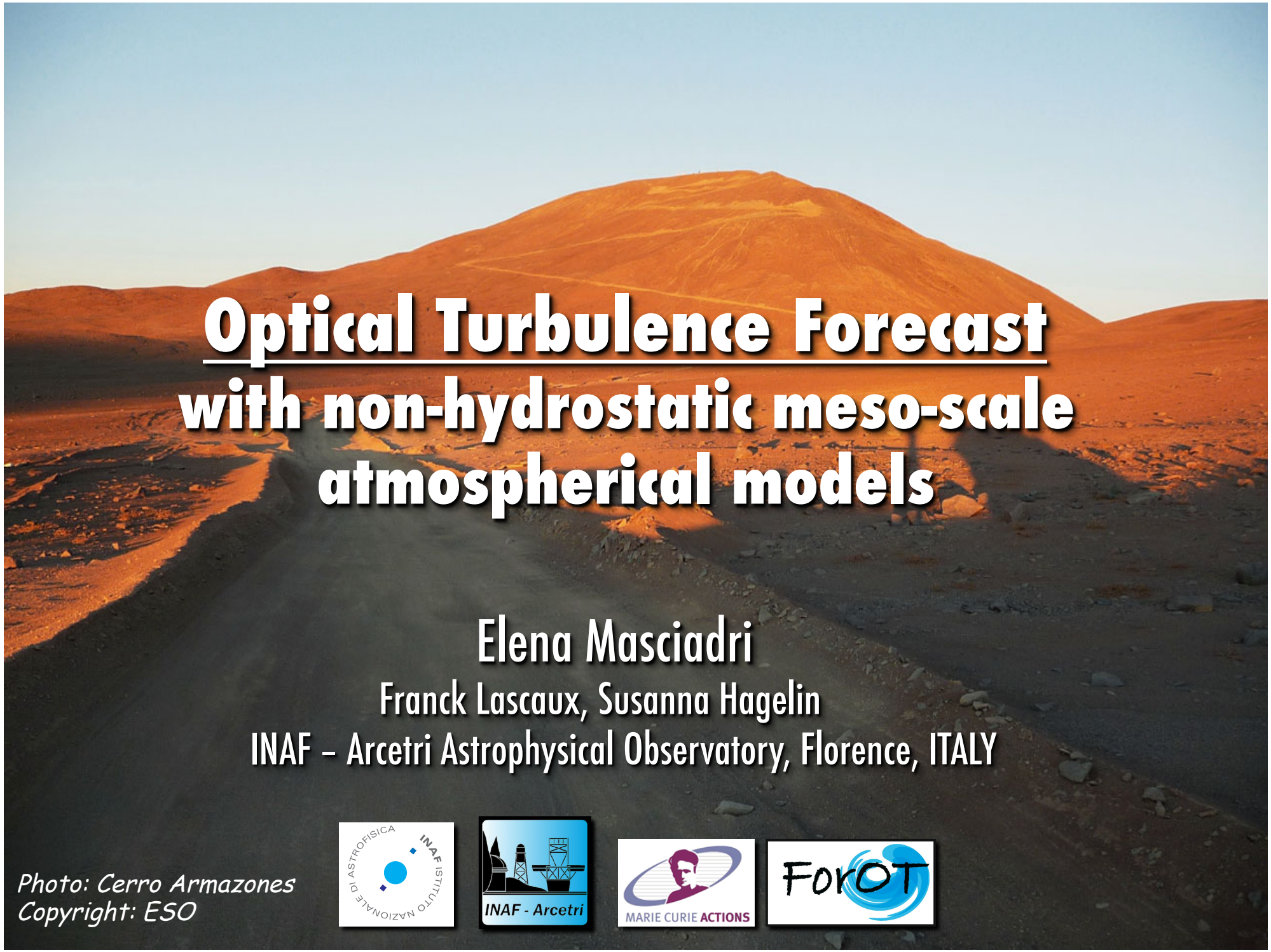

Optical Turbulence Forecast with non-hydrostatic meso-scale atmospherical models

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Franck Lascaux, Susanna Hagelin

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Photo: Cerro Armazones
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MARIE CURIE ACTIONS

ForOT

OUTLINE

- Scientific drivers
- Which parameters can be reconstructed by a meso-scale model ?
- How does the turbulence is described in a meso-scale model ?
- Why do we need a meso-scale models to forecast the OT ?
- How to forecast the OT with a meso-scale model ?
- Status of art: model reliability and challenges
- On-going projects
- Conclusions

SCIENTIFIC DRIVERS

1) Traditional queue system : *High scientific challenge of the program* **PARADOX** *Low probability that the program is executed*

2) Service Mode is mandatory to optimize the exploitation of an ELT

3) Cost of a night of observation at an ELT is of a few hundreds of K$!!!

4) The advantages of the Service Mode can be fully achieved **ONLY** if most of the available observing time is scheduled in this mode

★ The Service Mode has been established to be the baseline observing mode at the E-ELT (E-ESO-SPE-066-0283)

★ Permanent instruments at different focal stations. Typical time required to move the beam from an instrument to another one: **ΔT ~ 10-20 min.** (E-ESO-SPE-066-0283)

SCIENTIFIC DRIVERS

1) Traditional queue system : *High scientific challenge of the program* **PARADOX** *Low probability that the program is executed*

2) Service Mode is mandatory to optimize the exploitation of an ELT

★ The *optical turbulence forecast* is fundamental for the **success** and **feasibility** of the ELTs

★ The *meso-scale models* are the unique tool of investigation that can achieve such a scientific goal

★ Permanent instruments at different focal stations. Typical time required to move the beam from an instrument to another one: **ΔT ~ 10-20 min.** (E-ESO-SPE-066-0283)

FORTOT

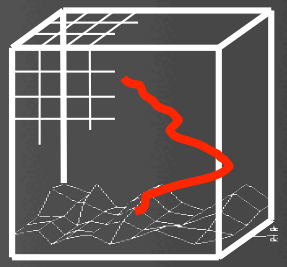
WHICH PARAMETERS CAN WE PREDICT ?

$$D_N(\rho) = \left\langle \left[n(r) - n(r+\rho) \right]^2 \right\rangle = C_N^2 \cdot \rho^{2/3}$$

$l_0 < \rho < L_0$

Kolmogorov Model

3D



3D : V, T , p, H, L_0 , C_N^2

(x,y,z)

wind speed

2D : $\int_0^\infty F(h^a, V^b, L_0^c) \cdot C_N^2 dh$ → ε, θ_0, τ_0, σ^2, $\mathcal{L}_0$, θ_M (M=1,2,3)

(x,y)

heigth

dynamic outer scale

WHICH PARAMETERS CAN WE PREDICT ?

ε: seeing $\varepsilon \sim \lambda^{-1/5}\left(\int_0^\infty C_N^2(h)\,dh\right)^{3/5}$ ⟷ **r_0: Fried paramter** $r_0 \sim \lambda^{6/5}\left(\int_0^\infty C_N^2(h)\,dh\right)^{-3/5}$

θ_0: isoplanatic angle $\vartheta_0 \sim \lambda^{6/5}\left(\int_0^\infty h^{5/3}\cdot C_N^2(h)\,dh\right)^{-3/5}$

τ_0: wavefront coherence time $\tau_0 \sim \lambda^{6/5}\left(\int_0^\infty V(h)^{5/3}\cdot C_N^2(h)\,dh\right)^{-3/5}$

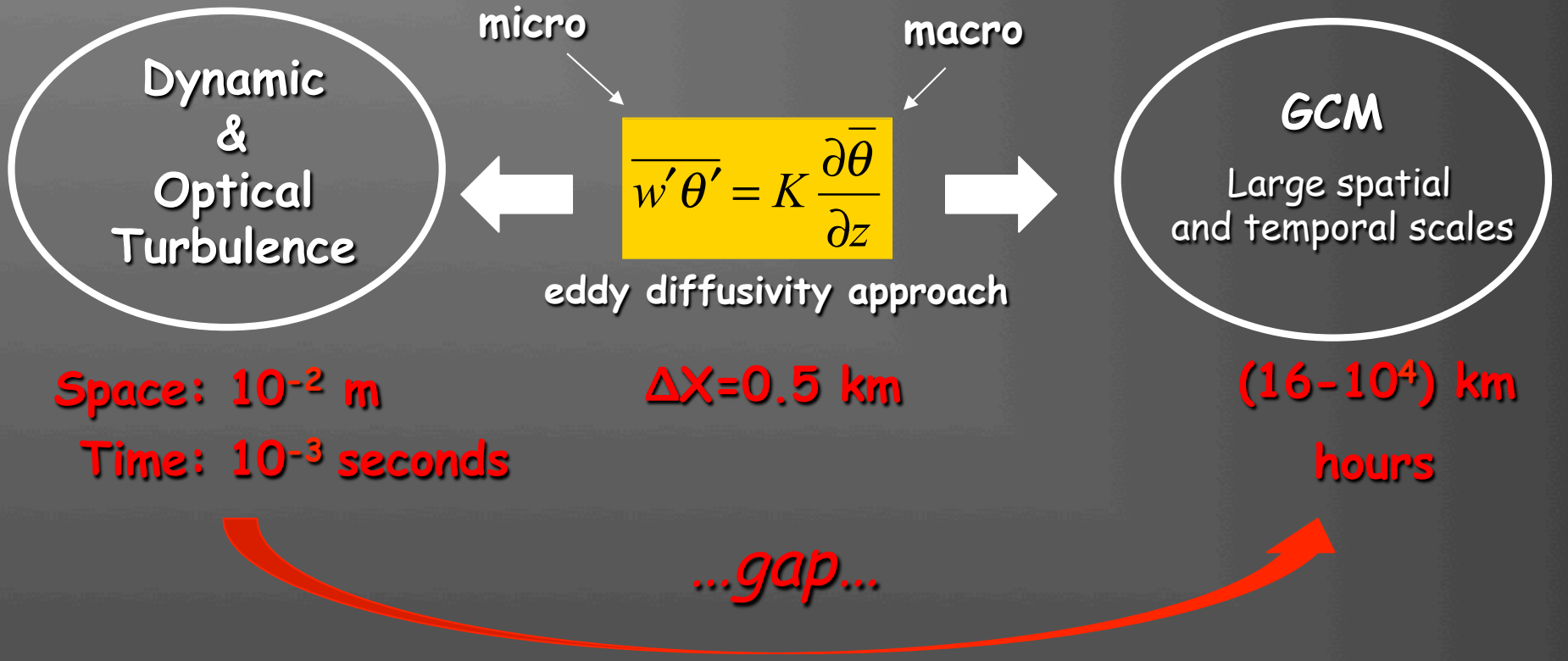
θ_M: isoplanatic angle for the MCAO $\vartheta_M \sim \lambda^{6/5}\left(\int_0^\infty F_M(h)\cdot C_N^2(h)\,dh\right)^{-3/5}$

$\mathcal{L}_0$: spatial coherence outer scale $\mathcal{L}_0 \sim \left(\int_0^\infty L_0(h)^{-1/3}\cdot C_N^2(h)dh \Big/ \int_0^\infty C_N^2(h)dh\right)^{-3}$

σ^2: scintillation rate $\sigma^2 \sim \lambda^{-7/6}\left(\int_0^\infty h^{5/6}\cdot C_N^2(h)\,dh\right)$

TURBULENCE PARAMETERIZATION: PRINCIPLE

GCM: General Circulation Models



OT Parameterization in Astro-MESO-NH

Masciadri et al. 1999, A&A
Masciadri et al. 2001, A&A

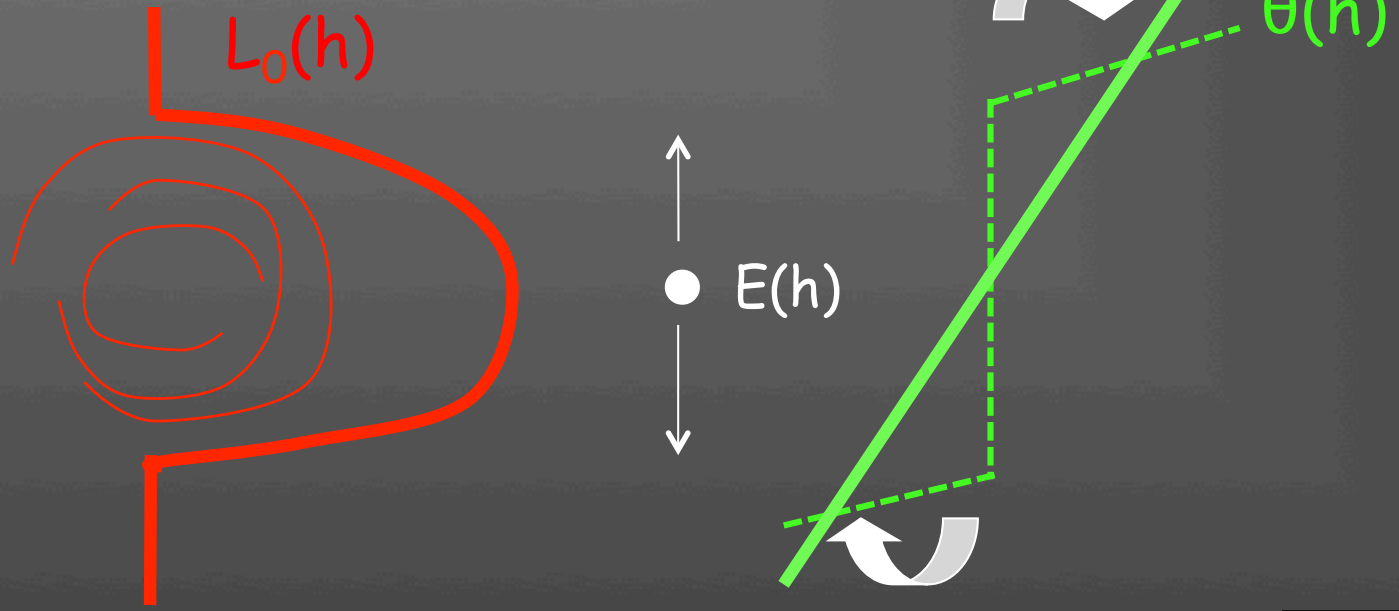
mixing length – $L_0(h)$

potential temperature

$$C_\theta^2 = 0.58 \cdot \phi_3 \cdot L^{4/3} \cdot \left(\frac{\partial \bar{\theta}}{\partial z} \right)^2 \Rightarrow C_N^2 = \left(\frac{80 \times 10^{-6} \cdot P}{T^2} \right)^2 C_\theta^2$$

thermo-dynamic stability term

Gladstone's law



ForOT

WHY MESO-SCALE MODELS ?

Large Eddy Simulation (LES)

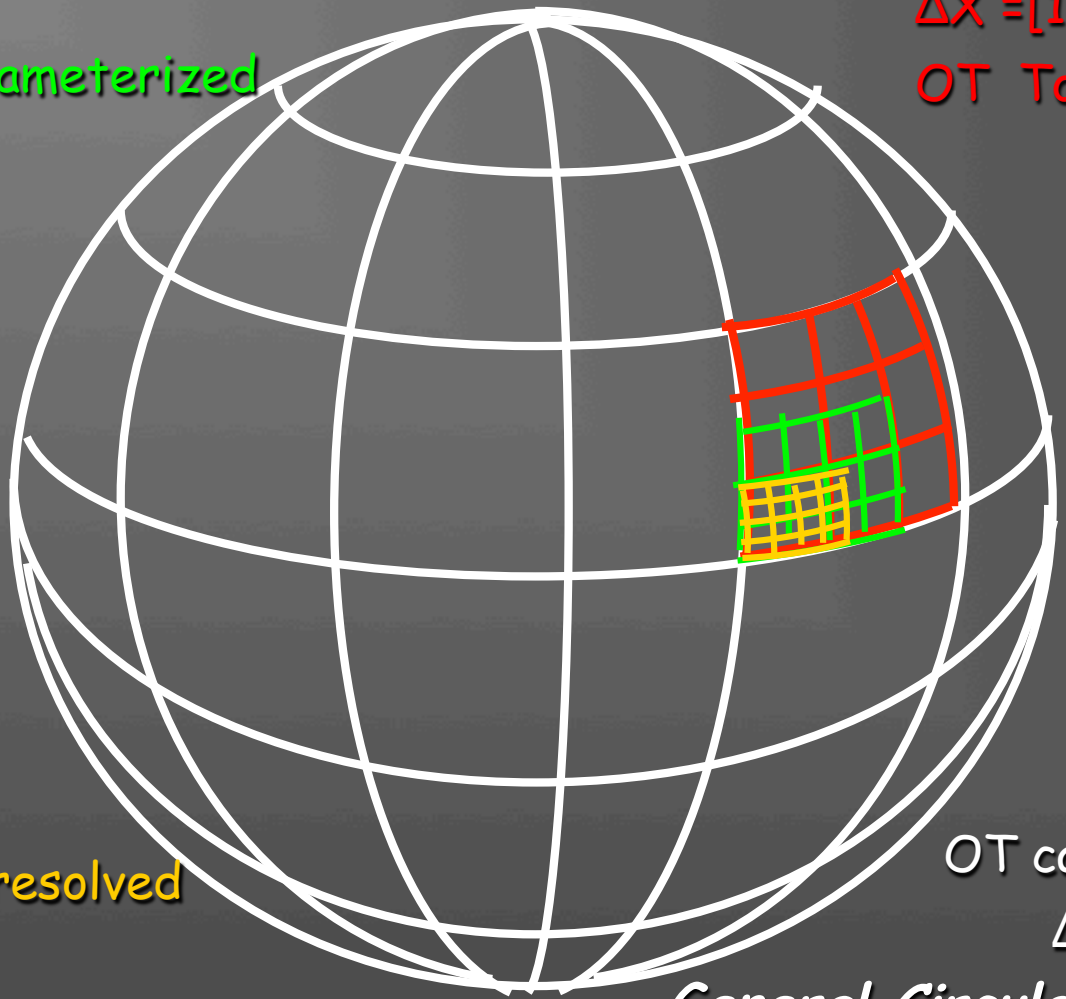
$\Delta X < 10^2$ m

OT Partially parameterized

Meso-scale models

$\Delta X = [10^2$ m - 10^2 km]

OT Totally parameterized



OT Completely resolved

$\Delta X \sim 10^{-2}$ m

Direct Numerical Simulation (DNS)

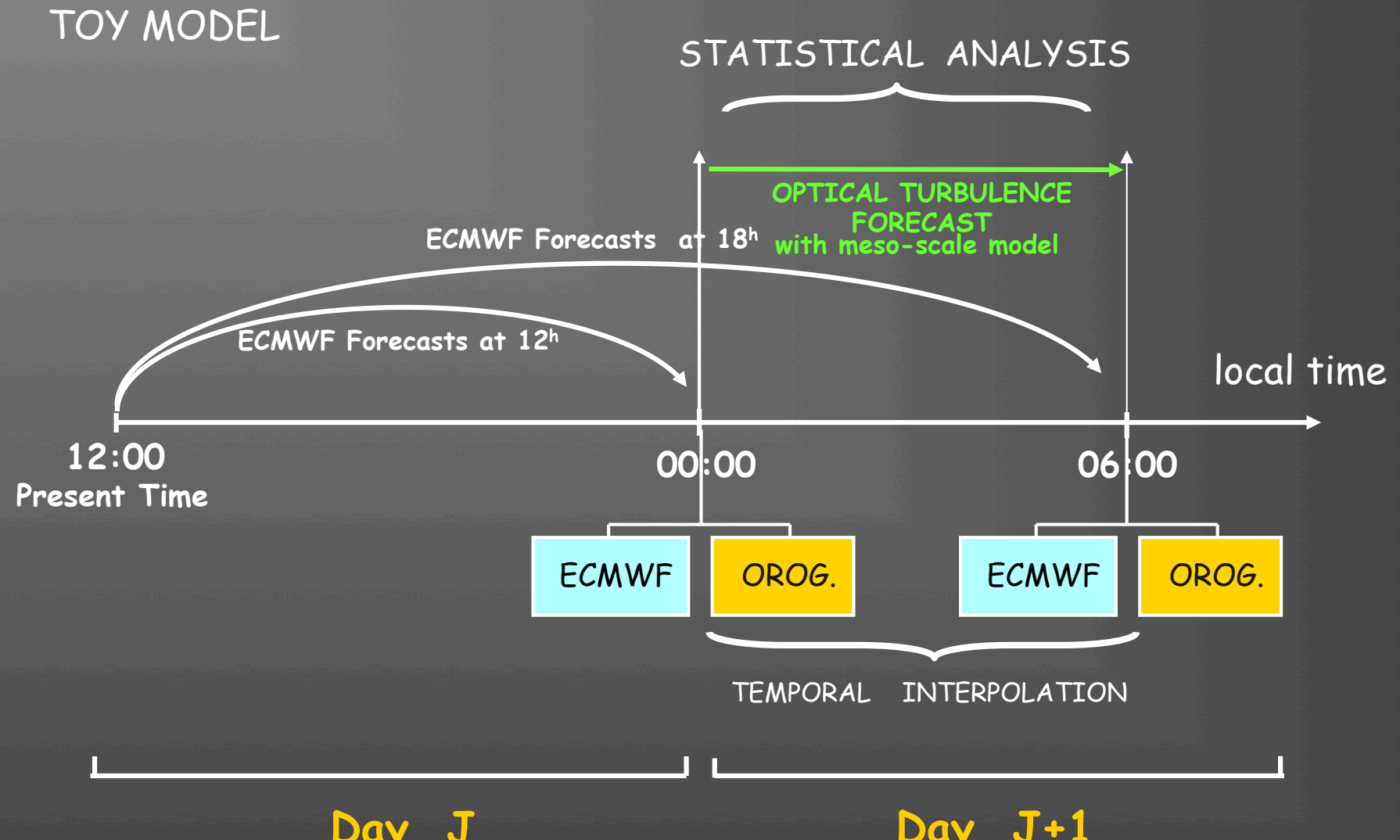
OT can not be represented

$\Delta X = [16$ km - 10^3 km]

General Circulation Models (GCM)

ForOT

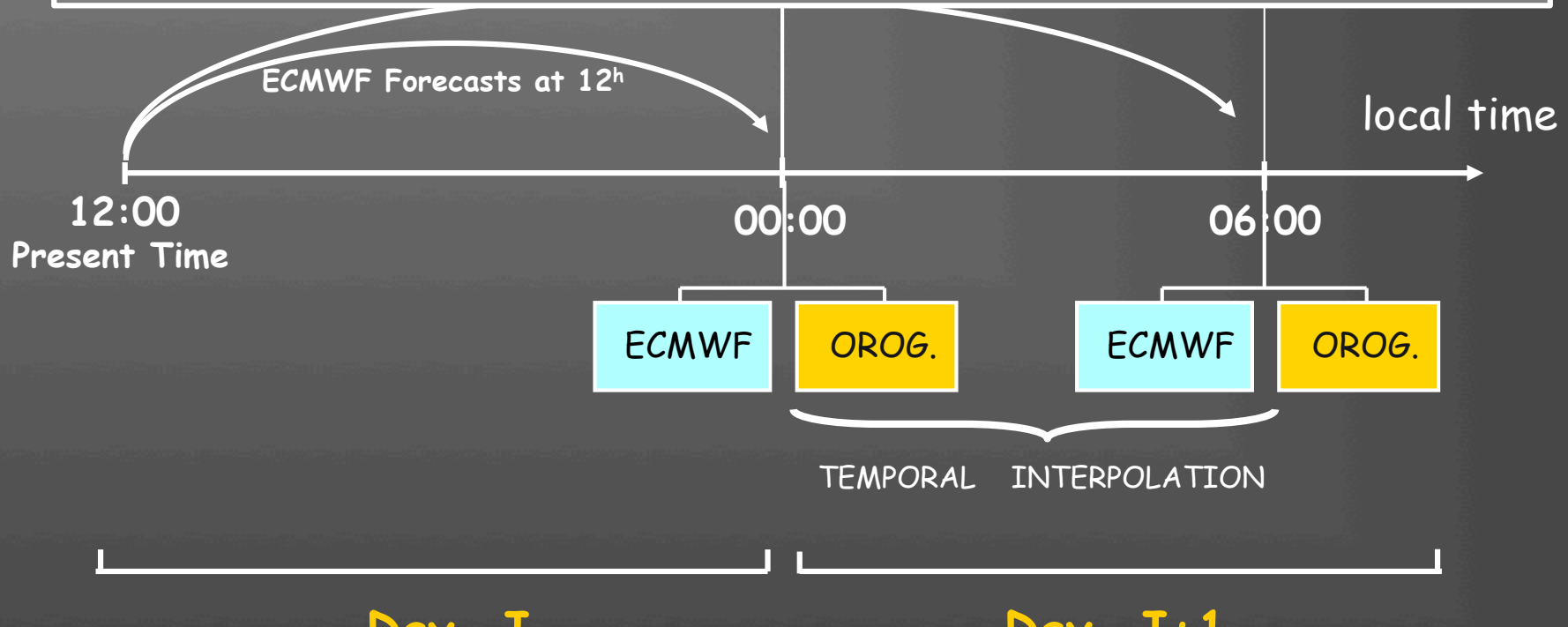
OT FORECAST: PRINCIPLE



OT FORECAST: PRINCIPLE

★ Simulations are forced each six hours (00:00, 06:00, 12:00, 18:00) with forecasts from the ECMWF available in the meanwhile

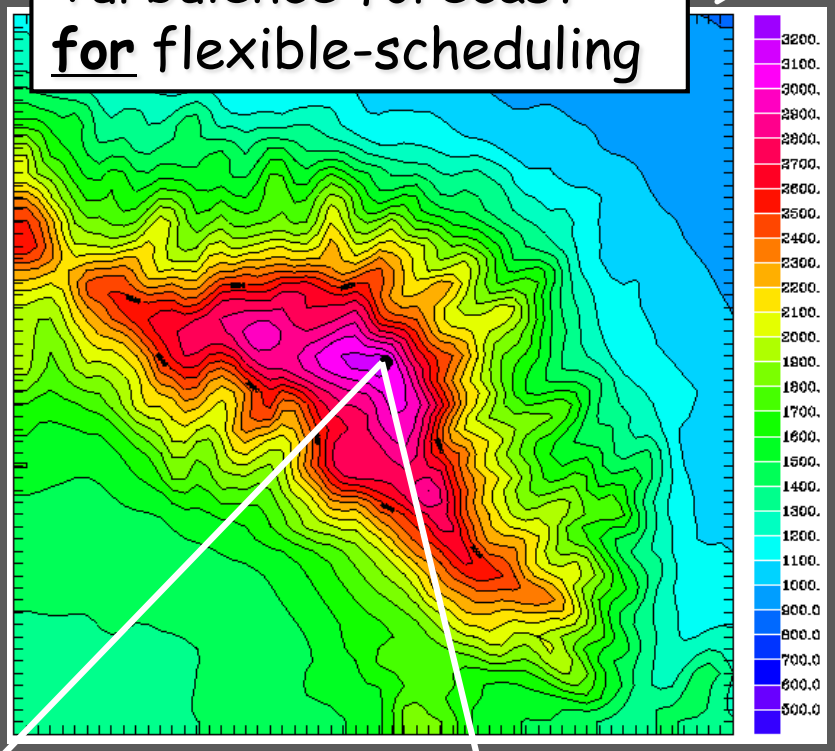
★ Simulations are performed with *grid-nesting technique* that permits to increase the resolution in a region around the telescope with a set of imbricated models



ForOT: CORE PROJECT

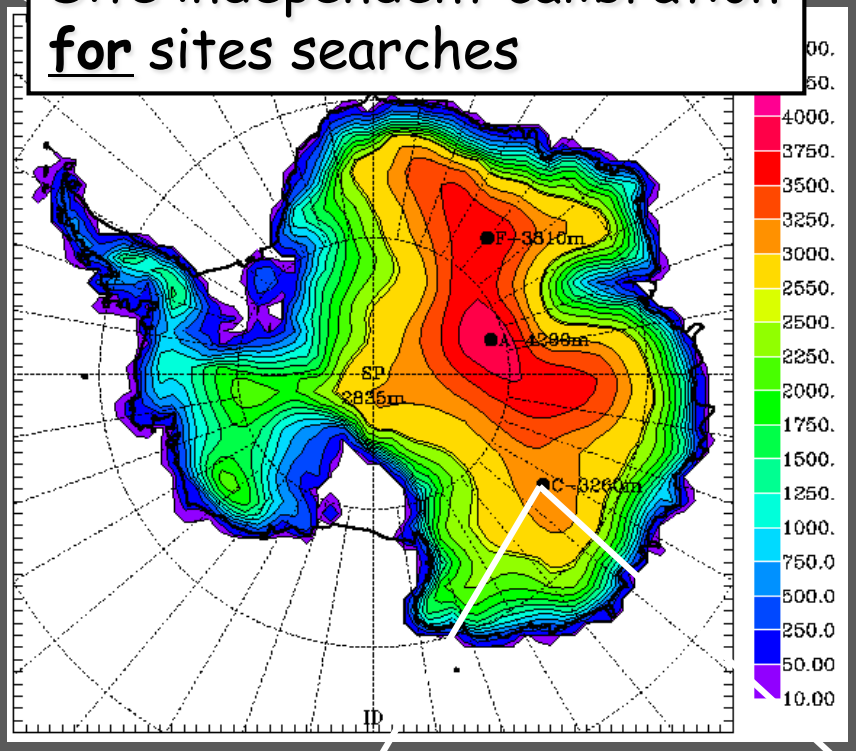
http:://forot.arcetri.astro.it

Main goal:
Turbulence forecast
for flexible-scheduling



Δx = 500 m

Main goal:
Site independent calibration
for sites searches



Δx = 100 km

MODEL VALIDATION ON DOME C: (h_{sl}, ε_{TOT}, ε_{FA})

C_N^2 in winter time associated to 15 nights – (balloons) Trinquet et al. 2006

Surface thickness: h_{sl}

$$\frac{\int_{8m}^{h_{sl}} C_N^2(h)\,dh}{\int_{8m}^{1km} C_N^h(h)\,dh} < 0.90$$

grid-nesting monomodel

STAT	OBS (m)	MODEL (m) ΔX=1km	MODEL (m) ΔX=100km
median	35.3	44.2	68.4
σ	19.9	24.6	26.5

Lascaux et al., 2010, MNRAS

Good correlation
measurements/simulations
with the grid-nesting configuration

FORCOT

MODEL VALIDATION ON DOME C: (h_{sl}, ε_{TOT}, ε_{FA})

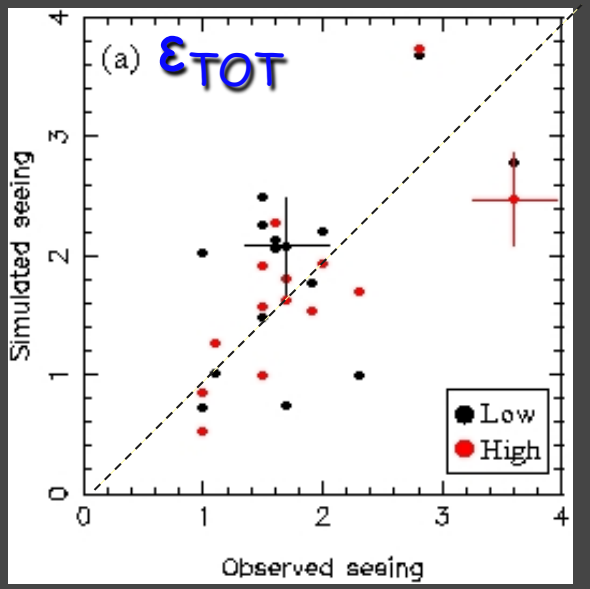
$$\varepsilon_{TOT} \sim \left(\int_{8m}^{h_{top}} C_N^2(h)dh \right)^{-3/5}$$

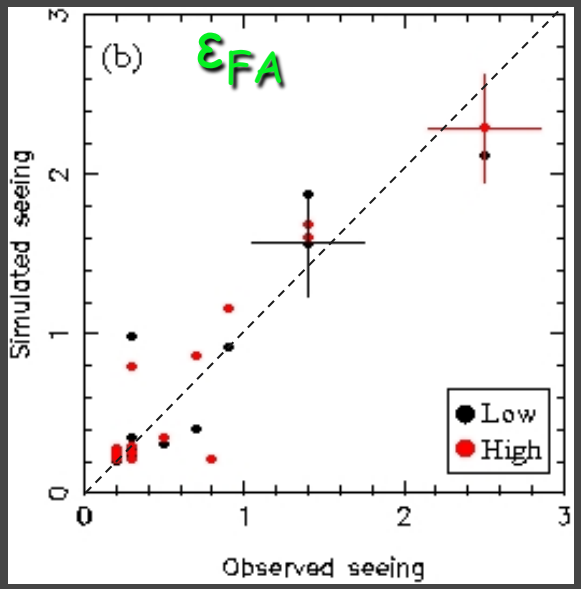
$$\varepsilon_{FA} \sim \left(\int_{h_{sl}}^{h_{top}} C_N^2(h)dh \right)^{-3/5}$$

High resolution - ΔX=1km

STAT	OBS (")		SIM (")	
	ε_{TOT}	ε_{FA}	ε_{TOT}	ε_{FA}
median	1.60	0.30	1.70	0.30
σ	0.70	0.70	0.77	0.67

very good correlation





● : grid-nesting and high resolution (1km)

● : monomodel and low resolution (100km)

Lascaux et al., 2010, MNRAS

ANTARCTICA: RESULTS

Lascaux et al., 2011, MNRAS

	h_{sl} (m)	σ	$\sigma/\sqrt{N}$	ε_{FA} (arcsec)	σ	$\sigma/\sqrt{N}$	ε_{TOT} (arcsec)	σ	$\sigma/\sqrt{N}$
Observations – Dome C	35.3	19.9	5.1	0.30	0.70	0.20	1.60	0.70	0.20
Meso-NH – Dome C	44.2	24.6	6.6	0.30	0.67	0.17	1.70	0.77	0.21
Meso-NH – Dome A	37.9	30.2	8.1	0.23	1.08	0.28	2.37	1.03	0.27
Meso-NH – South Pole	165.0	67.3	17.4	0.36	0.43	0.11	1.82	0.90	0.23

15 nights

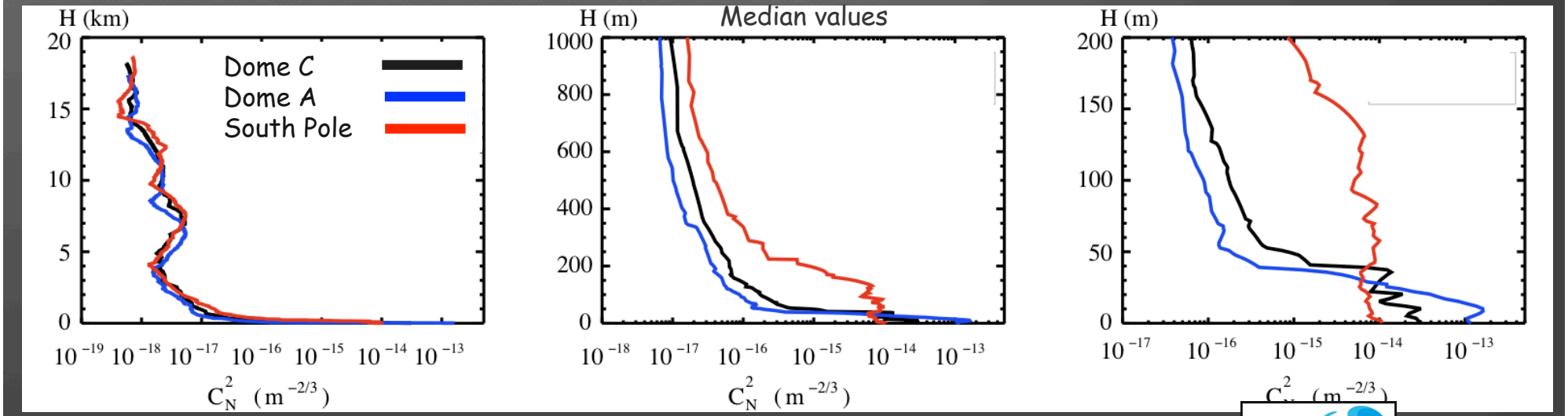
ΔX=1km

MEASUREMENTS

- South Pole: h_{sl}=220m
  ε_{TOT}=1.86arcsec
  ε_{FA}=0.37 arcsec

Marks et al. 1999 - balloons C_N^2

- Dome A: still NO seeing measurements (expected best site in the world…)



ANTARCTICA: RESULTS

Lascaux et al., 2011, MNRAS

	h_{sl} (m)	σ	$\sigma/\sqrt{N}$	ε_{FA} (arcsec)	σ	$\sigma/\sqrt{N}$	ε_{TOT} (arcsec)	σ	$\sigma/\sqrt{N}$
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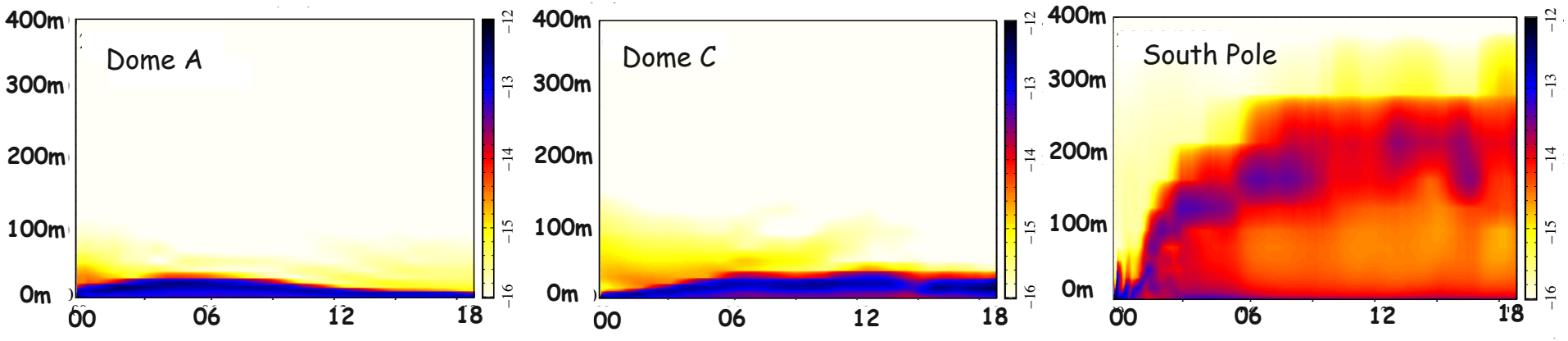
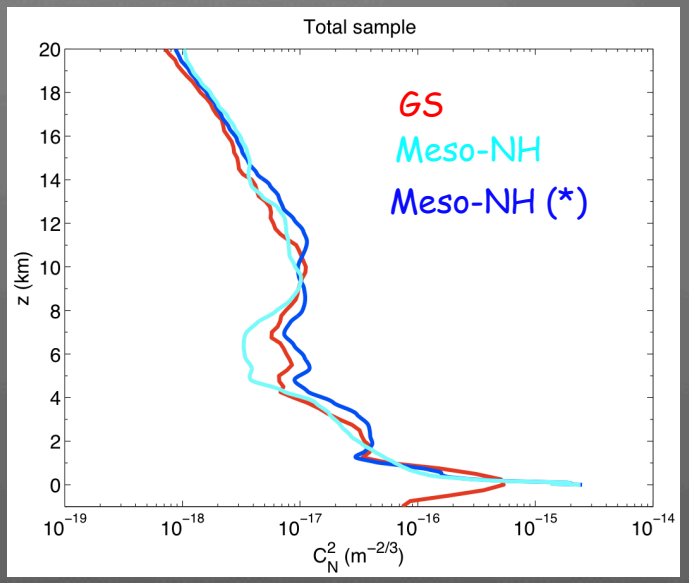
C_N^2 temporal evolution



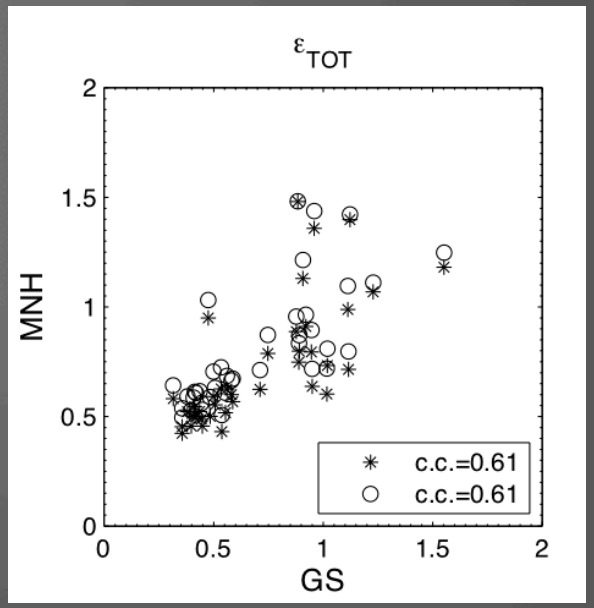
Mt. GRAHAM: RESULTS

Hagelin et al., 2011, MNRAS

Generalized Scidar 41 nights - uniformly distributed in the year

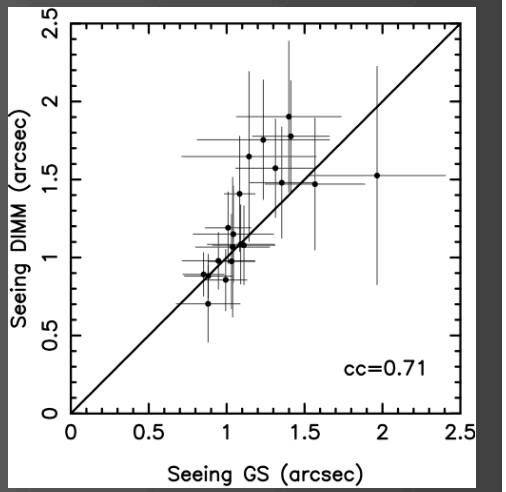


C_N^2 average



* Meso-NH

o Meso-NH (*)

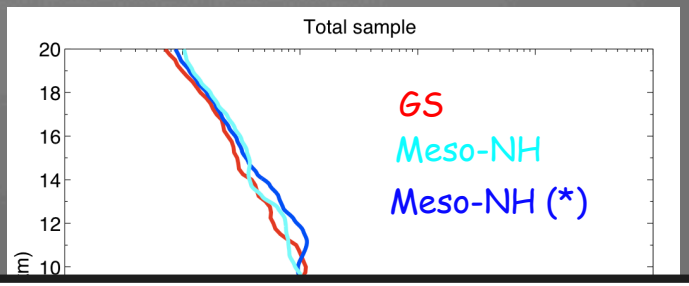


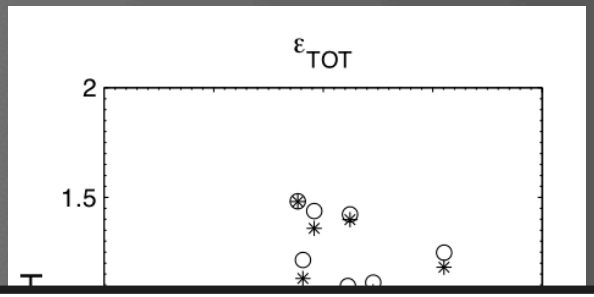
PARANAL – 20 nights
GS vs. DIMM

Mt. GRAHAM: RESULTS

Hagelin et al., 2011, MNRAS

Generalized Scidar 41 nights - uniformly distributed in the year





* Meso-NH

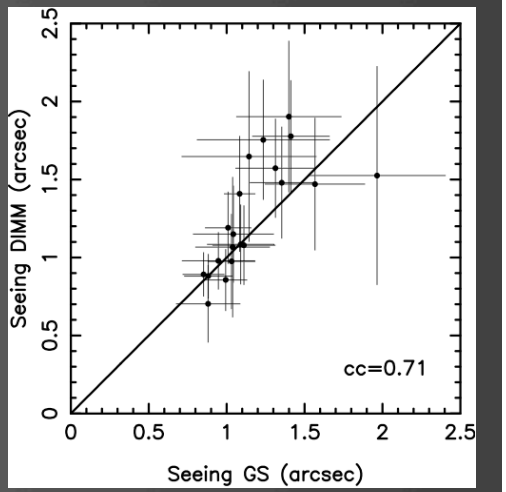
o Meso-NH (*)

TOTAL SAMPLE

	Relative error (%)			
	$\Delta\varepsilon_{TOT}$	$\Delta\varepsilon_{BL}$	$\Delta\varepsilon_{FA}$	
Total	3.6	9.2	0.4	41 nights
Summer	13.5	11.6	13.0	15 nights
Winter	10.1	14.9	6.3	26 nights

GS: dome seeing subtracted from the boundary layer

MNH: first 20 m subtracted from the boundary layer
(20m = height of the telescope)



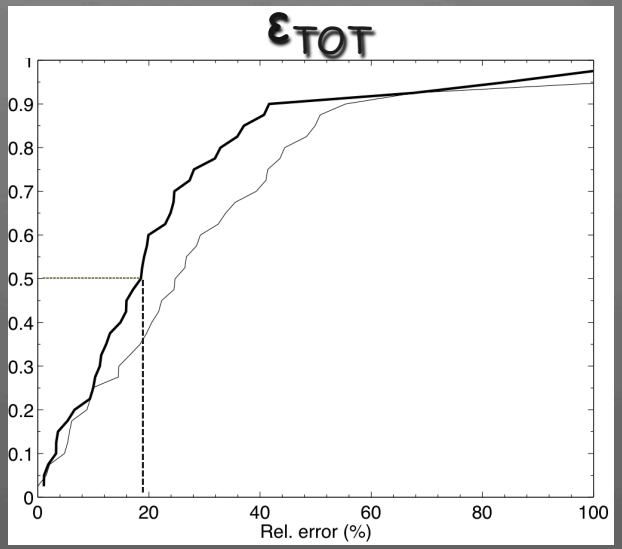
PARANAL – 20 nights
GS vs. DIMM

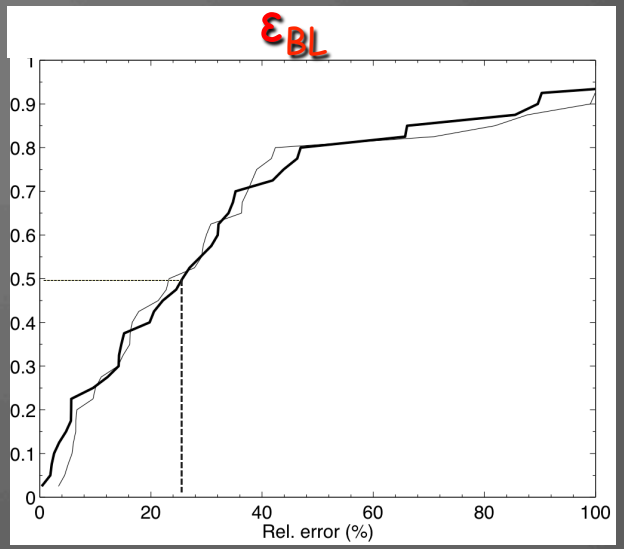
FORÔT

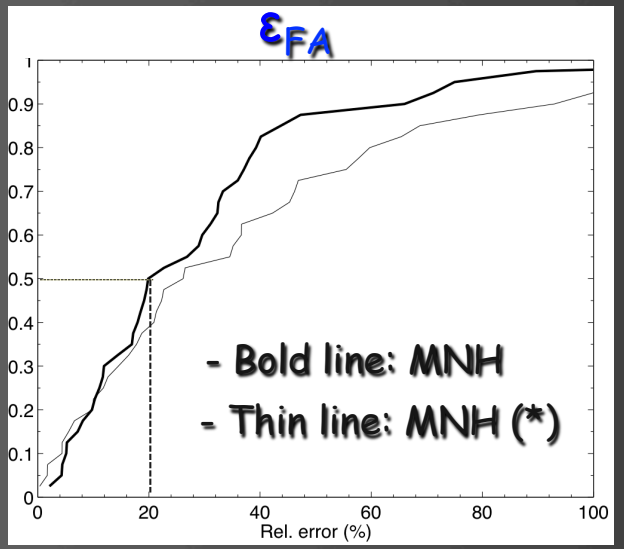
Mt.GRAHAM: RELATIVE ERROR – SINGLE NIGHTS

Hagelin et al., 2011, MNRAS

Cumulative distribution of the relative error for single nights







18.7% 26.3% 20%

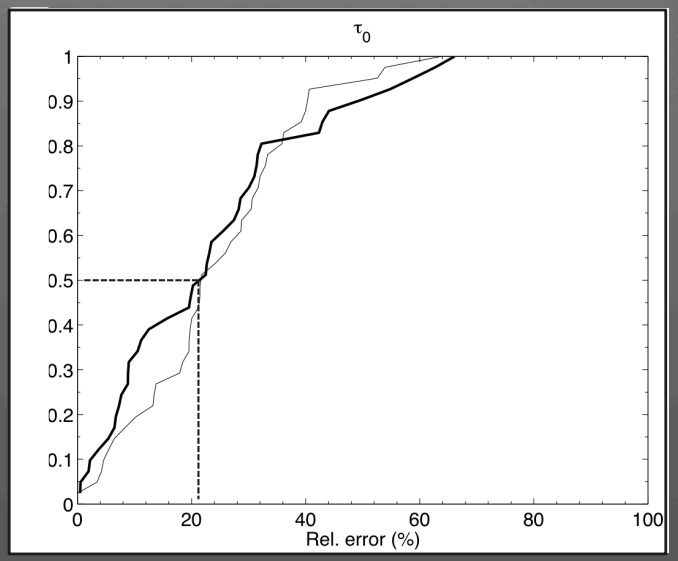
Dispersion comparable to that obtained with different instruments running simultaneously

see review Masciadri, 2011: Seeing Clearly: The Impact of the atmospheric turbulence on the propagation of extraterrestrial radiation, Ed. Businger – Cherubini, Virtual Book, Worm Publishing

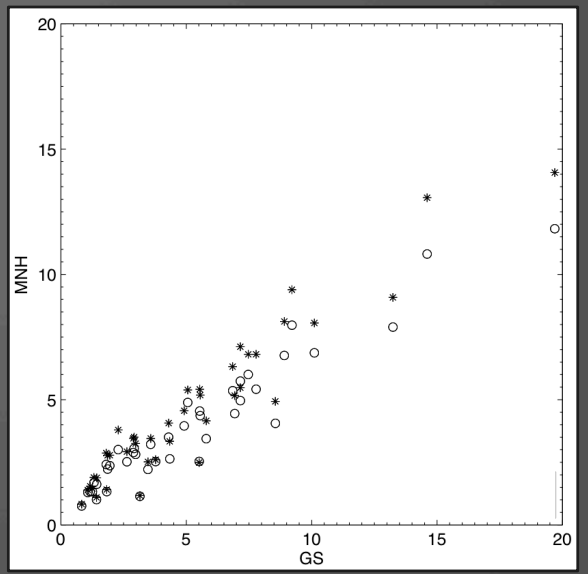
Mt.GRAHAM: RELATIVE ERROR – SINGLE NIGHTS

Cumulative distribution of the relative error for single nights

Wavefront coherence time τ_0



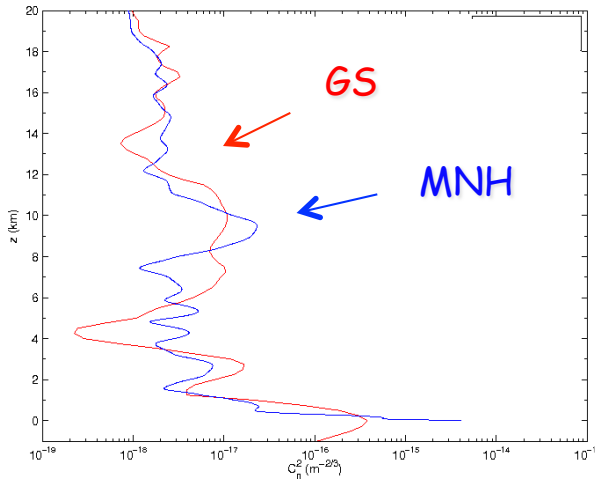
22.5%



- cc=0.96
- cc=0.95

Hagelin et al., 2011, MNRAS

Mt. Graham – Night of 2/2008

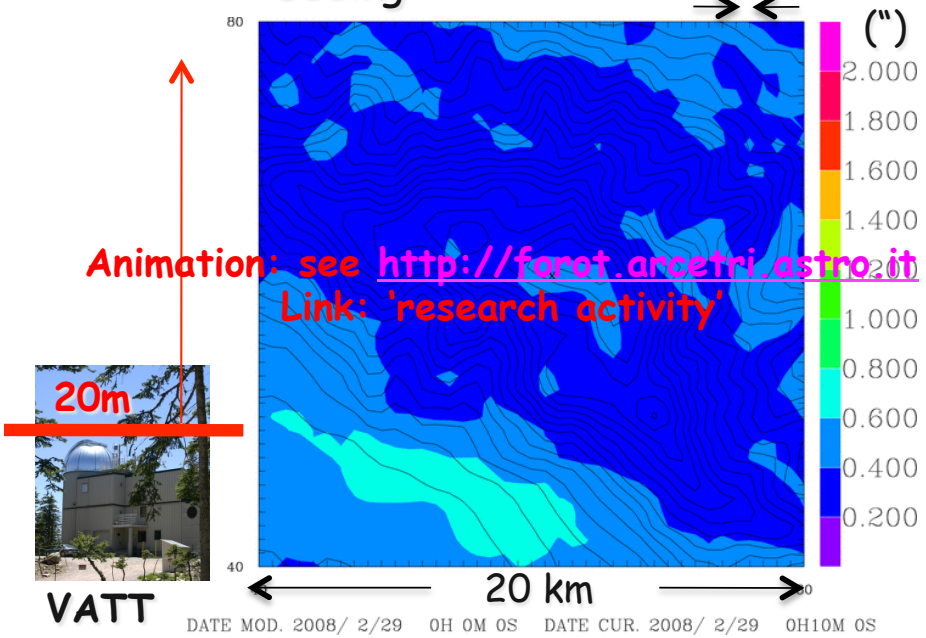


average

ε_{MNH} = 0.57″

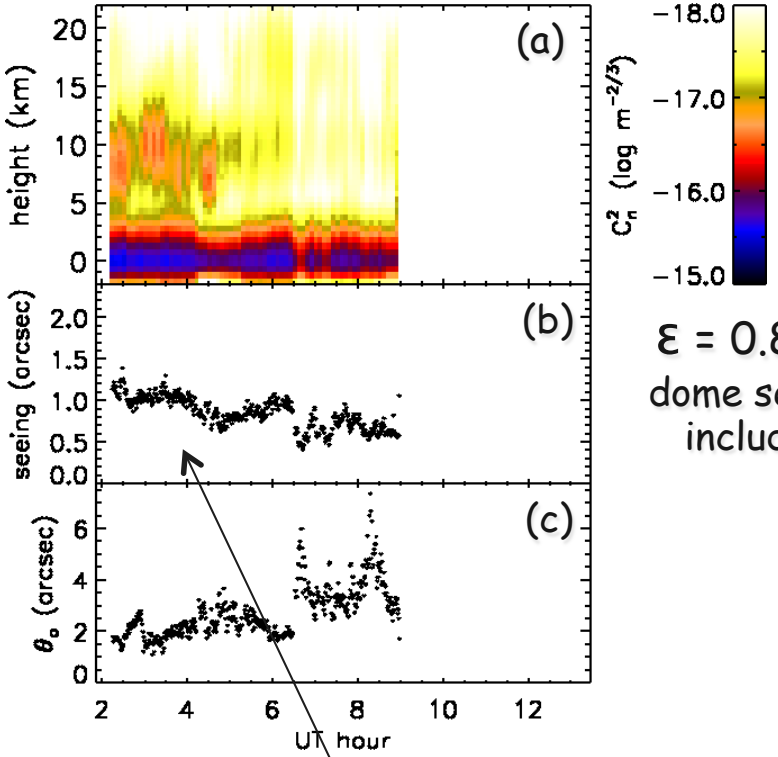
seeing

Δx=500m



Animation: see http://forot.arcetri.astro.it
Link: 'research activity'

Generalized Scidar MEASUREMENTS



ε = 0.86″
dome seeing included

(a) Temporal evolution of the optical turbulence vertical distribution (C_N^2 profiles).
(b) Temporal evolution of the seeing ε
(c) Temporal evolution of the isoplanatic angle θ_0

average

ε_{GS} = 0.53″

dome-seeing excluded

SIMULATIONS with the non-hydrostatic atmospherical meso-scale model (Meso-Nh)

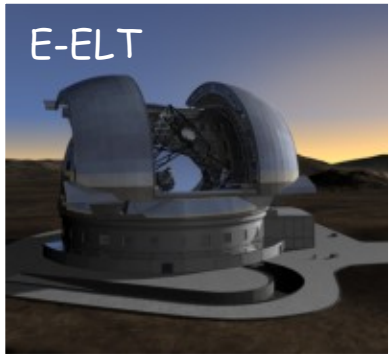
ΔT=12 hours: (00:00 - 12:00) UT; sampling=10 min

On-going project: MoSE MOdeling ESO Sites

Cerro Paranal

GOAL

Feasibility study to set-up a system for the ***forecast*** of the ***Optical Turbulence*** (C_N^2) and all the main integrated astroclimatic parameters (ε, θ_0, τ_0)



Cerro Armazones

OVERCOME MAJOR LIMITATIONS

1) Difficulty in having **independent samples** of measurements for the model calibration and model validation to estimate **if** and **how** the correlation between calculations/measurements decreases with increasing the number of nights

2) Difficulty in having a large number of **simultaneous measurements** done with different and independent instruments for the OT estimate (vertical profilers) to quantify the model score of success

CONCLUSIONS

- The OT forecast is definitely an ***'accessible goal'*** for the near future.

- Excellent results have been already obtained on different time scales (months and single nights) for some parameters (***seeing*** and τ_0).
- It has been proved that a meso-scale model can provide an exhaustive reconstruction of the C_N^2 (from a qualitative and quantitative point of view).
- Models prediction scores are not worse than the accuracy achieved using different instruments.
- The most important limitation to overcome is, at present, the improvement of the temporal variability in the high part of the atmosphere. This limitation affects mainly the prediction of the ***isoplanatic angle*** and the ***free atmosphere seeing***
- On-going studies on the parameterization (algorithms) for the C_N^2 to improve model performances
- We expect an important step ahead from ***MOSE*** projec

ACKNOWLEDGEMENTS

This work has been funded by the "*Marie Curie Excellence Grant* ForOT "
MEXT-CT-2005-023878