Propagation channel characterization
Impact on optical systems performance

SET – 241 – 9th Military Sensing Symposium (Quebec City)

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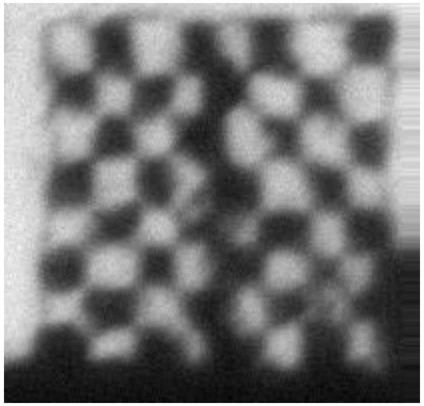
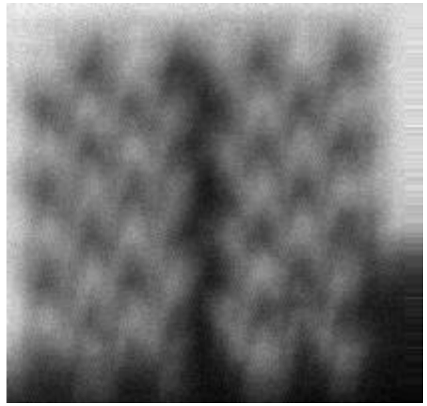
return on innovation

Turbulence and imaging and laser systems

$C_n^2 = 10^{-16}\ m^{-2/3}$

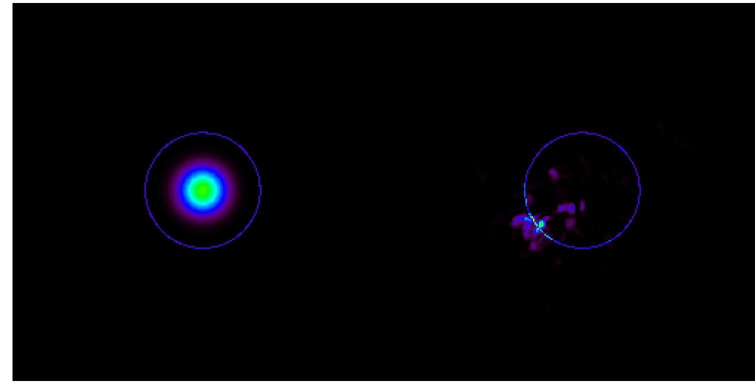


$C_n^2 = 10^{-15}\ m^{-2/3}$



Passive images in visible – Range 7 km
Recorded during trial in Dayton OH – 2011 (SET 165)

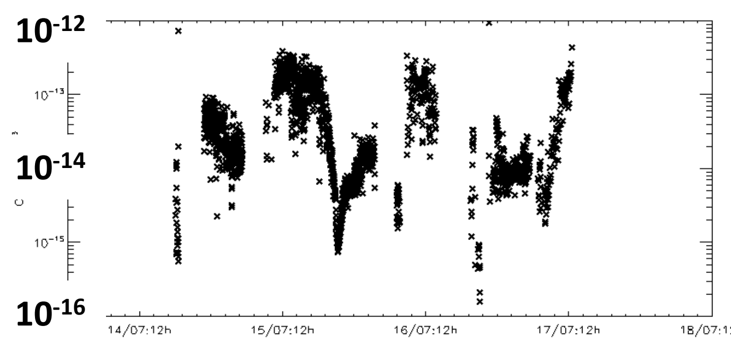
$C_n^2 \sim 0\ m^{-2/3}$ $C_n^2 = 10^{-14}\ m^{-2/3}$



Laser beam intensity
10 km, λ = 1.55 µm (simulation)

- Atmospheric turbulence degrades EO system performance in terms of resolution / range
- Atmospheric turbulence varies in a « huge » range
  - Day/night; saison, location
  - C_n^2 : 10^{-17} up to $10^{-12}\ m^{-2/3}$

OCA 14-17 July 2013



Evaluation of turbulence impact

Turbulence characterization

Compensation ?

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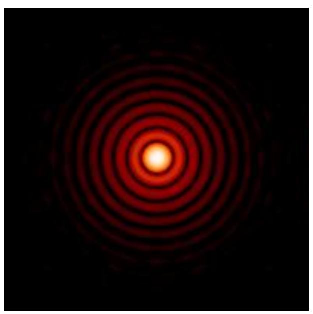
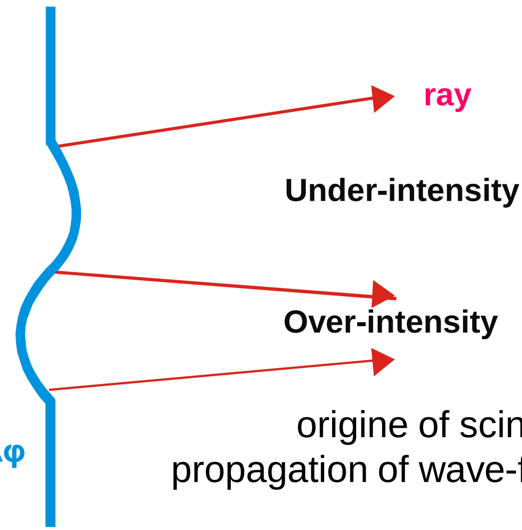
Atmospheric turbulence and propagation effects

Starry sky, Van Gogh, 1889

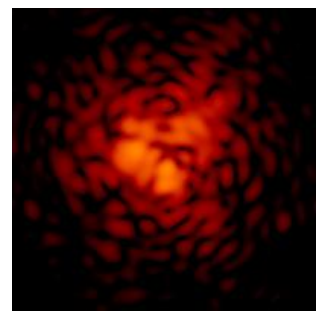
- Local variations of air temperature ⇨ local variations of refractive index (Δn) ($\Delta\phi \propto \Delta n/\lambda$)
- C_n^2 quantifies turbulence strength : $Cov(\Delta n) = C_n^2\, \rho^{2/3}$

Output beam gaussian





Far field



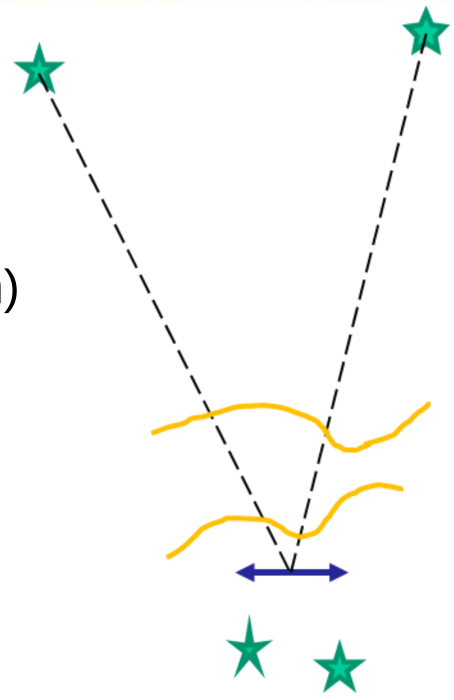
origine of scintillations
propagation of wave-front curvatures

+ time evolution

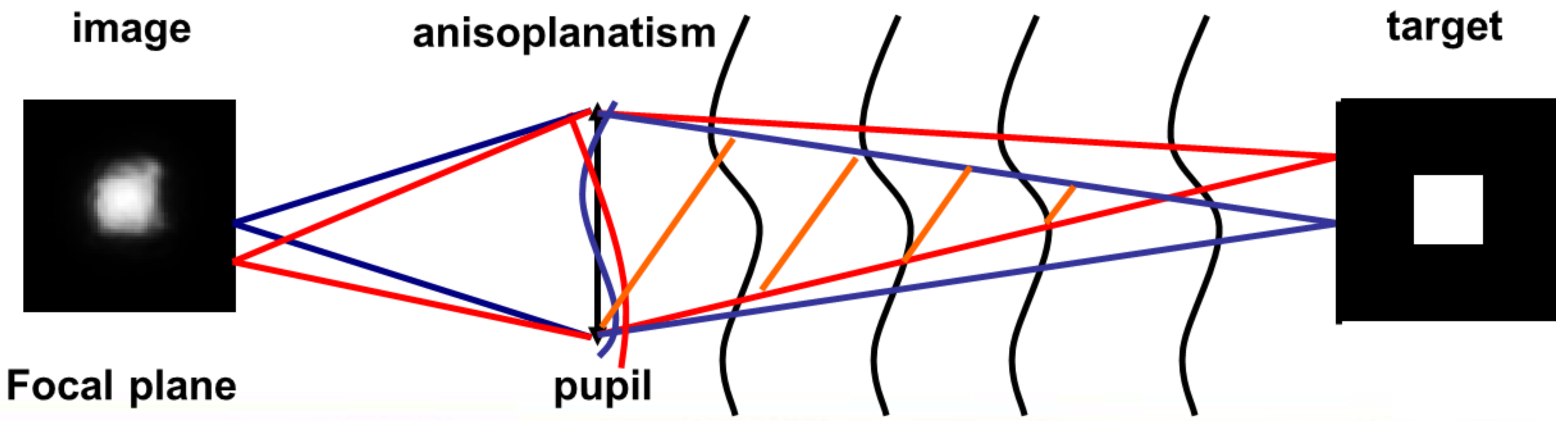
⇨ **Effect on system performance ?**

System performance : main parameters and modelling

- **Parameters of interest of EO and laser systems**
  - Resolution ($\mathcal{R}$)
  - Isoplanatism domain (θ_0)
  - Axis movement or angle of arrival (AoA) (tracking system)
  - Power in the bucket (PIB) (scintillation)

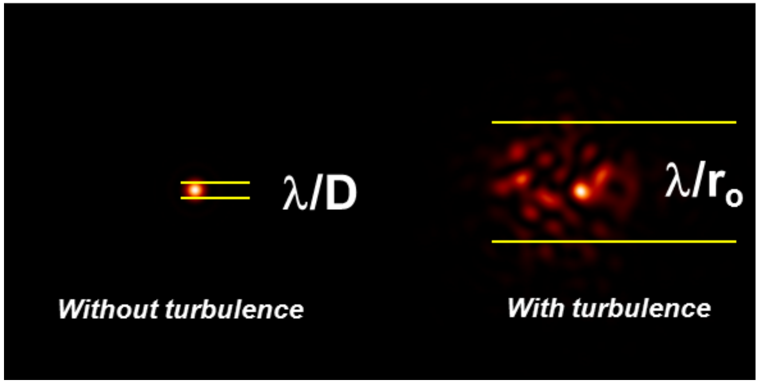


- **Tools**
  - Analytical models – domain of validity limited
  - Wave optics propagation - computional cost
  - Dedicated simplified models based on analytical ones

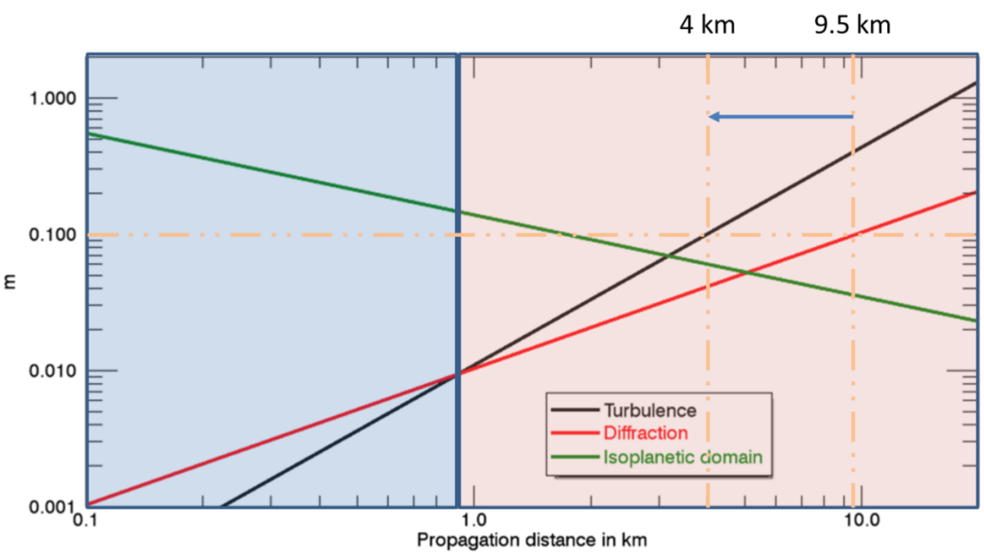


Resolution – anisoplanatism

r_0 : coherence length



- *Vertical propagation* λ = 0.6 µm, **r_0 = 10 cm**
- *Horizontal propagation @ 3 km high*,
  λ = 0.6 µm, L = 20 km, **r_0 = 10 cm**
- *Horizontal propagation @ ground level*
  λ = 1.55 µm, L = 1 km, **r_0 = 2 cm**



D = 0.15 m
$C_n^2 = 5.10^{-15}\ m^{-2/3}$; horizontal path
λ = 1.55 µm
Required resolution = 0.1 m

Range is reduced 9.5 km → 4 km.
Turbulence effect at 0.9 km
$\Theta_0 * L < \mathcal{R}$ after 2 km.

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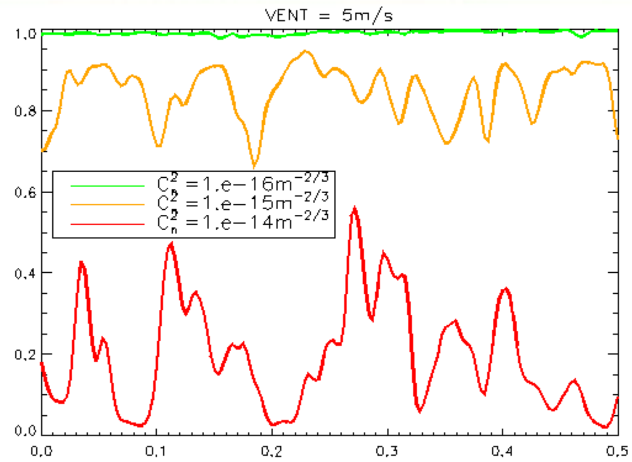
Power in the Bucket

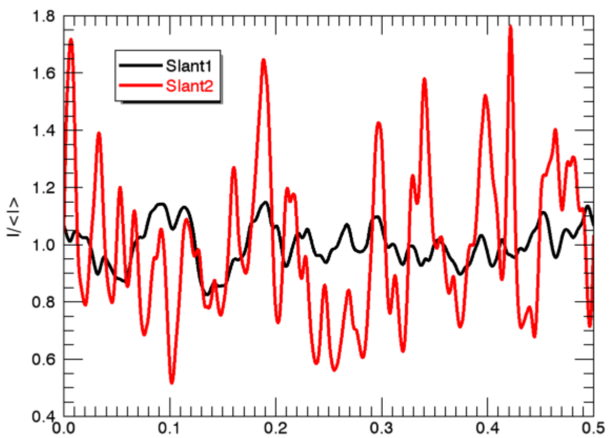


Time in s

Wave optics modelling

- D = 30 cm , λ = 1.55 µm
- horizontal propagation, range 10km,
- transverse wind speed constant and equal to 5 m/s

C_n^2 ⬀ ⇨<I> ⬂ and Intensity fluctuations ⬀



black air ⇨ground,
red ground ⇨ air,

Simplified model

- D = 30 cm , λ = 1.55 µm
- different slant paths geometries (elevation 0.5°), range 10km, C_n^2 @ ground = 10^{-14} $m^{-2/3}$
- transverse wind speed constant = 5 m/s,

Intensity fluctuations depends on C_n^2 profile

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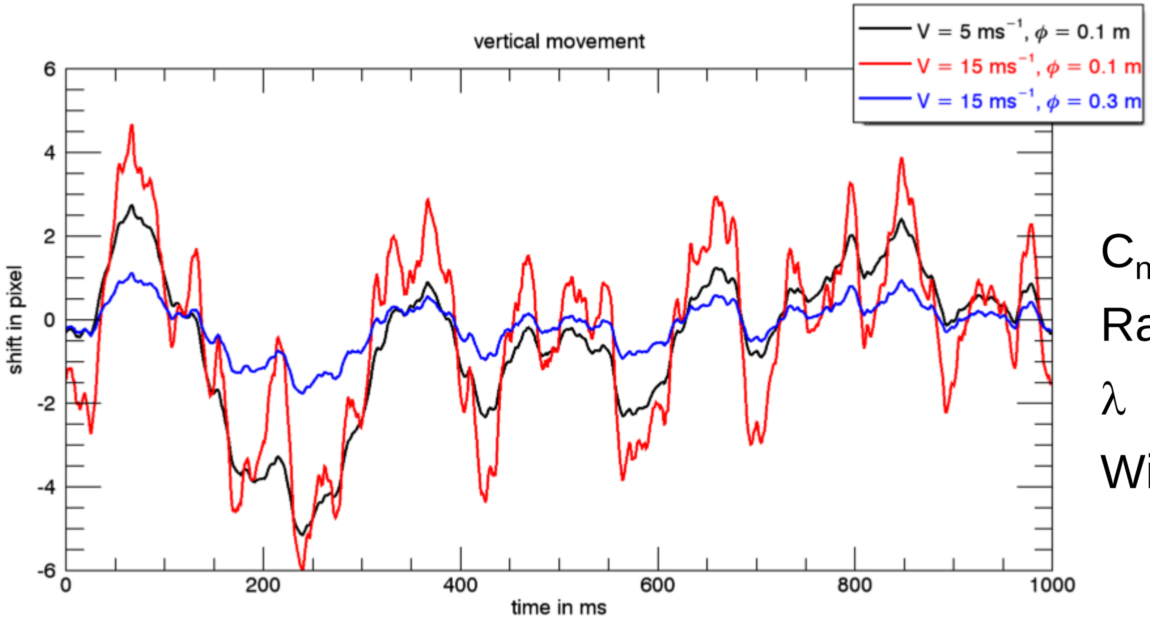
Angle of arrival



Simplified model

$C_n^2 = 10^{-14}$ $m^{-2/3}$; horizontal path

Range : 5 km

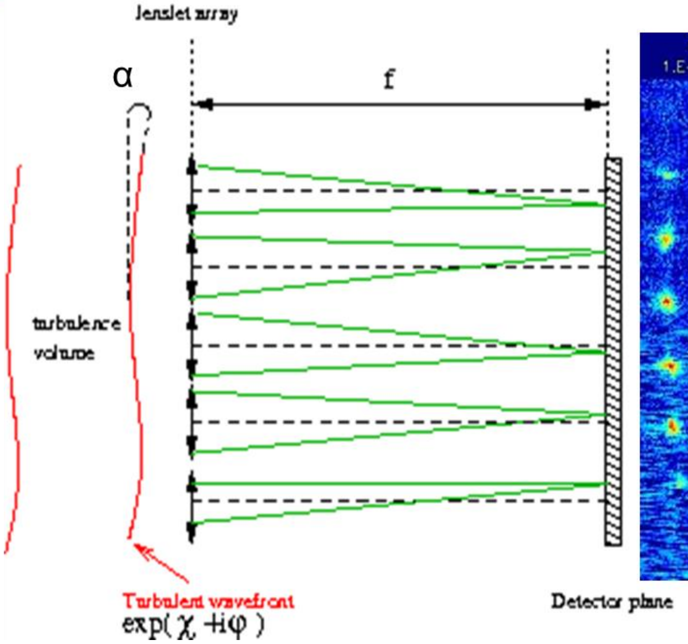
λ = 1.55 µm

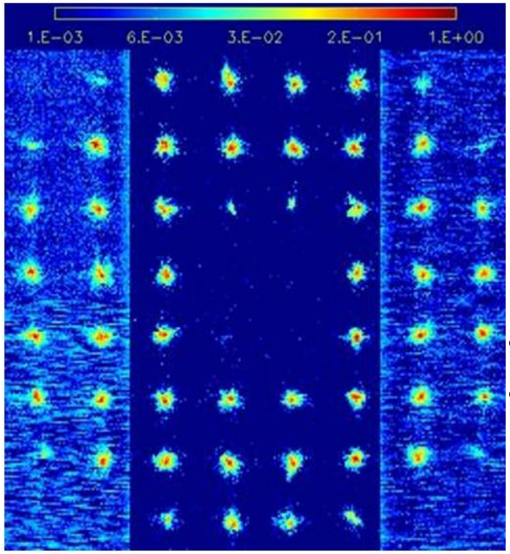
Wind speed constant and horizontal

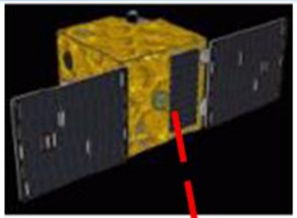
Modulation depends on the wind speed (red/ black

Fluctuations depends on the system diameter (blue/red)

Vertical profile estimation on optical link : sensor







Measurements

- Slopes
- Total Intensity / sub-ap.

Wavefront sensor:

- E2V EMCCD220 OCAM² Firstlight Imaging
- 8x8 square subapertures
- 1500 Hz

- Temporal spectra
  - Collected flux per sub-aperture (I_{sb})
  - Slopes or phase
- Probability density function of I_{sb}

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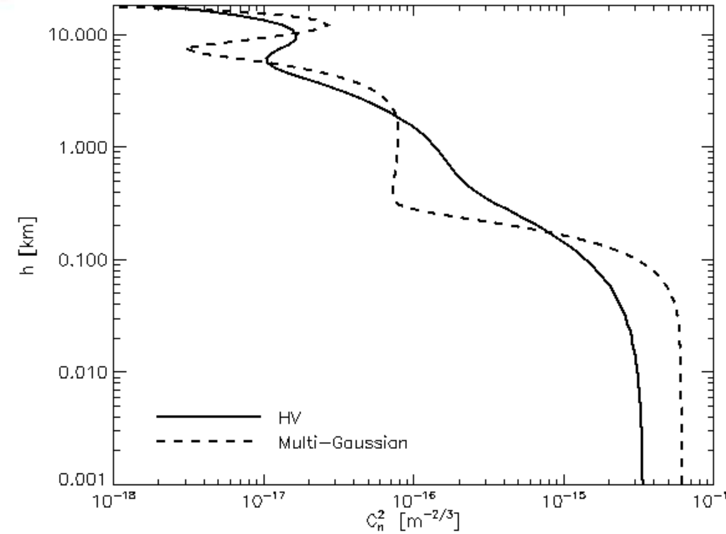
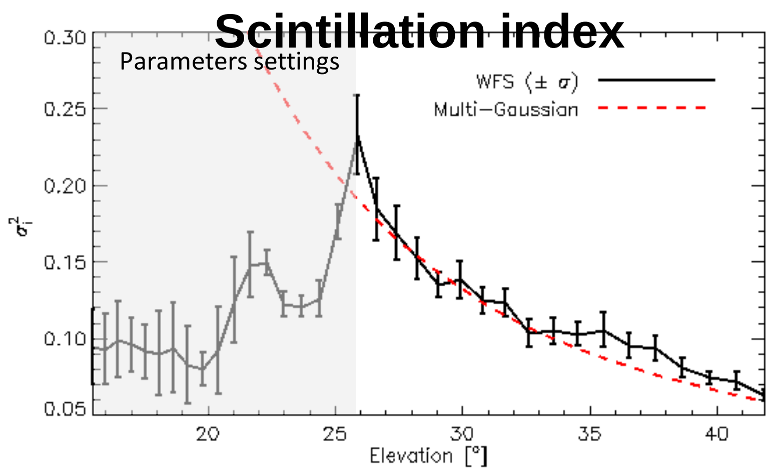
Vertical profile estimation on optical link : results

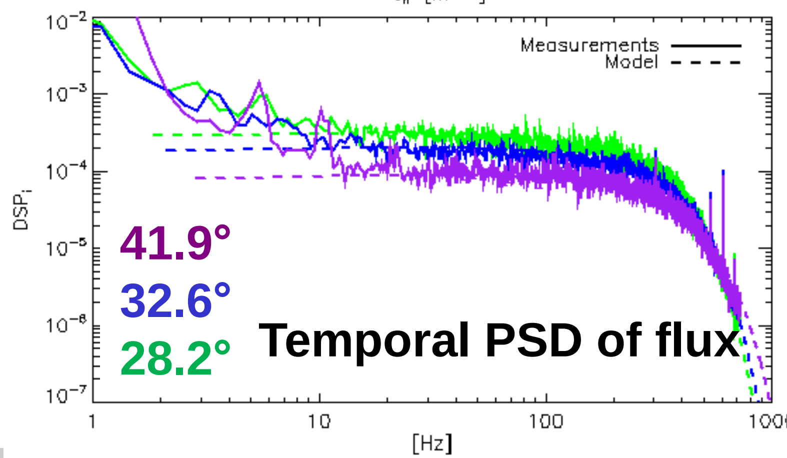
Adjustment of a Hufnagel Valley profile or a Multi-gaussian profile based on slopes and intensities information

- 3 layer profile, Altitude =[0,1.3,12.4] km
- C_n^2 =[6.1 10^{-15}, 7 10^{-17}, 3 10^{-17}]
- Wind = [1,20,133] m/s (driven by satellite speed)

⇨ Multi-gaussian proves to fit better



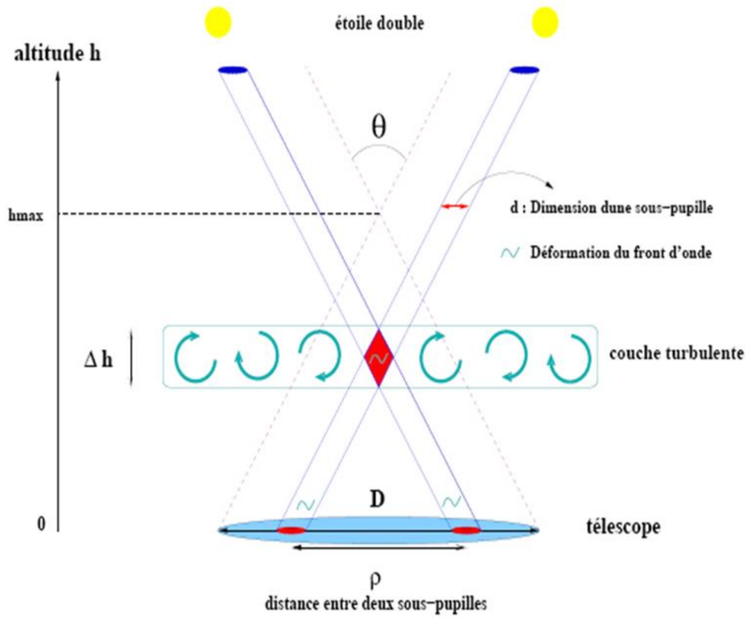


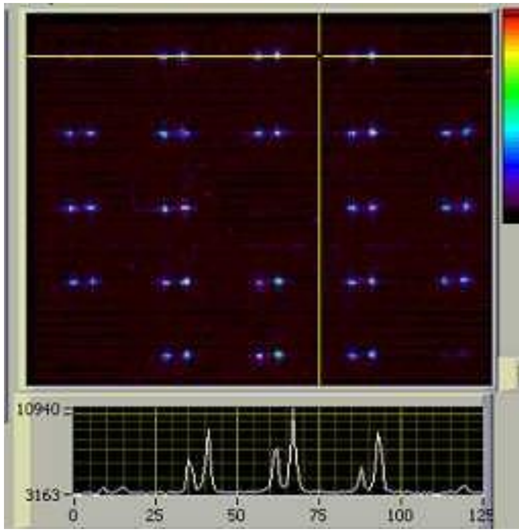


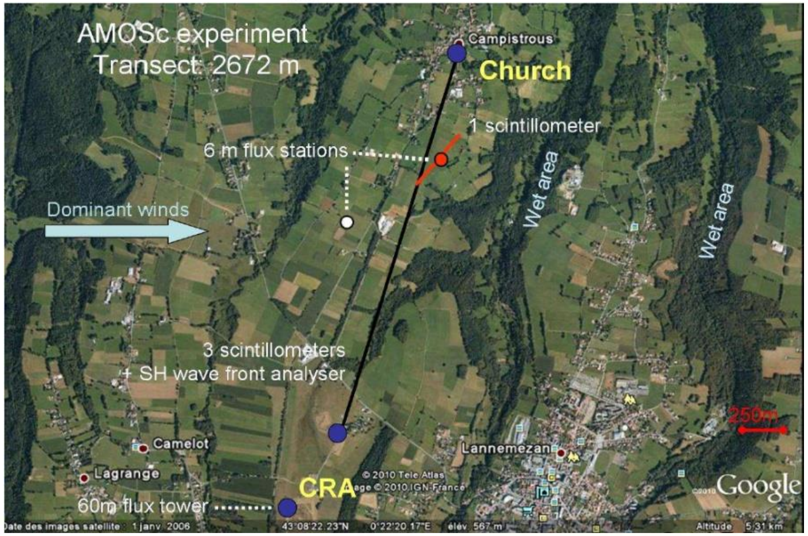
Very good agreement with flux fluctuations for elevations > 26˚

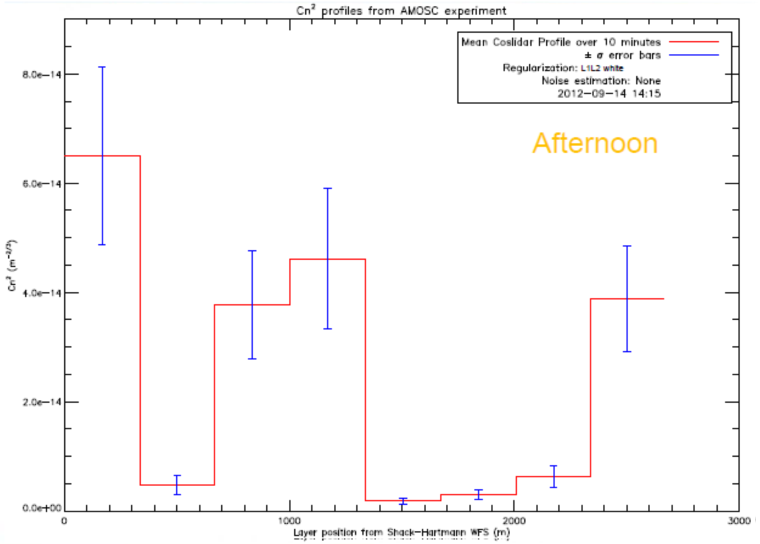
Temporal Power Spectrum Densities and statistics

Turbulence characterization : profiler









C. Robert et al, Near ground results of the COSLIDAR C2n profiler. In Journal of Physics: Conference Series (Vol. 595, No. 1, 2015)

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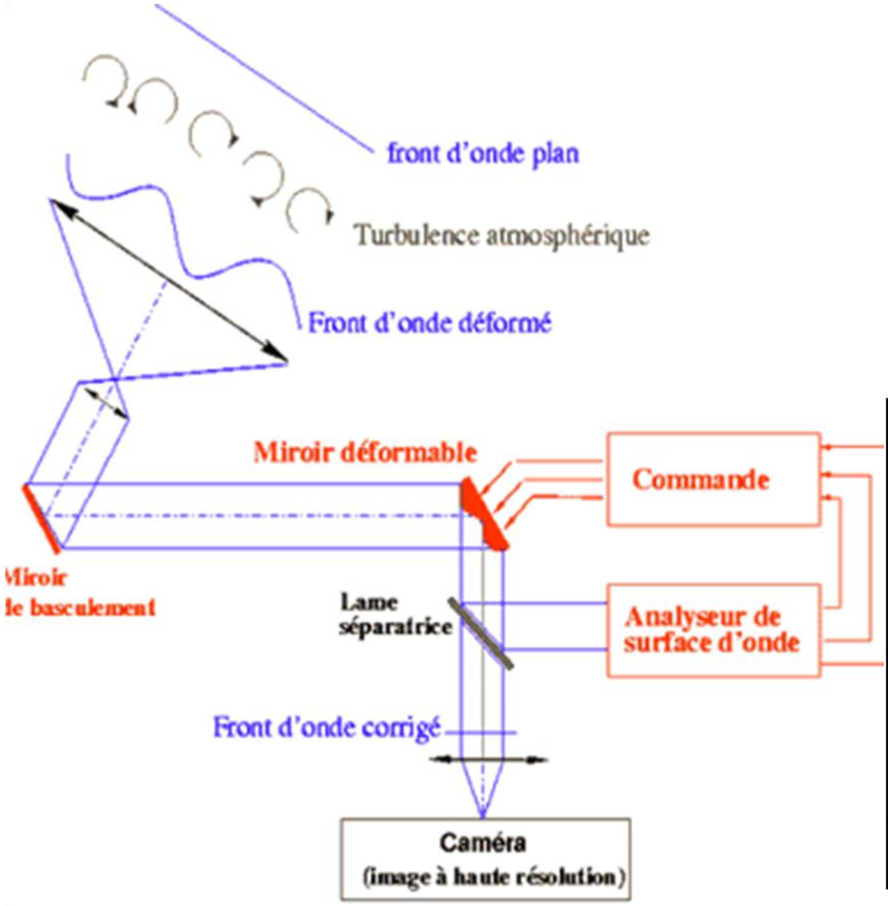
Adaptive optics for imagery



- Telescope : Canjuers military camp (1000 m height) (South of France)
- Target Mont Lachens (1700 m height) in summer and autumn 2008 (France).
- Range 11km – IR (3 – 5 µm)
- Shack-Hartmann WFS – sensing on extended target

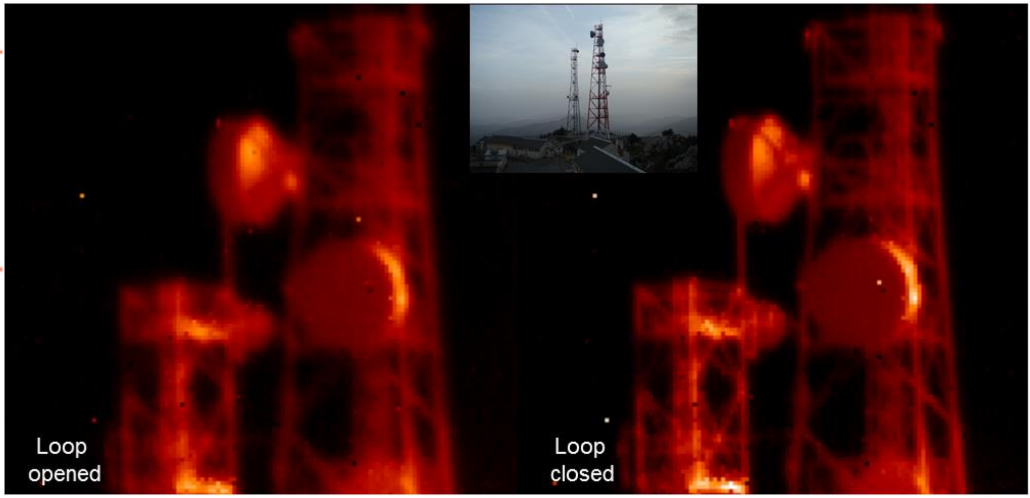


Image quality enhancement (contrast, thinner details)

Limited in the field because of anisoplanatism

Image processing

12/10/11 15h34
Range 7 km
$C_n^2 = 7.10^{-16}\ m^{-2/3}$
T_e = 25 ms / 69 fps

Comparison Criteria

- Blur (in pixel)
- Tilt (in pixel)

Quantification of the enhancemer
Comparison between techniques

Excellent tilt correction
Limitation in blur correction (exposure time ? Focus calibration ?, …)

A. Van Ekeeren et al "Patch-based local Turbulence Compensation in anisoplanatic Conditions ", SPIE 8355 (2012)

Mitigation techniques

- **For Imaging**, solution depends on
  - The field of view
  - Turbulence strength

Field-of-view	Solution
< isoplanatic angle	Adaptive optics
< isokinetic angle	image stabilization (in hardware or software)
> isokinetic angle	real-time image processing

⇨ **Image processing more appropriate**

- **For laser beam delivery ⇨Adaptive optics systems**
  - Precompensation of the outgoing beam
  - Strong turbulence case
    - Specific wavefront sensings (scintillation) – sensorless AO systems
    - Correction of both phase and amplitude (beam shaping)
    - Adaptive optics systems under development or in validation in laboratories

To summarize

- System performance assessment - tools
  - Physical models (time consuming – not useful for system designing)
  - Simplified models based on knowledge of PSD and PDF
- Turbulence along the path
  - Great variability (day/night, location, …)
  - Inhomogeneity, turbulence volume
  - Characterization methods proposed (profiler – temporal resolution)
- Mitigation techniques
  - Adaptive optics – limitation: anisoplanatism – strong turbulence
  - Image processing – limitation: strong turbulence – real time