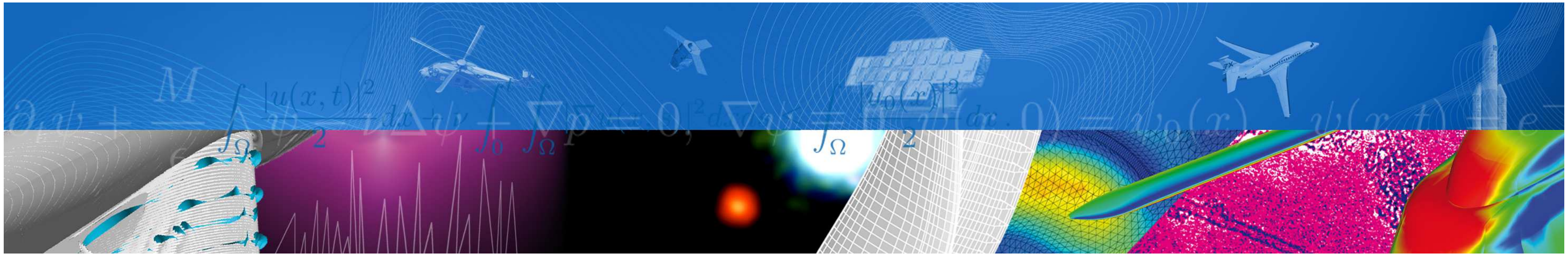

Modelling the Cn² and wind profiles for space-ground optical links with parametric models: cross-comparison with mesoscale models and in-situ measurements

C. ROBERT[1], M.-T. Velluet[1], E. Masciadri[2], A. Turchi[2], J.-M. Conan[1], N. Védrenne[1], G. Artaud[3], B. Benammar[3]

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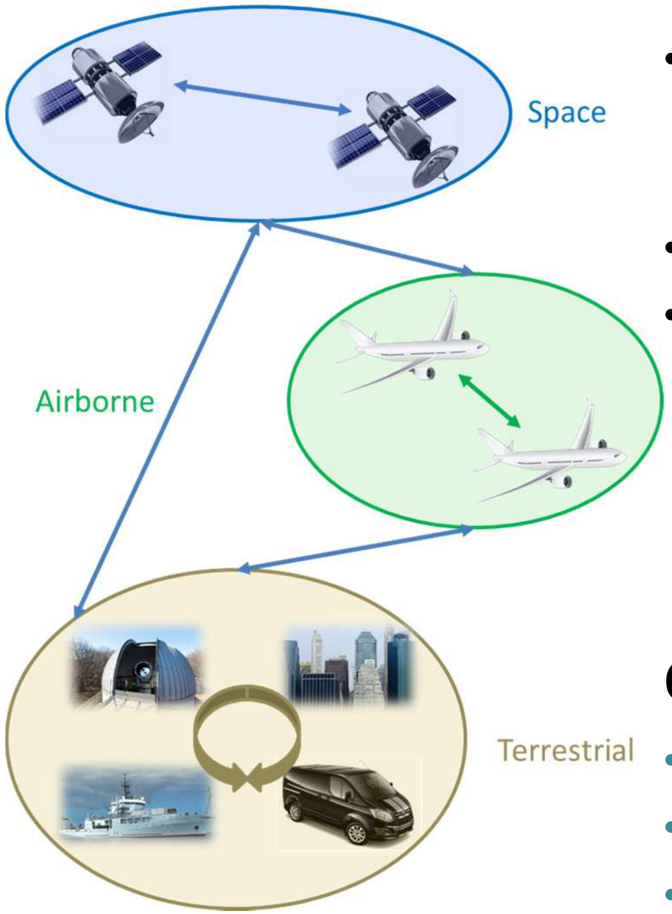
Context



High increase in data rate transfer

- For spatial applications
  - 2020 – 2025 : high resolution images download-> 1 Tbits/day
  - From 2025 : telecommunication with GEO links (1 Tbits/s)
- Air-ground applications (> 1 Gb/s)
- Marine applications : 10 -> 100 Mb/s

RF bandwidth saturation

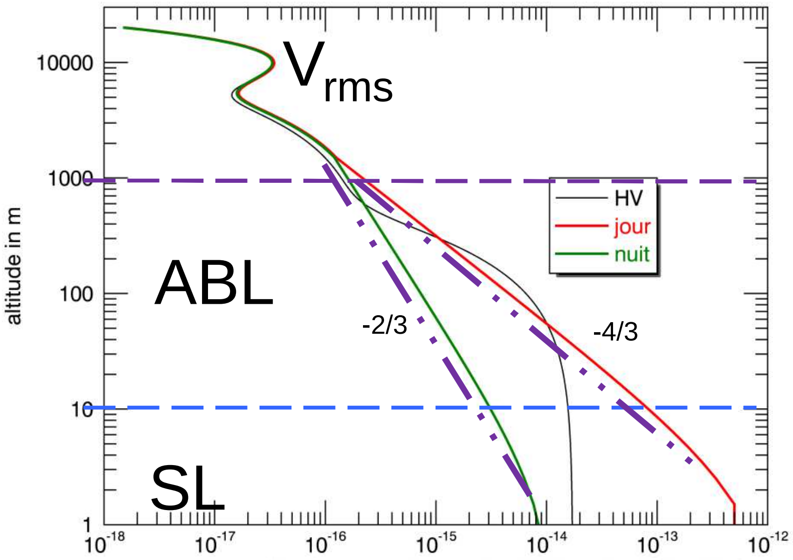
⇨ Using higher frequencies as optics

Comparison Optics / RF

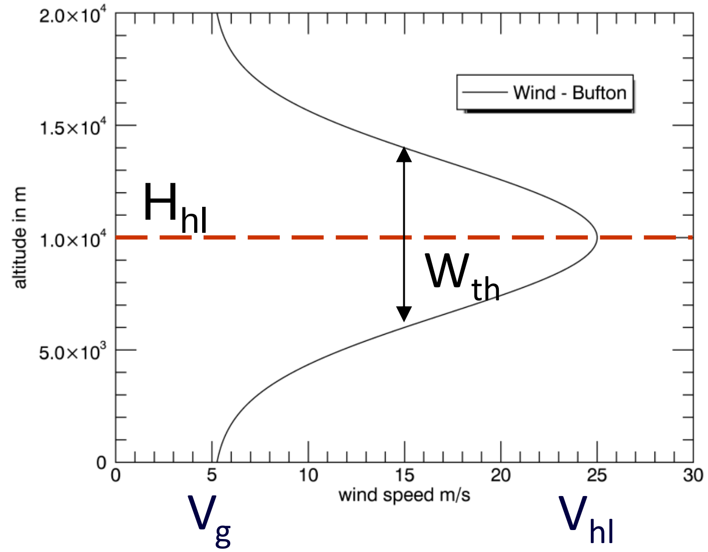
- Suspend and complete congestion problem in RF band
- No frequency regulation
- Low divergence beam ⇨ secure links , mass and power consumption reduction
- More sensitive to atmospheric effects (cloud, fog, **turbulence**)

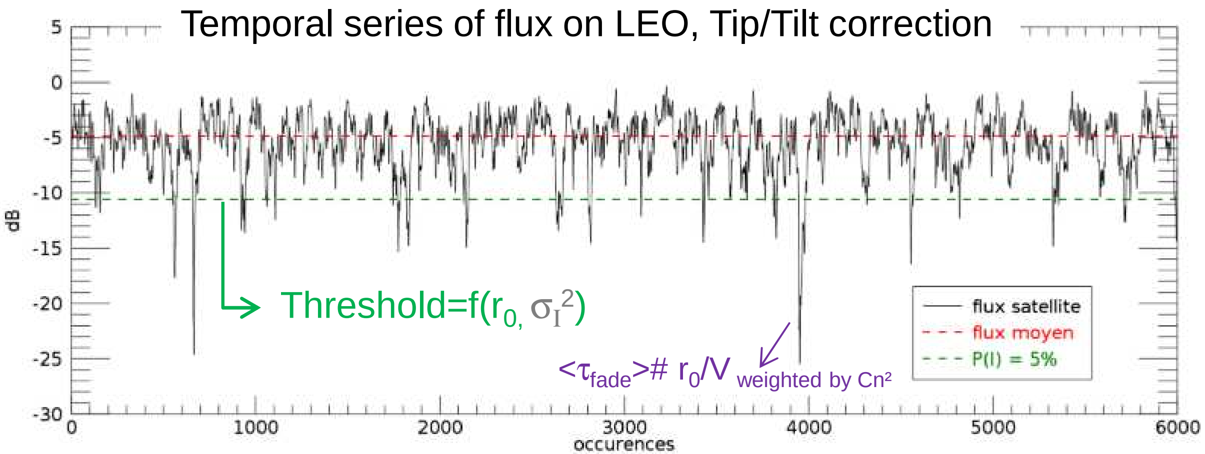
Turbulence profiles impacts telecom transmissions

Turbulence (C_n^2) profiles



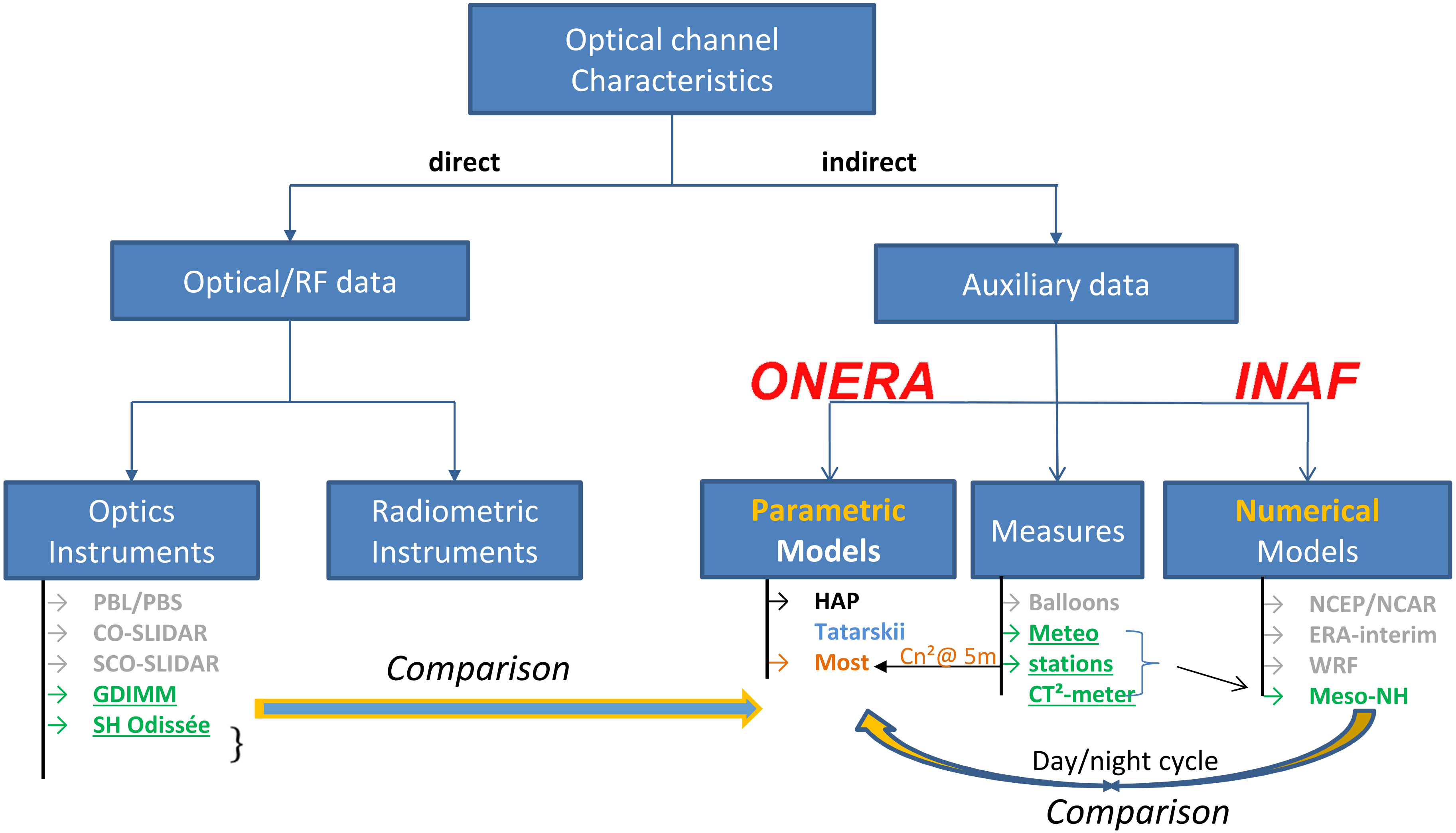
Wind profile [2]





Hypotheses on profiles
to be confirmed
experimentally and numerically

Characterization of the turbulent atmospheric channel

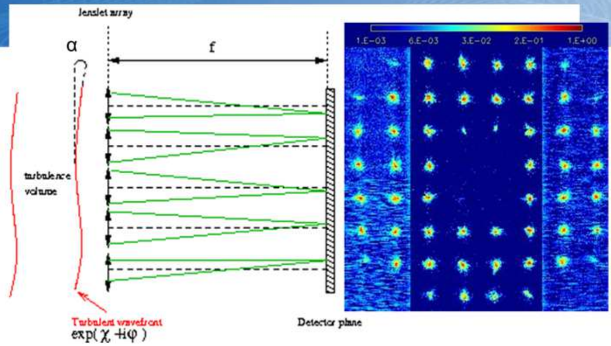


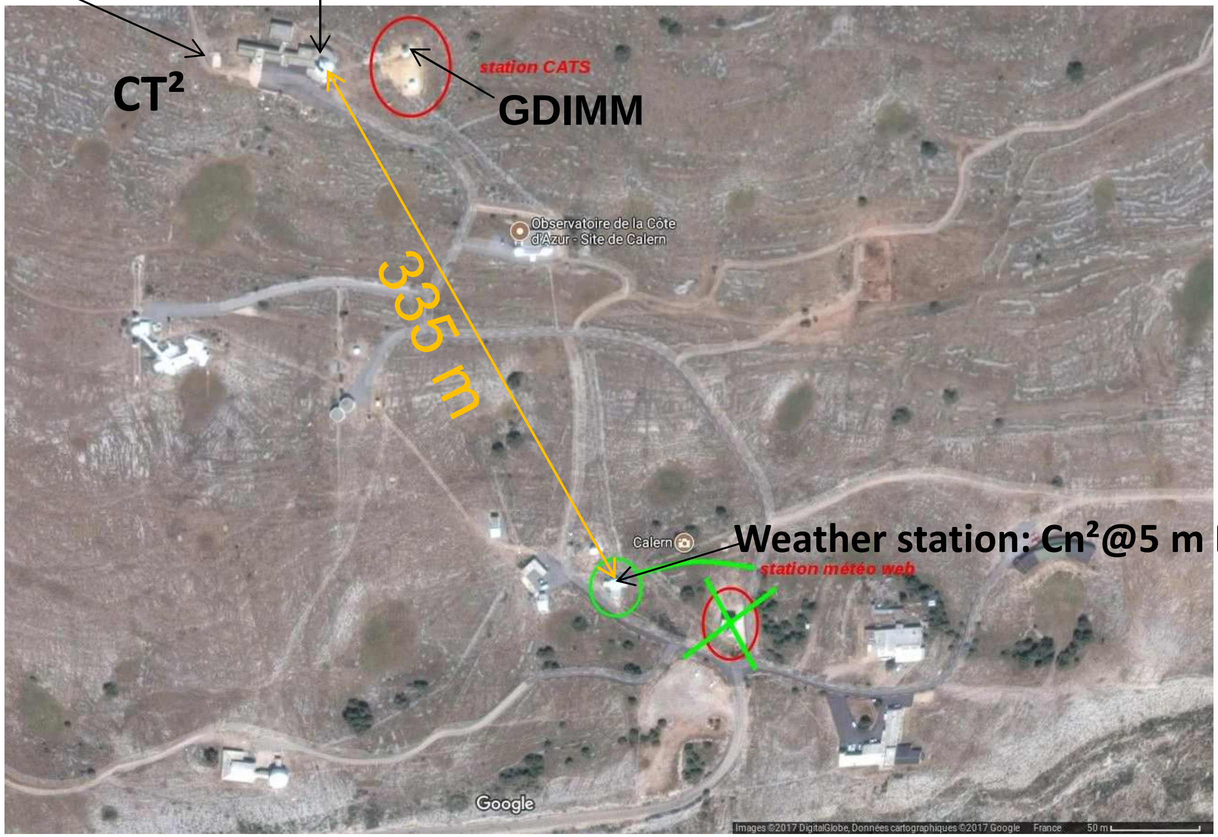
We look for an automatic characterization of the turbulent channel on the globe

Turbulence measurements : how ?

micro-thermometers

SH WFS @ MEO





Altitude 1270 m

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Cross-comparison : measures & models with metrics

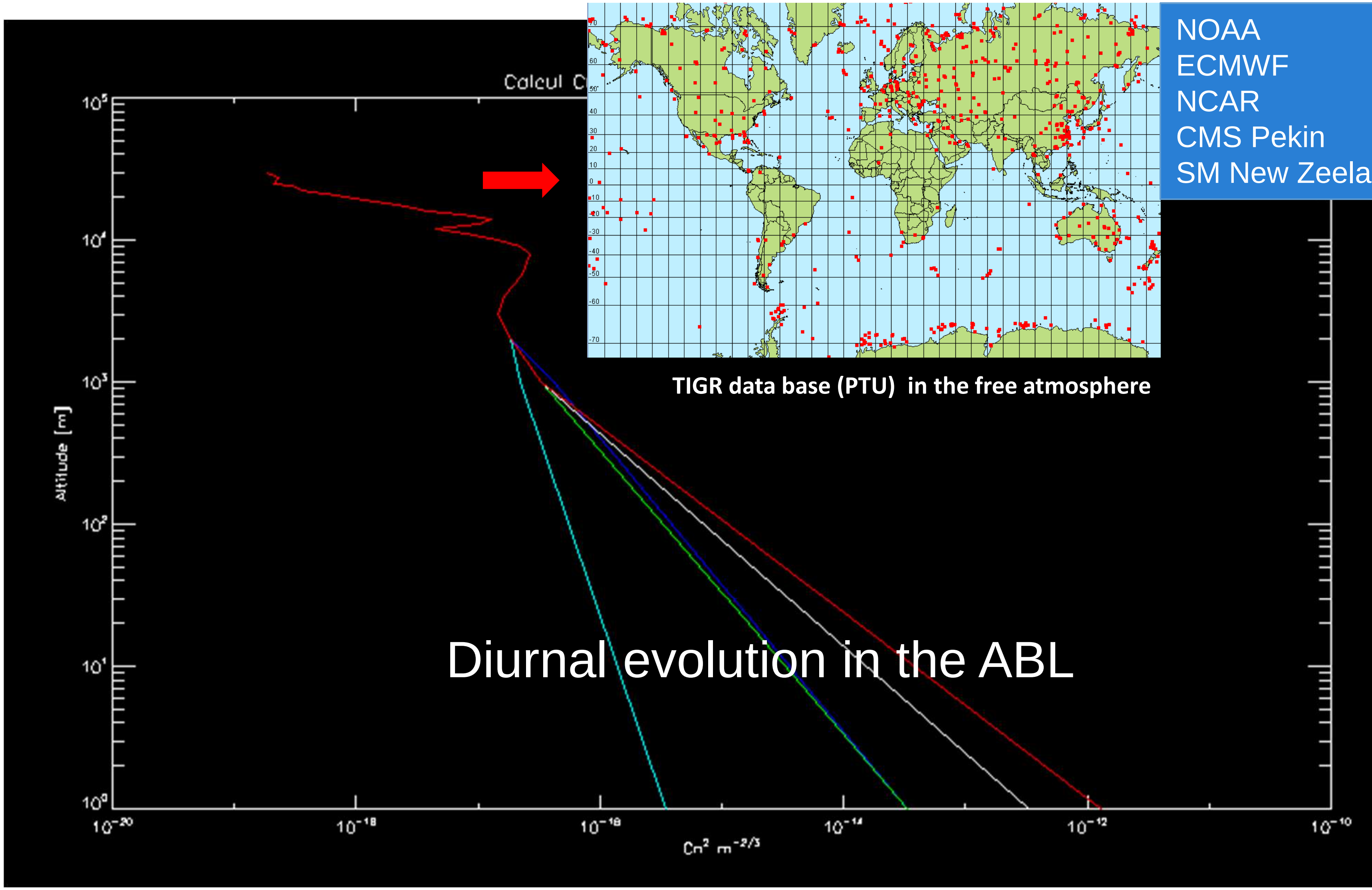
1. Measures
   A. Shack-Hartmann -> r_0, σ^2_I @ λ = 600 [976] nm on the line of sight
   B. Weather data -> Bulk models -> Cn^2 @5 m for parametric profiles
   C. CT^2 -> Cn^2 @ 3 m -> to compare with Cn^2 @5 m for parametric profiles
   D. GDIMM -> seeing, r_0, σ^2_I @ λ = 500 nm & @ zenith

   -> We compare all parameters @ zenith
2. Parametric turbulence profiles (Cn^2 and wind) provided by ONERA
   - MOST+Tatarskii
   - MOST+HAP
3. Numerical profiles (Cn^2 and wind) *from ASTRO*-Meso-NH provided by INAF

The criteria proposed for the comparison study are:

- Fried parameter r_0
- Scintillation index σ^2_I
- Cn^2 @ 5 m above ground
- Cn^2 piecewise integrals: J1 [0-150] m, J2 [3-5] km, J3 [10-14] km
  wind averages V1 [0-150] m, V2 [9-13] km

MOST+Tatarskii Cn² profiles in MATISSE V3.5



TIGR data base (PTU) in the free atmosphere

NOAA
ECMWF
NCAR
CMS Pekin
SM New Zeeland

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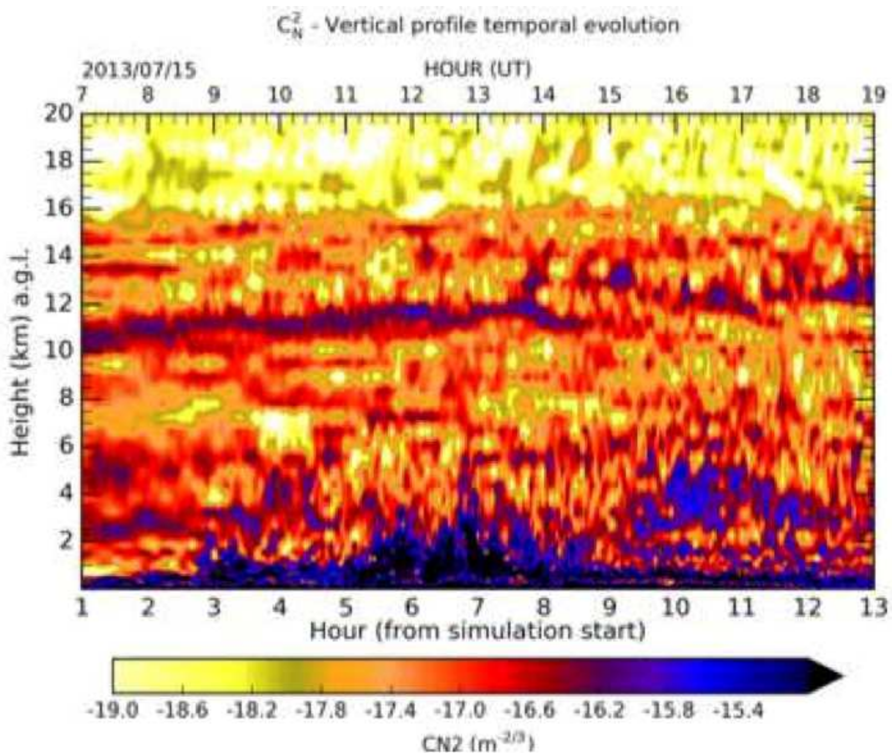
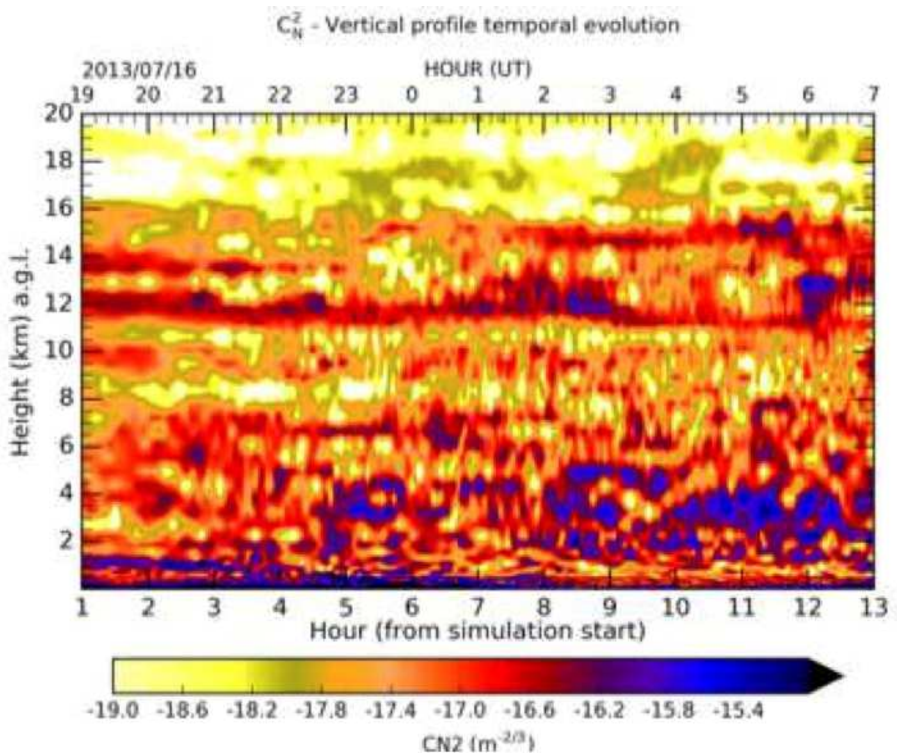
Temporal evolution of the C_n^2 profile by the Astro-Meso-NH

day

successive night





The turbulence close to the ground in day time disappears during the night.

Selection of data & measurements

N°	dates	Time TU	Sources Star mag	Elevation, Azimuth	Wind speed [m/s] avg, min, max	SH frame rate Central wavelength and spectral band	Other data
1 ☆	15/07/2013	14:25 -> 14:52	Arcturus, 0.15	36-41°, 98-103°	1.5, 0, 3.6	700 Hz; λ_0 = 600nm, dλ=80 nm	Weather station
2 ☆	15/07/2013	22:31 -> 23:02	Vega, 0	85-82°,176-229°	0.75, 0, 1.34	1500 Hz ; λ_0 = 600nm, dλ=80 nm	Weather station
3 ☆	16/07/2013	09:17 -> 09:56	Sirius, -1.45	26-28°,157-167°	2, 0, 4.9	700 Hz; λ_0 = 600nm, dλ=80 nm	Weather station, CT²
4 ☆	16/07/2013	21:05 -> 21:09	α Herculis, 3.35	60°, 179°	2, 1.3, 2.7	1500 Hz ; λ_0 = 600nm, dλ=80 nm	Weather station, CT²
5 	21/07/2015	22:37 -> 22:39	SOTA	21°->44.5°	0.05	1450 Hz ; λ_0 = 976 nm	Weather station, GDIMM

The criteria proposed for the comparison study are:

- Fried parameter r0
- Scintillation index σ^2_I
- Cn² @ 5 m above ground
- Cn² piecewise integrals: J1 [0-150] m, J2 [3-5] km, J3 [10-14] km wind averages V1 [0-150] m V2 [9-13] km

Metrics for each model/measures vs. selected cases

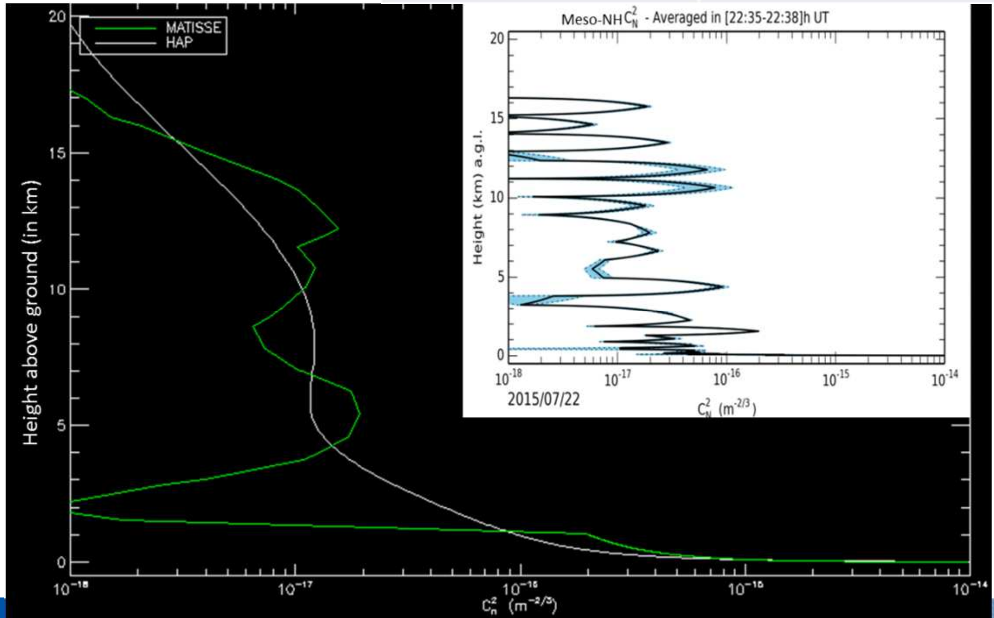
	Numerical Cn² Profiles Astro-Meso-NH					Parametric Cn² profiles MOST+Tatarskii					Parametric Cn² profiles MOST+HAP					Other data SH : Shack Hartmann CT² : micro-thermal sensor GDIMM : generalized DIMM							
Case N°	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3		4		5	
																SH	SH	SH	CT² @3m	SH	CT² @3m	SH	GDIMM
Seeing ('')	3.7	2.1	3.9	1.9	1.1	3.3	1.6	3.2	1.4	1.1	3.0	2.1	3.5	1.1	1.1	2.1	1,3	1.7		0,8		1,2	1.0
r0 (cm)	2.7	4.8	2.6	5.2	9.4	3.0	6.4	3.1	7.4	9.0	3.3	4.9	2.9	9.6	9.5	4.9	8.1	7.4		13.1		8.8	10.8
σ^2_I (%)	41	22	67	20	22	26	20	26	18	16	49	27	59	14	15	6	4	6		1		26	2
$Cn^2 \times 10^{14}$ ($m^{-2/3}$) @ 5 m	11	2	14	1	3	11	1	15	1	1	12	6	15	1	1				10		1		

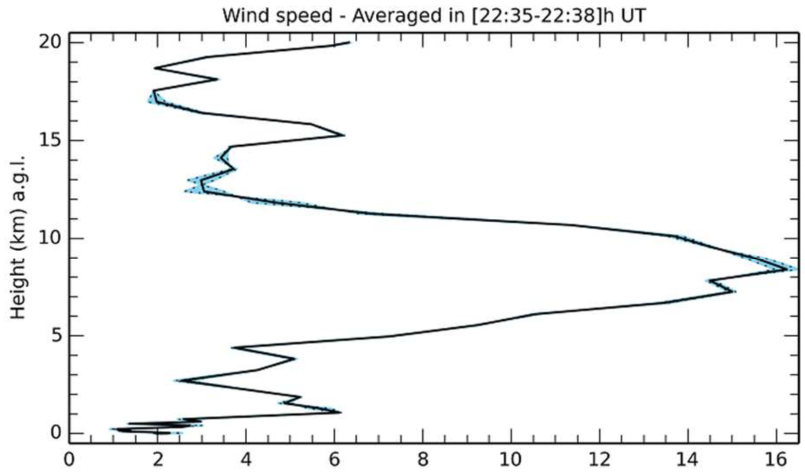
- SH on laser satellite (high flux) r_0, σ^2_I vs. models OK
- SH/GDIMM on stars (low flux) r0 ~OK, σ^2_I not OK vs. models
- σ^2_I day > σ^2_I night (ASTRO-Meso-NH & HAP) influence of the altitude wind
- Adequacy of Cn² @ 5 m : Bulk-model & ASTRO-Meso-NH Day > night

Turbulence during the SOTA rendez-vous at OCA in July 2015

C. Robert *et al*,
SPIE Remote Sensing,
11153, 2019
doi = {10.1117/12.2534659}

21/07/2015 night (case N°5)		MOST+Tatarskii *	MOST+HAP**	Astro-Meso-NH	Relative error (%) vs. Astro-Meso-NH	
SOTA rendez-vous	Shack-Hartmann frames	From MATISSE Weather station data for the Bulk-Model PTU profiles N° 414 from TIGR database	Unstable conditions High altitude wind parametrization from Meso-NH		*	**
Seeing (“)	1.17±0.08	1,12	1.06	1.05±0.04	1	3
r0 (cm)	8.84±0.65	9,02	9.47	9.36±0.39	4	1
σ^2_I	0.26±0.13	0,16	0.15	0.22	26	33
Cn² piecewise integrals ($m^{1/3}$)						
J1		2.42E-13	2.89E-13	3.76E-13	36	23
J2		1.76E-14	3.17E-14	5.84E-14	70	46
J3		4.43E-14	2.58E-14	1.01E-13	56	74
Wind averaged (m/s) V1, V2		1.26, 8.85		1.70, 8.97	26, 1	
Wind @ 5 m		0.91		1,25	1	





Astro-Meso-NH

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Conclusions and perspectives

- **Comparisons of measures & models: MOST+ Tatarskii, MOST+HAP, Bufton, ASTRO-Meso-NH, by using metrics : Cn² @ 5 m, r0, σ^2_I, $J_{1,2,3}$ $V_{1,2}$**
- **Adequacy of Cn² @ 5 m : Bulk-model & ASTRO-Meso-NH, [CT²]**
- **Profiles structure study with piecewise integrals vs. ASTRO-Meso-NH**
  - ✓ Bufton wind profile : good model
    - V_2 [9-13] km OK : RE ≤ 25%
    - V1[0-150] m wind shearing near ground but local ground measurement sufficient
  - ➢ Cn² profiles
    - ✓ Mean envelope captured with MOST+Tatarskii
    - ✓ best Cn² metrics on $J_{1,3}$ i.e. surface and high layers
    - ➢ Day/night variation of σ^2_I with HAP/ ASTRO-Meso-NH ➡ wind parametrization usefull
    - ➢ need of profiles (P, T, wind) closer to the place and in time ➡ Matisse V3.6

➢ Characterisation of the FSO turbulent chanel

- Global with parametric profiles including wind parametrization
- MATISSE V3.6 (mid 2020) in operational mode = data assimilation from Météo France
- SH measures in situ using the laser source on a satellite optical payload

⇨ *Data inversion to jointly get Cn² and Bufton wind profiles in prep.*