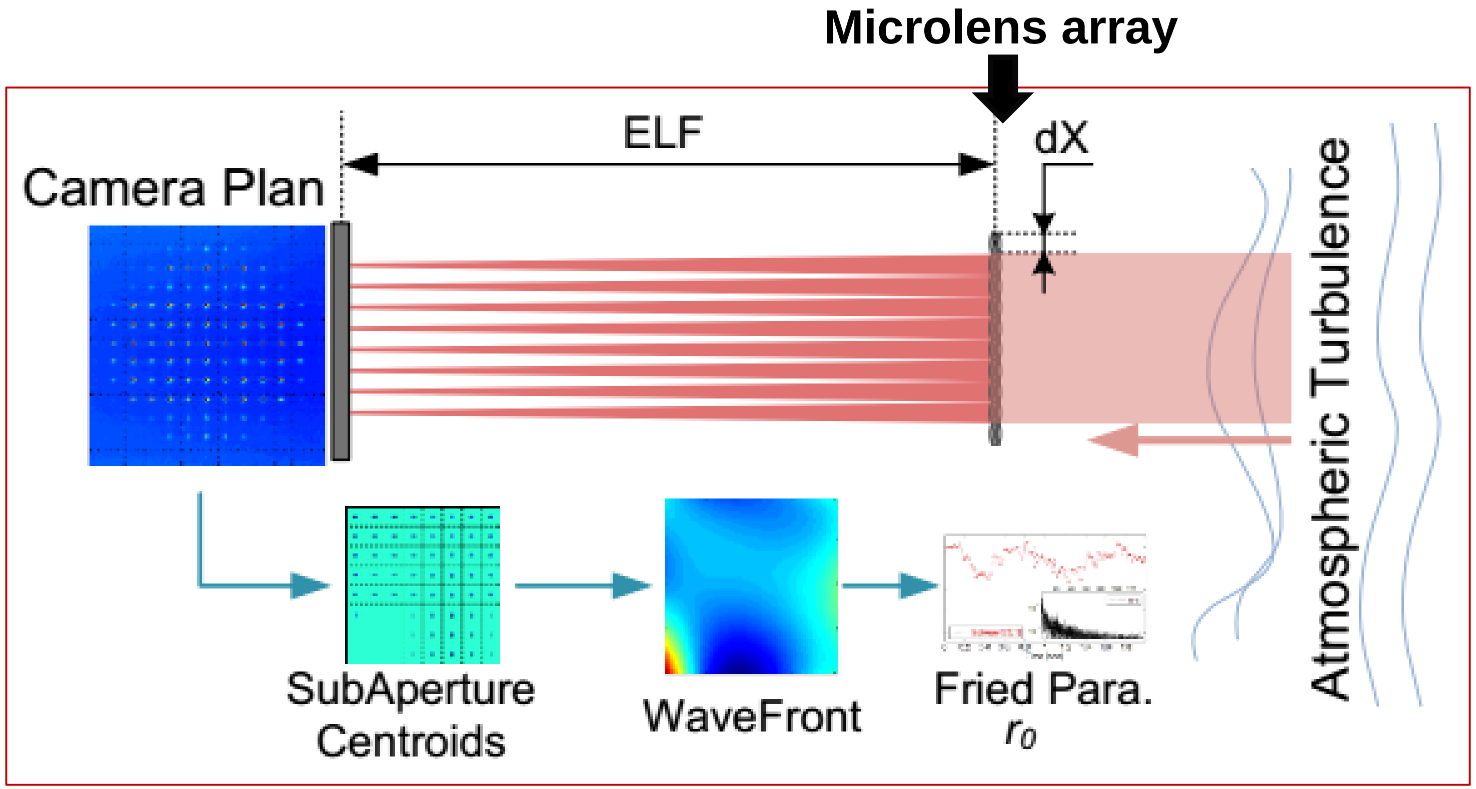
How to quantify turbulence ?

- In Kolmogorov theory of turbulence : injection of energy occurs at a large scale : the outer scale L_0
- The **outer scale** L_0 is not easy to evaluate but it is important parameter often neglected…
- **The outer scale** L_0 it is reponsible for tip/tilt effect -> 80% of the turbulence

Kolmogorov theory

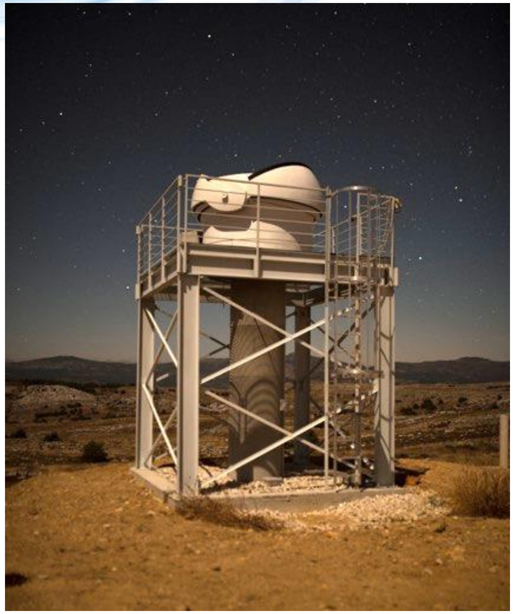


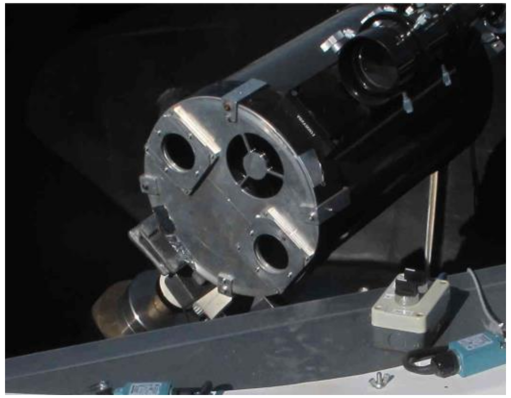
Shack-Hartmann analysis



- Downlink laser beam wavefront distortion analysis: The Shack-Hartmann Wave Front Sensor measures the local slope of incoming wavefront
- Fried parameter r_0 determination (radius of coherence of the wavefront)

Generalized Differential Image Monitor





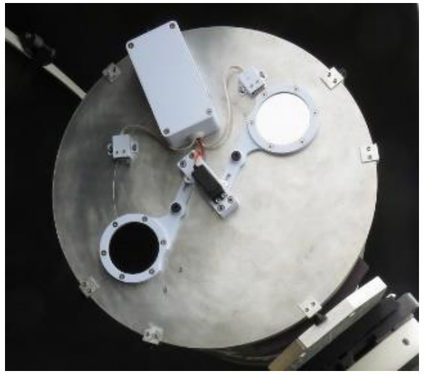
Differential image motion of stars

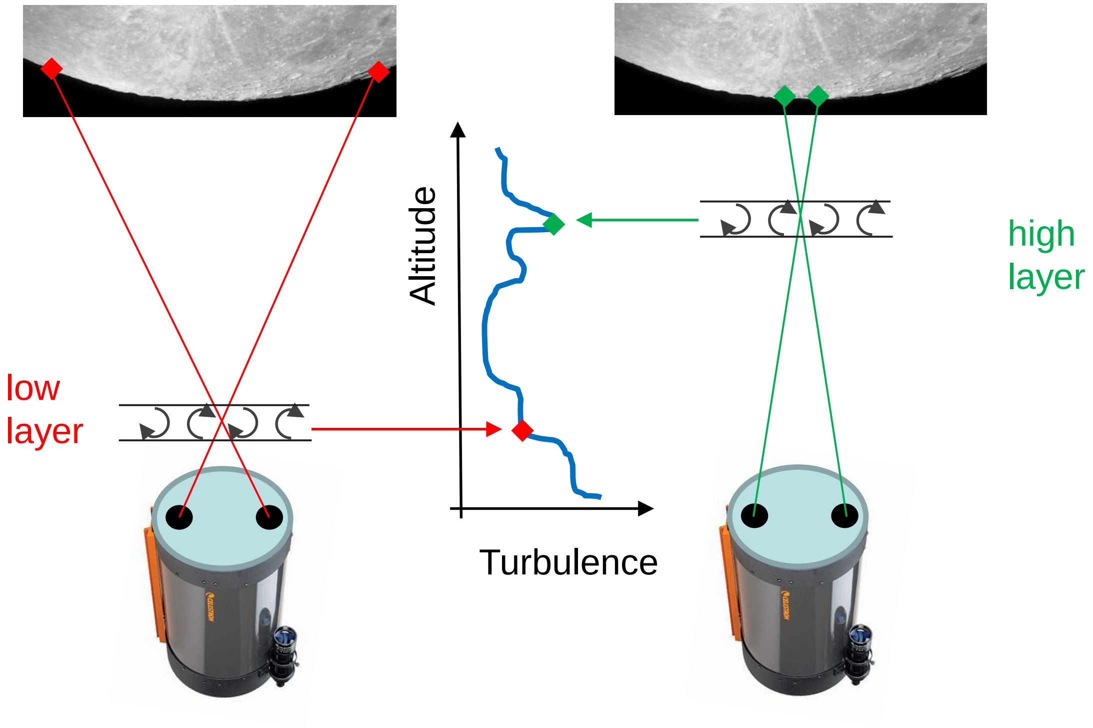
- Independant atmospheric turbulence analysis:
  - Fried parameter r_0
  - Scintillation index
  - Isoplanatic angle
  - Outer scale of turbulence: L_0

[Aristidi 2019] E Aristidi, A Ziad, J Chabé, Y Fantéi-Caujolle, C Renaud, C Giordano, A generalized differential image motion monitor, Monthly Notices of the Royal Astronomical Society, Volume 486, Issue 1, June 2019, Pages 915–925, https://doi.org/10.1093/mnras/stz854

[Ziad 2016] Aziz Ziad. Review of the outer scale of the atmospheric turbulence. Adaptive Optics Systems V. SPIE, July 2016

C_n^2 (h) Profiler (Moon/Sun)

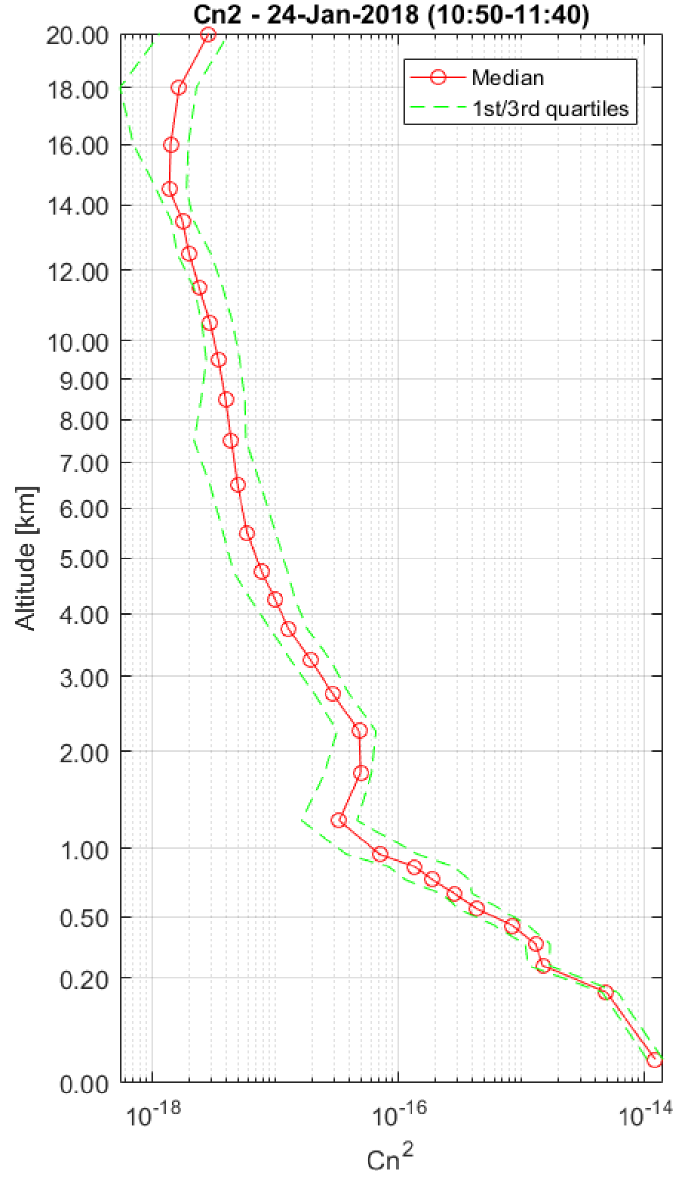




Principle : mesure the agitation at 2 points of the limb

→ 2 points far away : access to low altitude turbulent layers

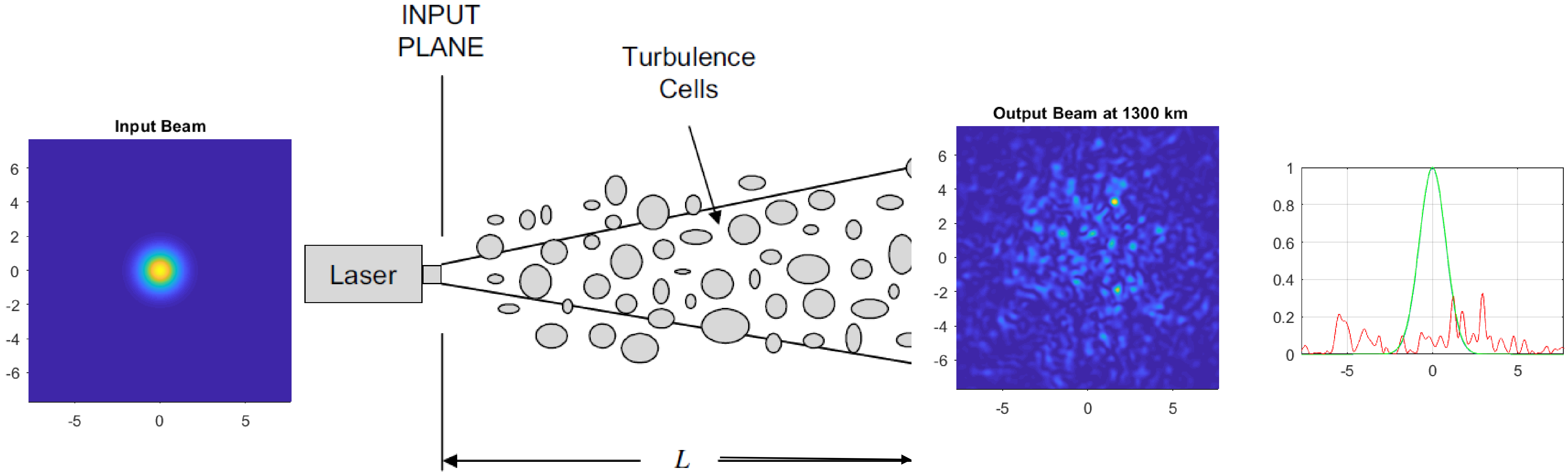
→ 2 close points : high altitude layers



- Estimation of the turbulence profile C_n^2 (h) up to h=24km : 33 layers
- 1 profile every minute
- Resolution: 100m (low altitude) to 2km (high altitude)

Laser + atmosphere

- The coherence of the laser beam wavefront is destroyed by the turbulent atmosphere:



Laser + atmosphere

- The speckle pattern has coherence time of ~ms
- The instantenous center of the beam (hot spot) where the intensity is the strongest is moving randomly around the average central position
- When we average on a long time, the beam looks gaussian but is larger than the original one
- Scintillation of the light in the detector plane

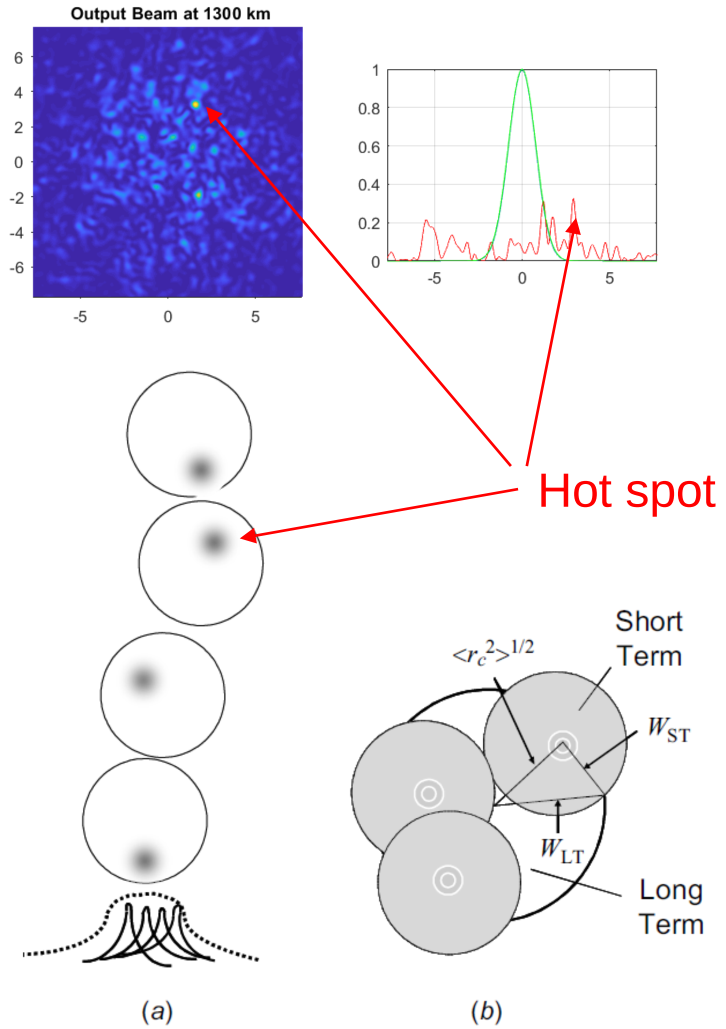
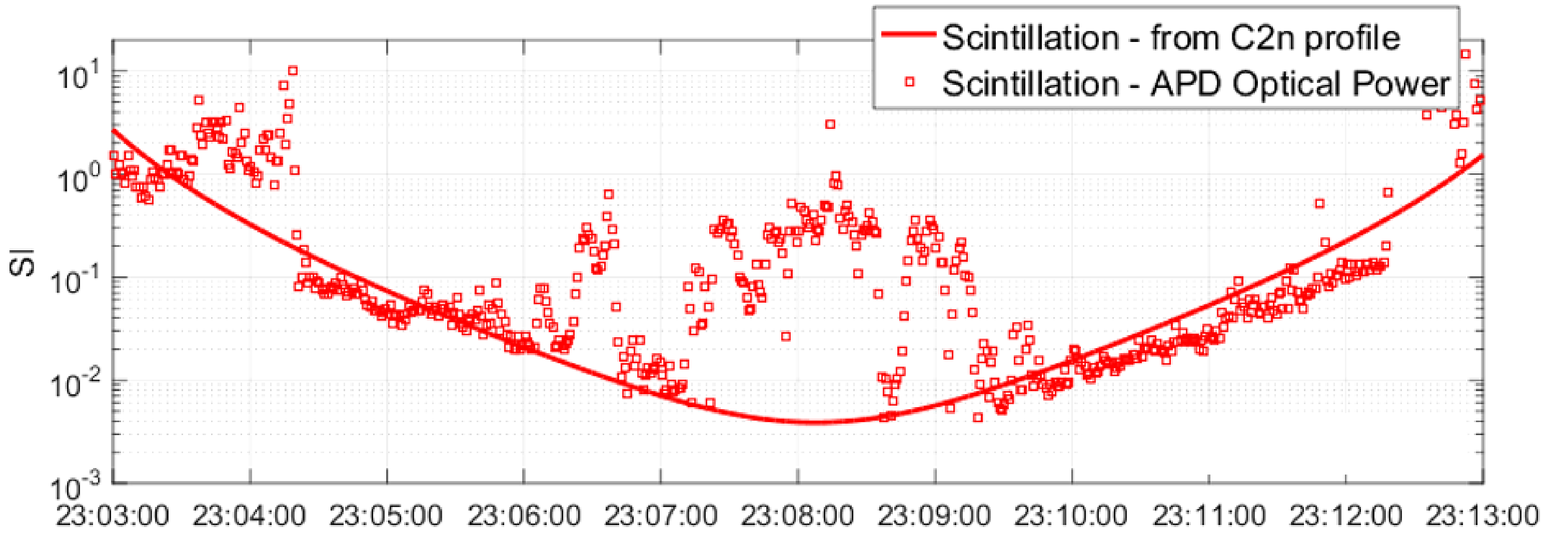


Figure 6.7 (*a*) Beam wander as described by movement of the "hot spot" (instantaneous center) within the beam. (*b*) The long-term spot size is the result of beam wander, beam breathing, and diffraction. The shaded circles depict random motion of the short-term beam in the receiver plane.

Scintillation of the laser beam

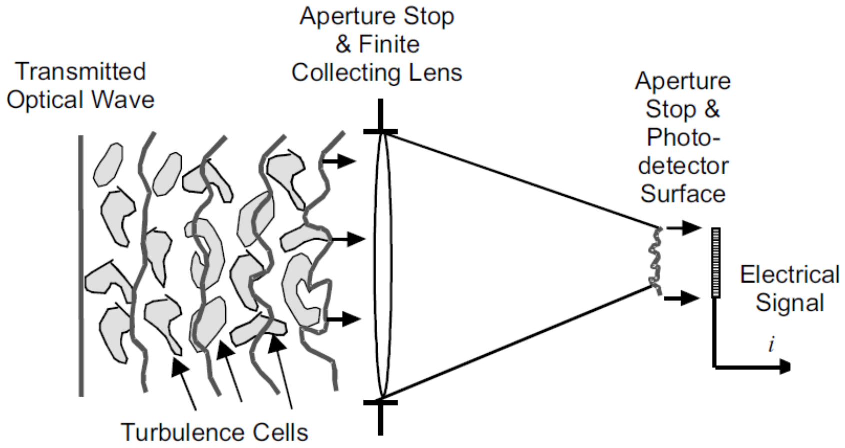
- Example of the scintillation of a telecom downlink laser beam

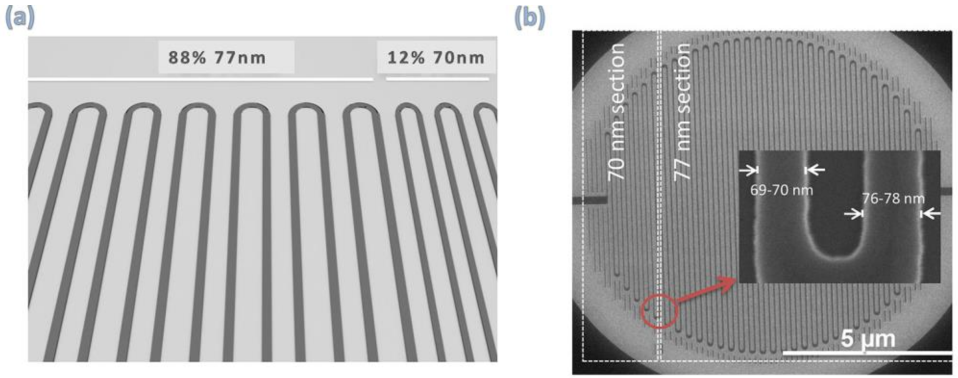
$$\sigma_I^2 = \frac{\sigma^2}{I^2} \qquad \sigma_I^2 = 17 D^{-7/3} \cos(\theta_{zen})^{-3} \int_0^L h^2 C_n^2(h) dh$$

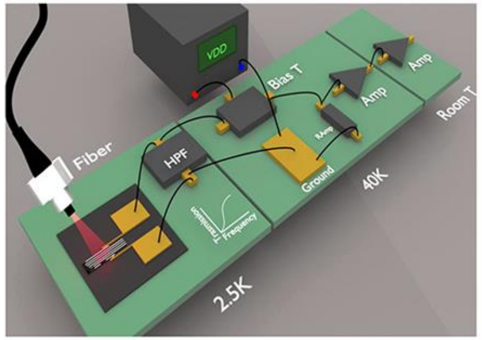


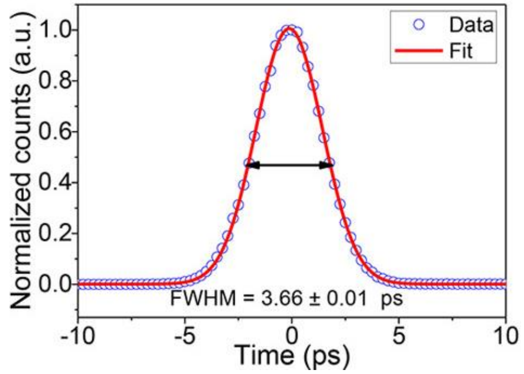
Fading

- The turbulence effects (scintillation, wavefront distortion) induce fades in the detection.
- These fades can occur 10s to 100s of times per second for vertical links between the ground and space
- This problem increases with small size detectors
- Good detectors with low timing jitter:
  - Small active area : tens of µm
  - Single mode fiber coupling (SMF 28 -> 10µm core diameter) for **superconducting nanowire single-photon detector :** D~10 µm at Delft university





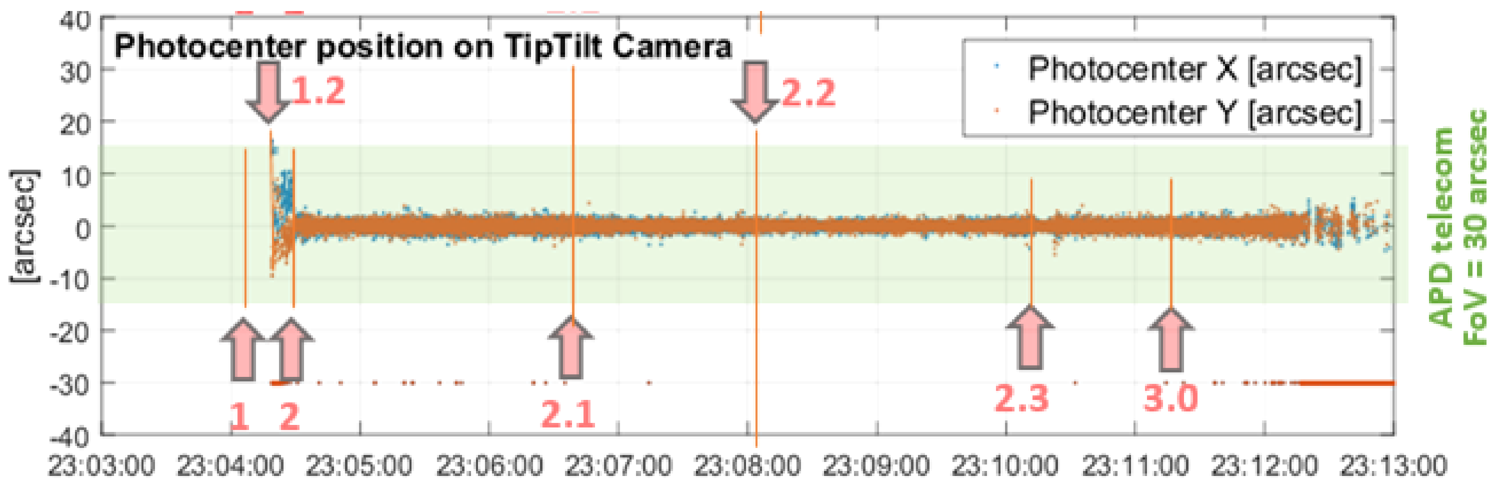


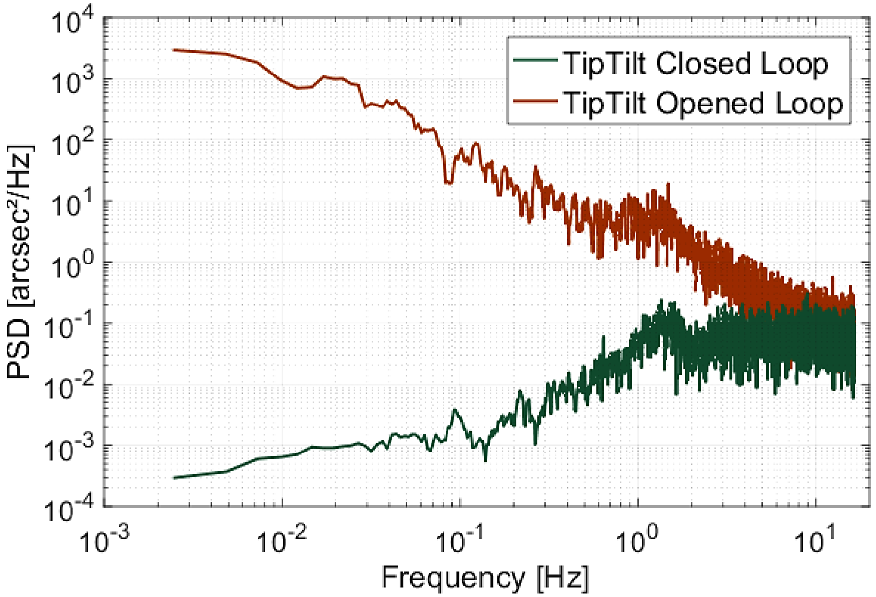


ACS Photonics 2020, 7, 7, 1780–1787
https://doi.org/10.1021/acsphotonics.0c00433

Example for telecom downlink laser at Grasse

- Received Laser is splitted into:
  - 90% Laser com analysis:
    - APD telecom : 80µm diameter (30 arcsec FOV)
  - 10% for Fine tracking by TipTilt mirror
    - Spot laser position on TipTilt camera
      was stabilized with RMS < 1.1 arcsec
      during satellite pass, at 50 Hz from low (10 deg) to high (48 deg) elevation

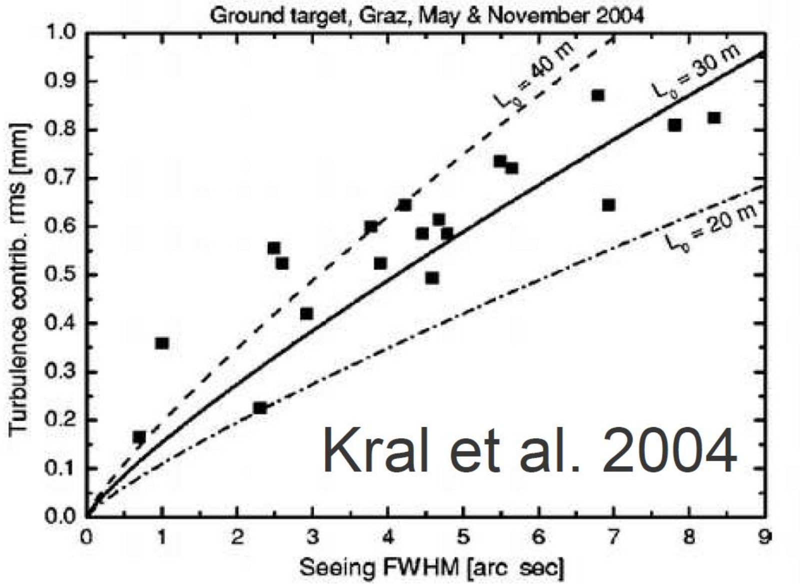




Turbulence induced Ranging jitter for SLR

$$\langle \Delta L^2 \rangle = 3.127\, L_0^{(5/3)} \int C_n^2(h)dh$$

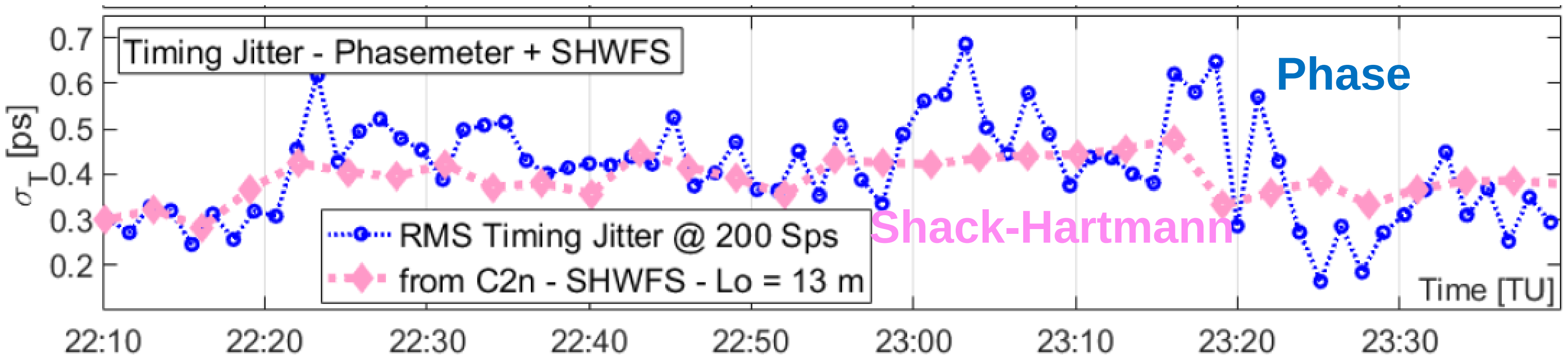
- Turbulence gives a piston like effect -> Timing jitter
- This effect is dependent on L_0 the outer scale of the turbulence (~10 to 100m)
- Few µm to mm (strong turbulence like horizontal path over several kms)

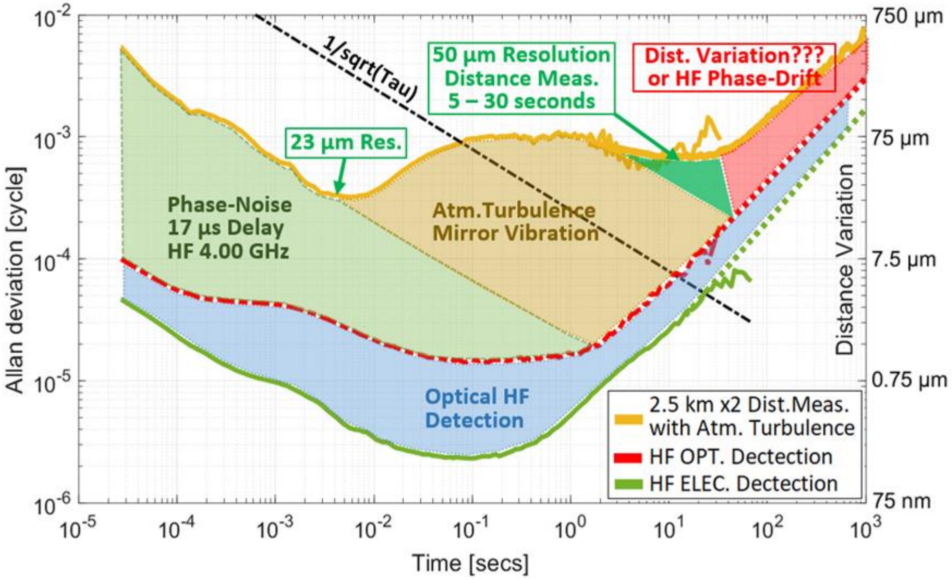


[Gardner 1976] C. S. Gardner. Effects of random path fluctuations on the accuracy of laser ranging systems. Appl. Opt., 15(10):2539–2545, Oct 1976
[Kral 2005] Lukas Kral, Ivan Prochazka, and Karel Hamal. Optical signal path delay fluctuations caused by atmospheric turbulence. Opt. Lett., 30(14):1767–1769, Jul 2005.

Turbulence induced Ranging jitter for SLR

- Continuous telecom laser (10Gbits) **phase measurement** at Grasse (ground target):





Coherent optical Doppler Orbitography & frequency transfer

- Nice demonstrations on **ground target** of phase measurement with active phase noise compensation + tip tilt mirror
  - Dix-Matthews, B.P., Schediwy, S.W., Gozzard, D.R. et al. Point-to-point stabilized optical frequency transfer with active optics. Nat Commun 12, 515 (2021). https://doi.org/10.1038/s41467-020-20591-5
  - Dix-Matthews, B.P., Schediwy, S.W., Gozzard, D.R. et al. Methods for coherent optical Doppler orbitography. J Geod 94, 55 (2020). https://doi.org/10.1007

- Ground to space experiment still to be demonstrated
  - Point ahead angle vs isoplanatic angle ?
  - Fades ?

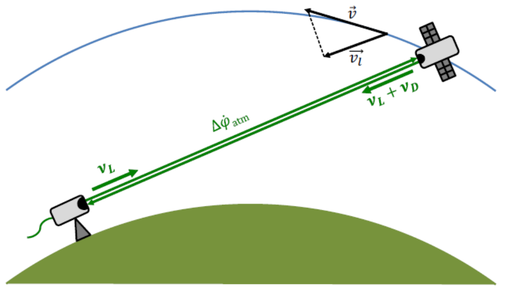


Fig. 1 An overview of the technique that is being considered. An optical frequency (ν_L) is reflected off a retro-reflector located on the satellite, where it undergoes a Doppler shift (ν_D) dependent on the satellite's radial velocity ($\vec{v_l}$). The satellite's radial velocity is then determined using the Doppler shifted return frequency. The transmitted and reflected signals also experience frequency perturbations caused by the atmospheric phase noise ($\Delta\dot{\varphi}_{atm}$).

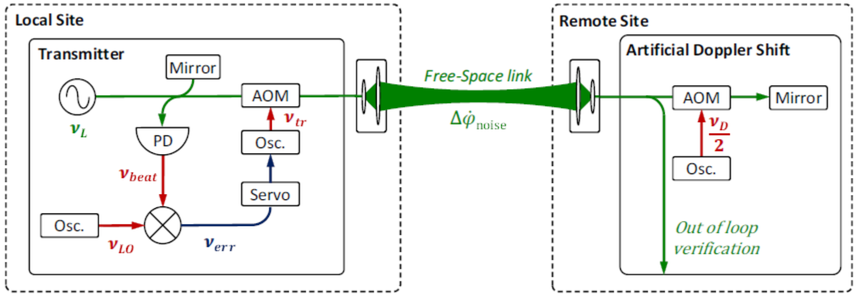
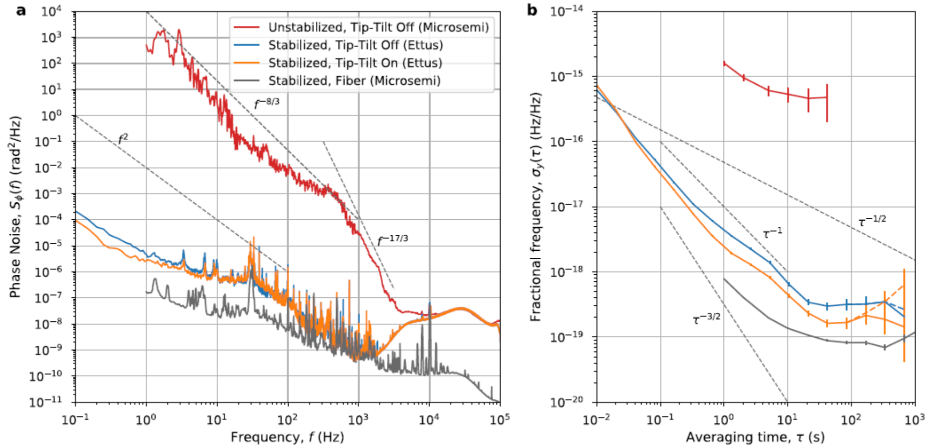


Fig. 2 Block diagram of the system used. Green represents optical signals, red represents radio frequency electrical signals, and blue represents the DC electrical control signals.



Conclusion

- Atmospheric turbulence induces : Beam wandering, Beam spreading, Scintillation, fading, phase noise
- Instrumentation to measure turbulence exist:
  - Shack-Hartmann analyser: In situ measurement, easy to built/analyse, gives r_0
  - Differential Image Monitor: independant instrument (stars), easy to built/analyse, cheap, gives r_0, L_0, θ_0
  - C_n^2 (h) Profiler : Very High resolution of all the params.
- For advanced SLR (100kHz - MHz, SNSPD):
  - Problematic with high performances (small) detectors and single mode fibers
  - A tip-tilt correction is a first step to mitigate this (~80% of the turbulence) and probably good enough for most « upgraded SLR system »
- Using the coherence properties of a laser beam: difficult but a lot of progress has been done
  - Some adaptive optics has be used to corrected wavefront degradation for single mode fiber injection
  - Active phase correction for coherent optical Doppler Orbitography & frequency transfer

GDIMM for ~5k€