Dealing with Ionospheric Complexity

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2nd International Conference and Exhibition on
Satellite & Space Missions
July 21-23, 2016 Berlin, Germany

PLAN OF THE TALK

- **EARHT'S IONOSPHERE AND THE HUMANS: IONOSPHERIC VARIABILITY AS A PROBLEM FOR HUMAN ACTIVITIES**

- **THE GEOSPACE AS A COMPLEX SYSTEM: LIMITS OF IONOSPHERE'S PREDICTABILITY AS A BYPRODUCT OF ITS COMPLEXITY**

- **OBSERVING PROPERLY LOCAL IRREGULARITY (MULTI-SCALE ANALYSIS OF VERTICAL TEC)**

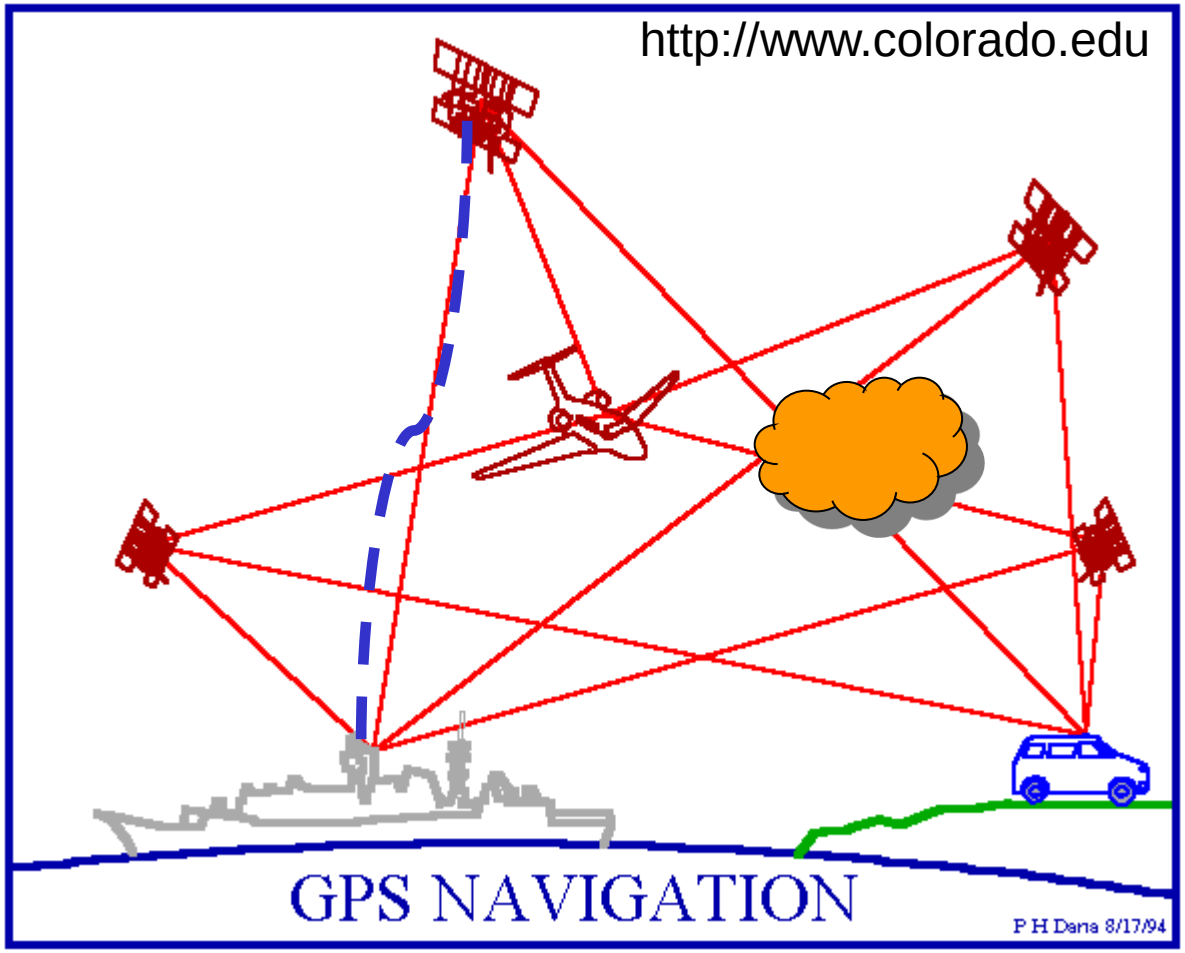
- **DEALING WITH GLOBAL COMPLEXITY AND PREDICTABILITY: PREDICTIVE SPACE WEATHER VIA INFORMATION THEORY**

- **CONCLUSIONS: WHAT STAKEHOLDERS SHOULD INVEST ON**

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- **EARHT'S IONOSPHERE AND THE HUMANS: IONOSPHERIC VARIABILITY AS A PROBLEM FOR HUMAN ACTIVITIES**

- **HOW EARHT'S IONOSPHERE AFFECTS HUMAN ACTIVITIES (e.g. on GNSS)**



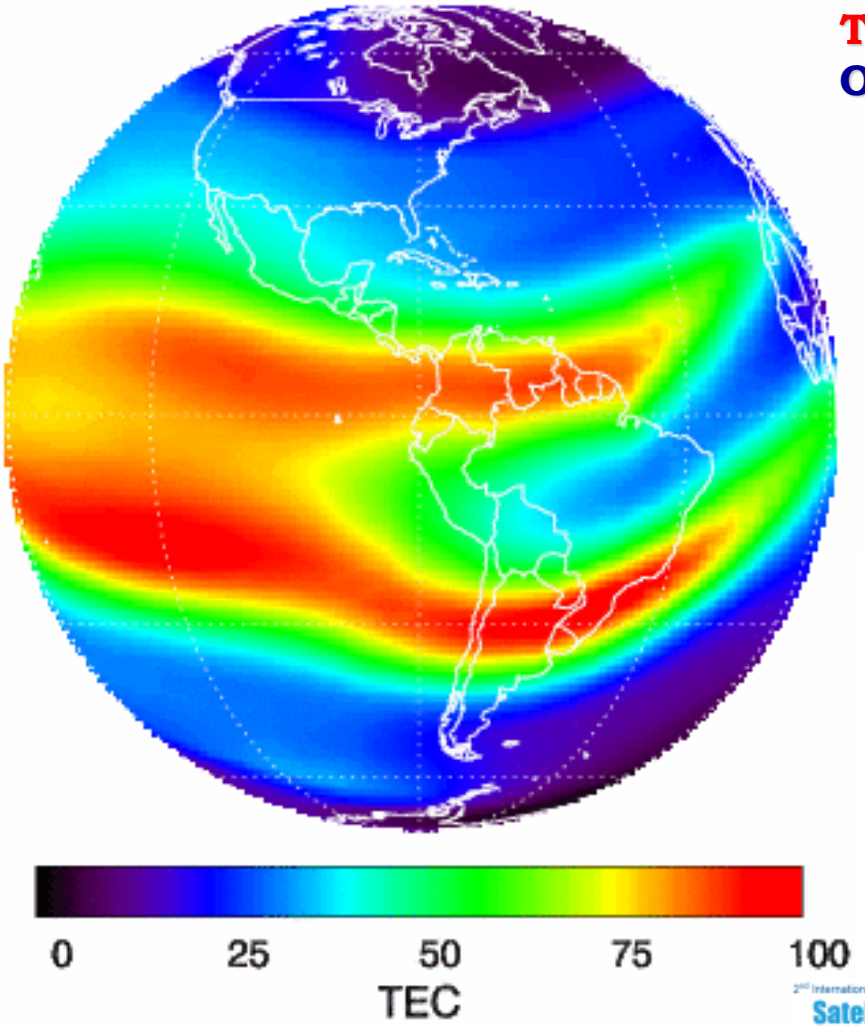
$$n = n_0 + \delta n$$

- IONOSPHERE CAN INTRODUCE BOTH RANGE ERRORS ("SMOOTH" GRADIENT EFFECTS), DUE TO THE EFFECTIVE OPTICAL PATH LENGTH...

- ...AND CYCLE SLIPPING AND LOSS OF LOCK ("ROUGH" EFFECT), DUE TO SMALL SCALE IRREGULARITY, PRODUCED BY TURBULENCE: RADIO SCINTILLATION

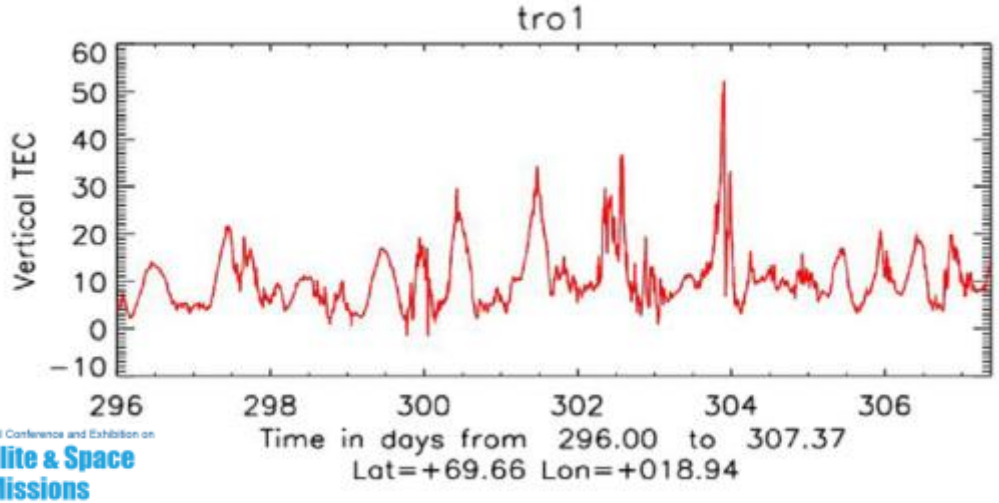
IONOSPHERIC VARIABILITY: TIME VARIABILITY OF THE VERTICAL TOTAL ELECTRON CONTENT (A PROXY OF IONIZATION AND RANGE ERRORS)

$$T_\gamma(t) = \int_\gamma N(\vec{x}, t)\, d\ell$$



THE TEC VARIABILITY ACCORDING TO "DETERMINISTIC" (1° PRINCIPLES OR EMPIRICAL) MODELS (CPI.COM)...

...OR TO REAL DATA:



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THE SENSIBLE, AND NOT AT ALL SILLY, QUESTION IS:



- IONOSPHERIC PROXIES ARE CLASSICAL PHYSICS THINGS…
- NO "FUNDAMENTAL" PROBABILISTIC LAWS ARE EXPECTED TO PALY A ROLE…
- SO, GIVEN THE "PRECISE" HELIO-GEOPHYSICAL CONDITIONS ONE SHOULD HAVE THE SAME DYNAMICS…
- …SHOULDN'T ONE?

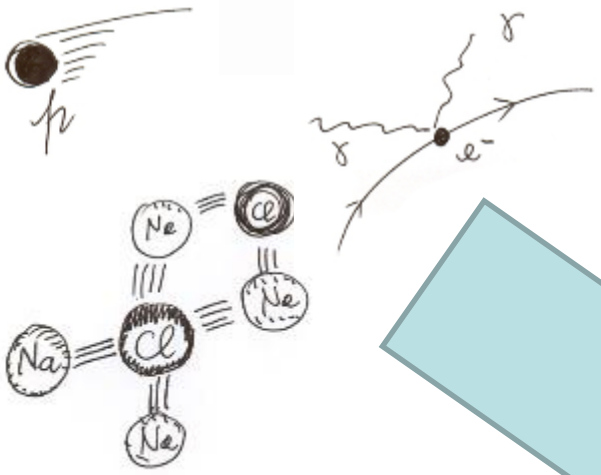
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"A ***complex*** *physical system is a* ***classical composite*** *system whose* ***macroscopic*** *quantities* ***do not*** *evolve* ***smoothly*** *and* ***deterministically*** *as the equilibrium statistical physics would predict"*

Origin of complexity…



Composite systems can be "non complex" only under very strong hypotheses (equilibrium, weak and short-range interactions, negligibility of extreme events), widely used in "traditional" statistical mechanics…





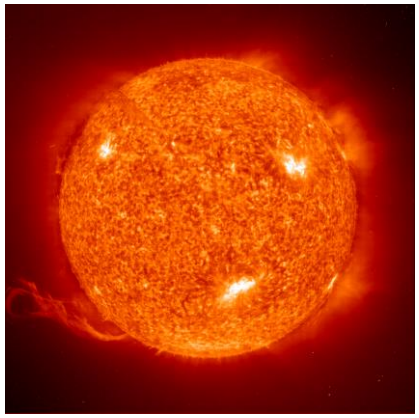
…but very rarely met in nature, and in particular in the helio-geophysical system!

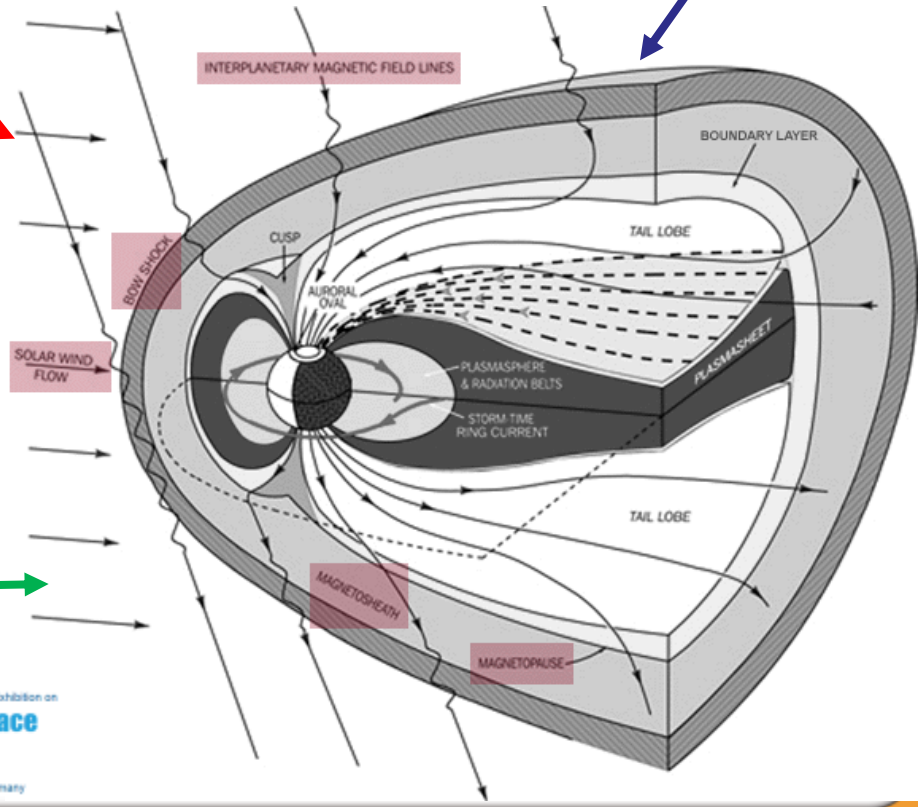
Failure of the "traditional" approach hypotheses yields (macroscopic) stochasticity, formation of hierarchical patterns, multi-scale dynamics

THE GEOSPACE

patterns

(macroscopic) stochasticity

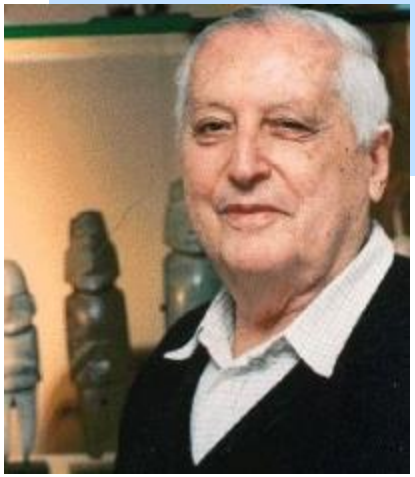




multi-scale

GEOSPACE COMPLEXITY DEMANDS A NEW THEORETICAL APPROACH

Iliya Prigogine's Phylosophy:



Highly unstable non-linear dissipative systems may be treated as probabilistic dynamical systems, intrinsically irreversible

$$\dot{X} = f(X, Y, t, \xi),$$

$$\partial_t P = F(P, \partial_X P, X, Y).$$

The Speaker's point of view: the Geospace quantities undergo a probabilistic dynamics, intrinsically conditioned by noises coming from "microscopic levels" and "external forcings".

Langevin and Fokker-Planck equations should be used...

PLAN OF THE TALK

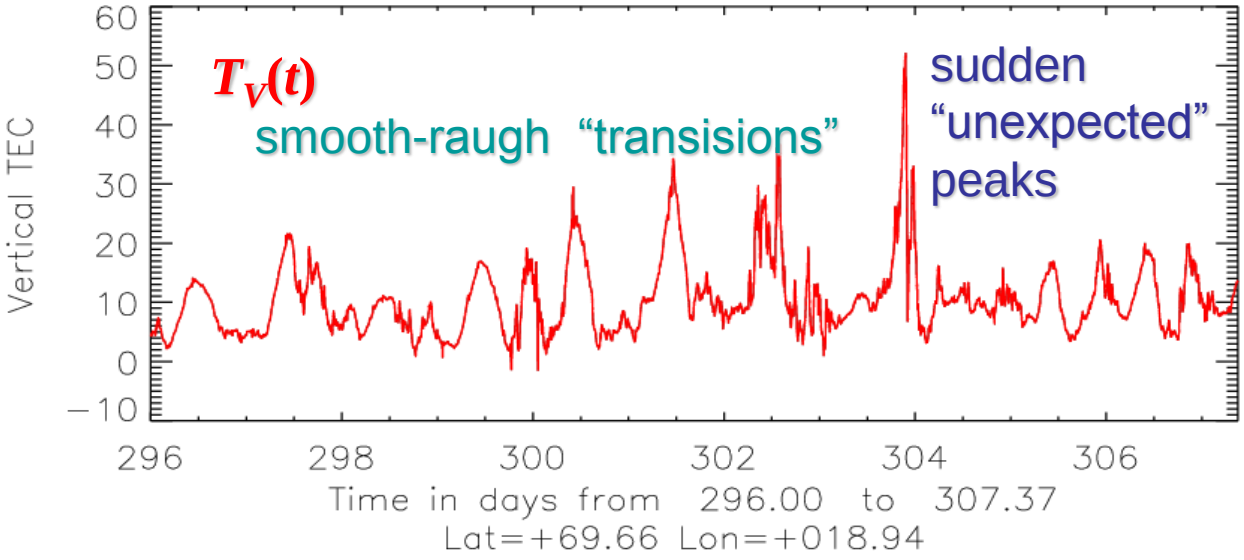
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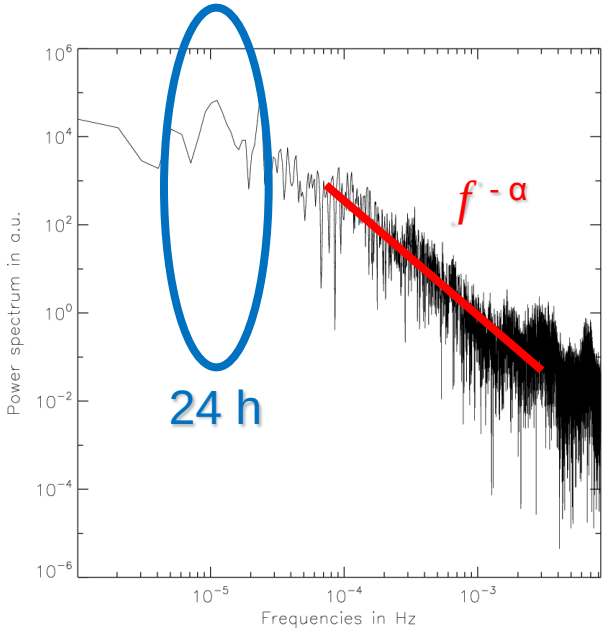
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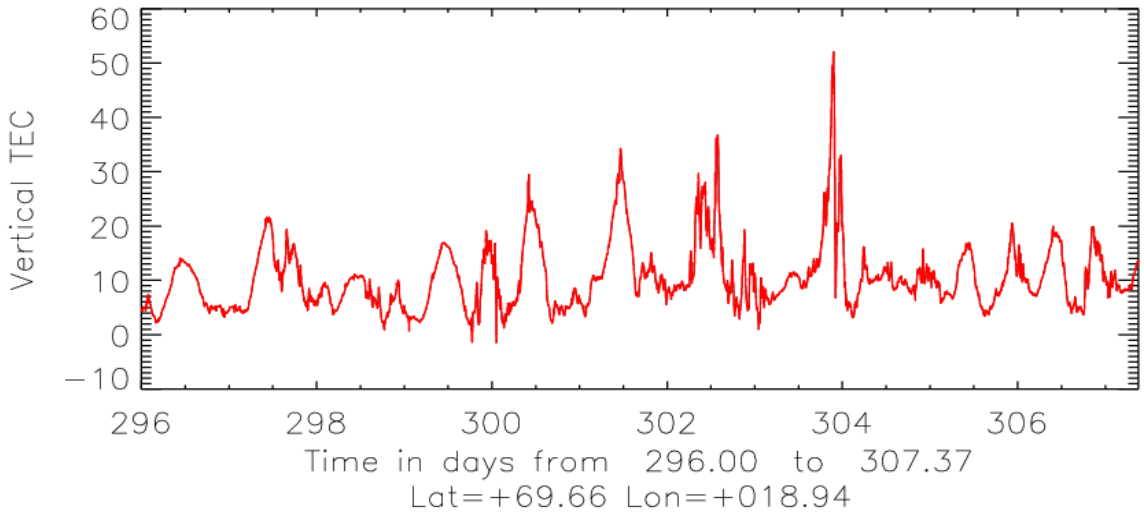
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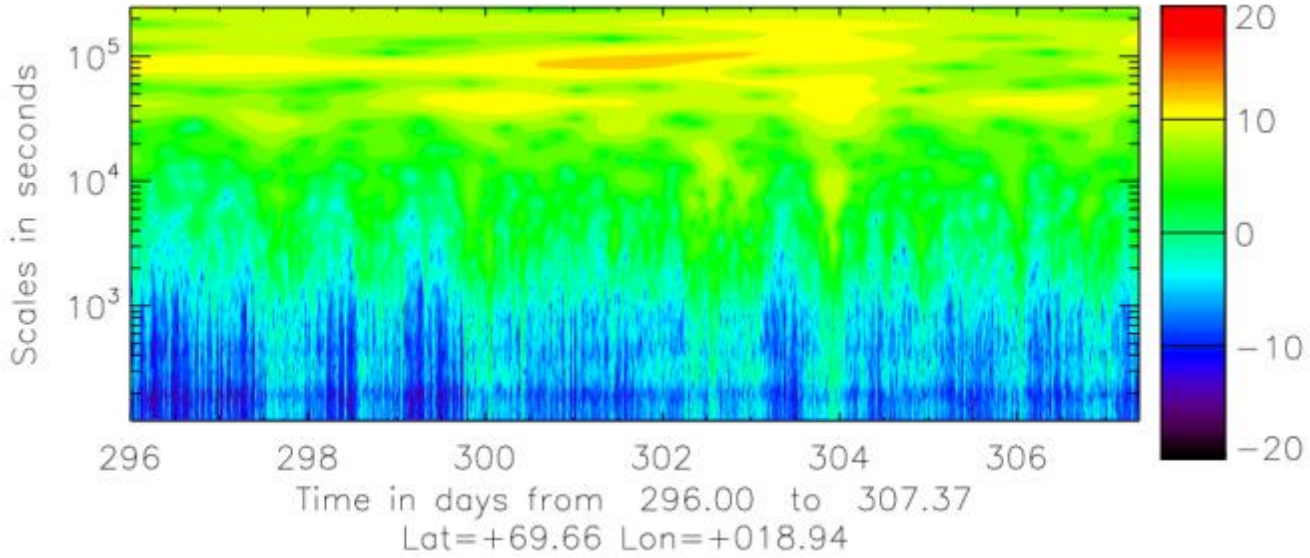
Time evolution of the vertical total electron content (TEC) on the top of GPS ground station located in Tromsø, 69.66N, 18.94E, days 296 to 308 of year 2003 (from October 23 to November 3), including the days of the "2003 Halloween Storm".

(1' IGS data, after single-station "verticalization" by Luigi Ciraolo of IFAC-CNR Institute, Italy)





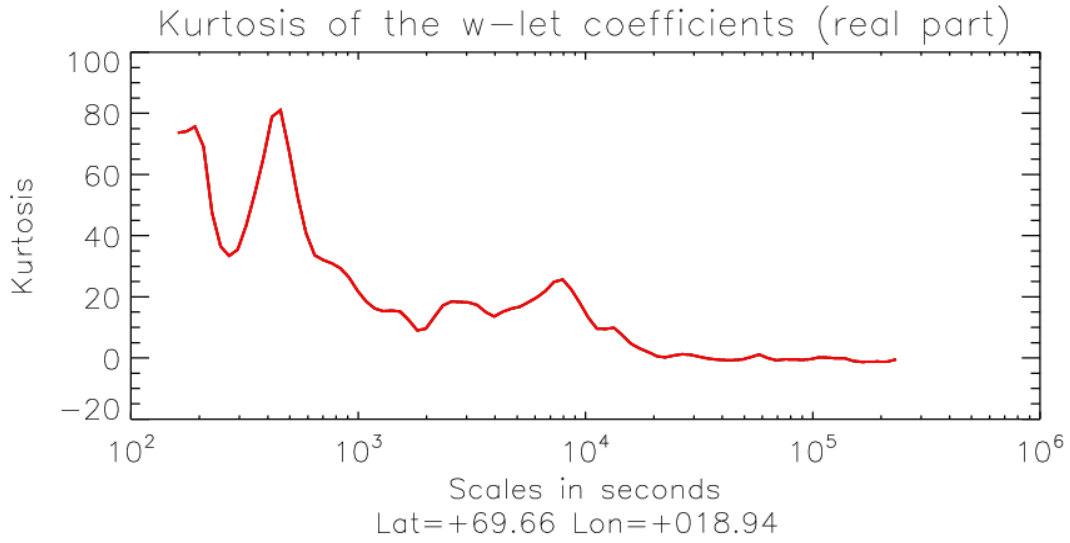




- **Multi-scale analysis**

Wavelet decomposition - the peaks of TEC appear as enhancement of "power" distributed over many time scales (peaks have a fine structure).

Scale-dependent statistics of the TEC fluctuations



Kurtosis of fluctuations: the TEC is intermittent. Extreme events grow more and more important for smaller and smaller time scales, but this "scale-covariance" depends on location (hence, on local geophysics). Coherent structures.

PLAN OF THE TALK

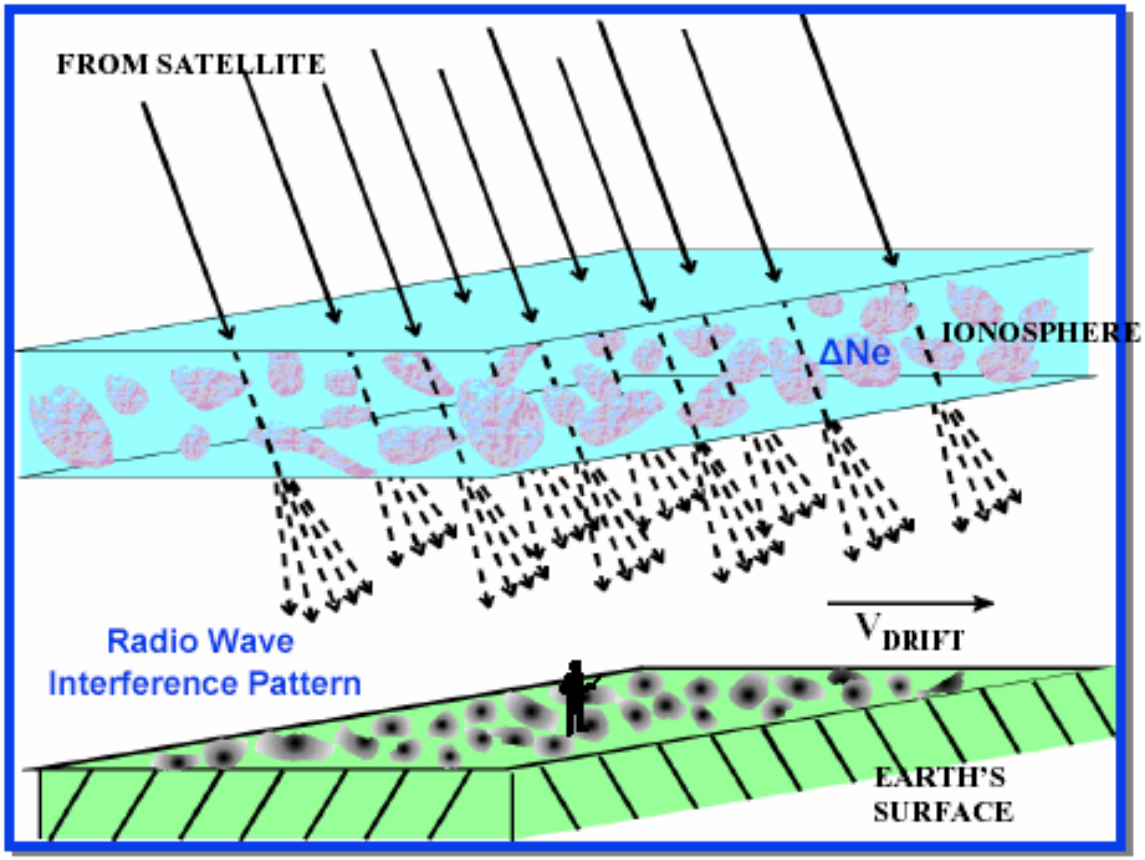
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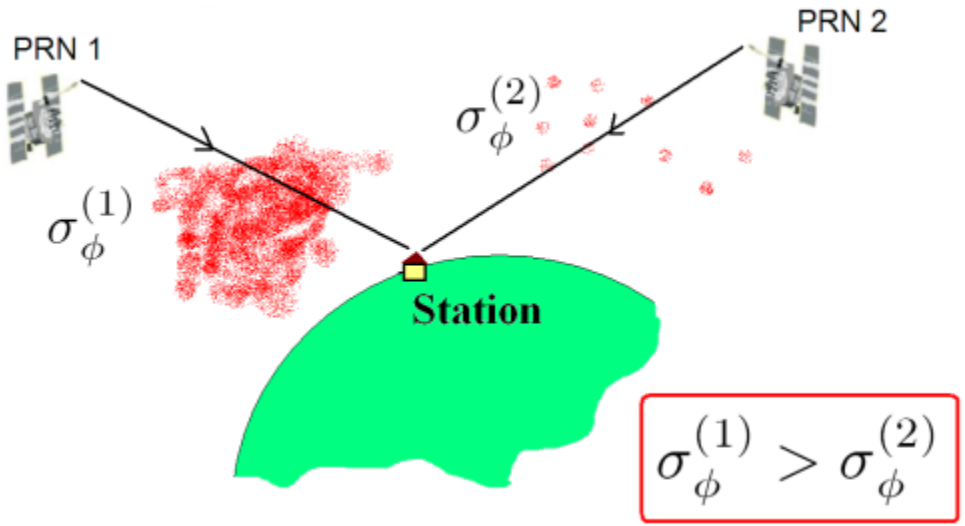
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THE ISSUE OF PREDICTABILITY: DELAY OF RADIO SCINTILLATION WITH RESPECT TO THE SUN'S FORCING (SOLAR WIND)



Small scale irregularities of the ionospheric medium, due to turbulence, cause erratic perturbations of radio signals, both in amplitude and phase, yielding loss-of-lock and cycle slip:

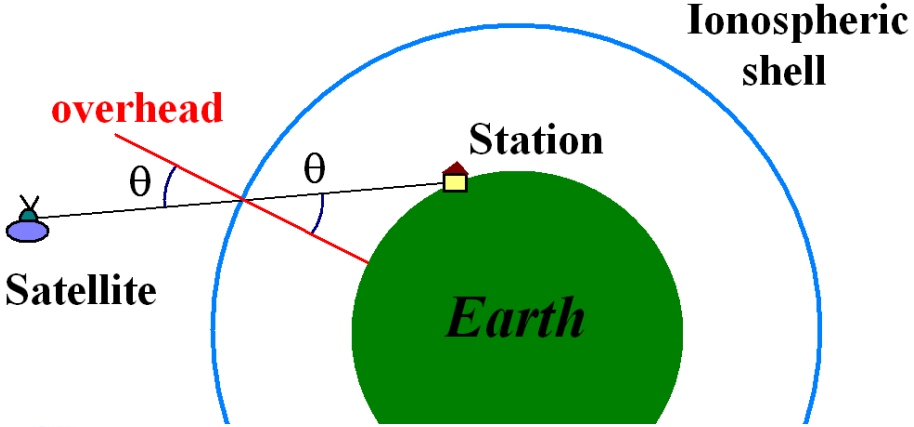
S_4 σ_ϕ



Due to the patchy nature of radio scintillation, scintillation indices do not describe the "state of scintillation" on the top of a location, but just along the radio link raypath

Definition of an effective scintillation index on the top of a station:

$$\sigma_\phi(t) = \sqrt{\sum_{i=1}^{N(t)} \frac{\cos\vartheta(t)}{N(t)} \left(\sigma_\phi^{(i)}(t)\right)^2}$$



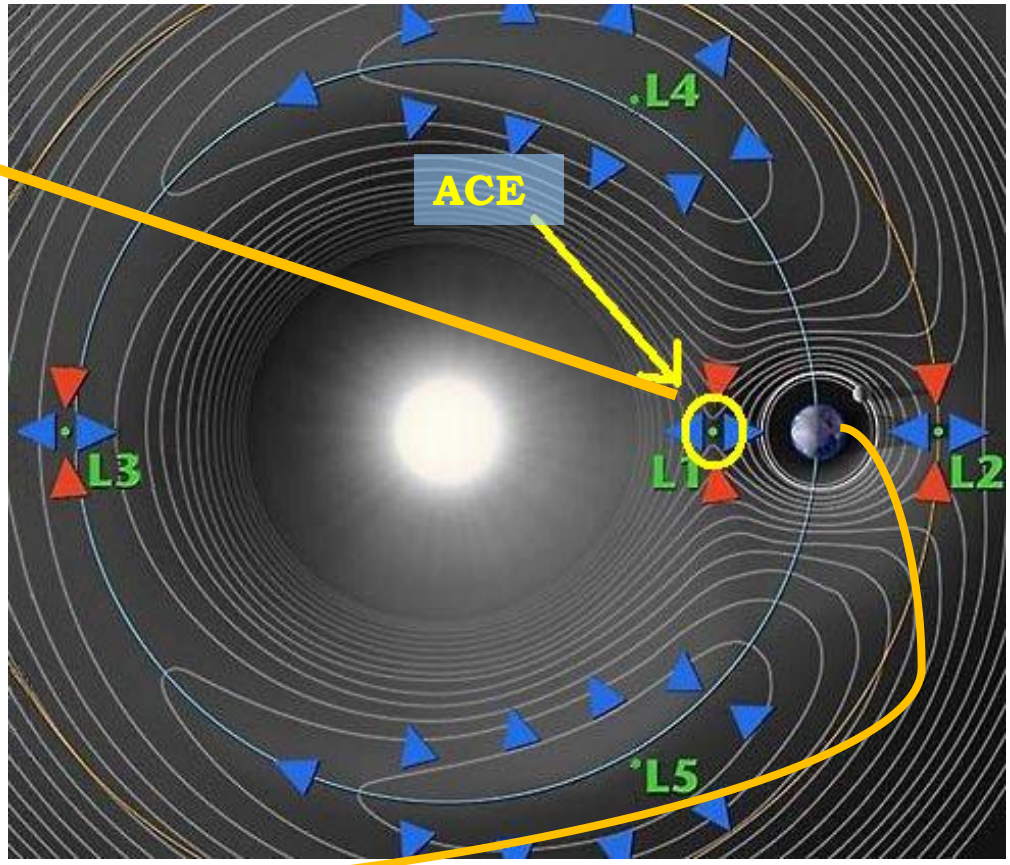
$$B_z(t), \quad N_i(t)$$

Link the features of the Sun-Earth forcing with those of the irregular ionosphere

Putting together Solar-Wind time series…

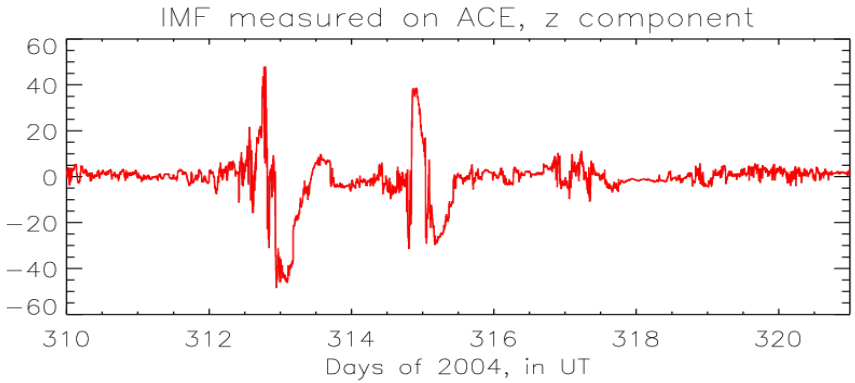
…and the time series describing GPS phase scintillation.

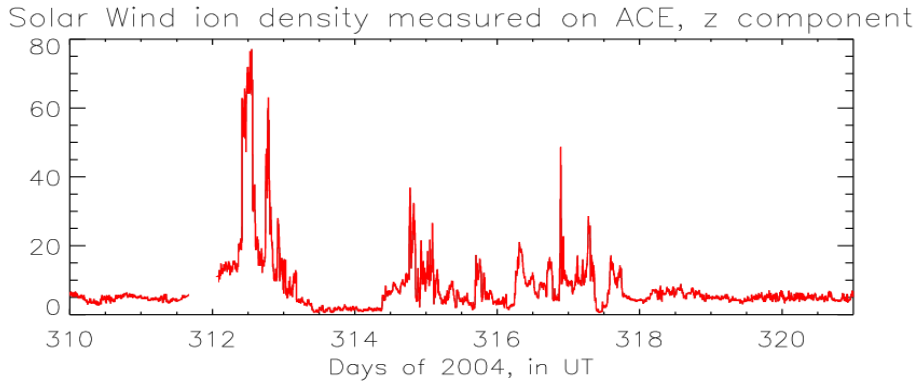
$$\sigma_\phi(t)$$



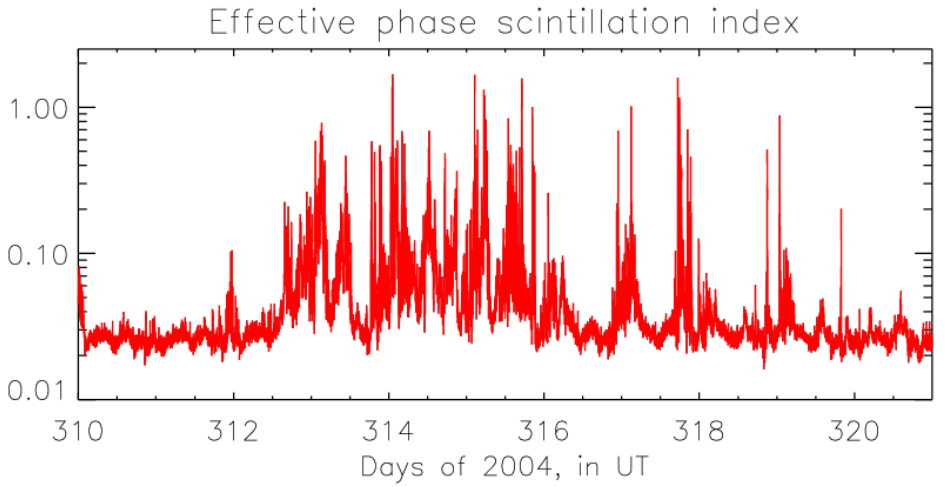
Solar Wind time series: the *z* component of the IMF and the ion density, as measured by the satellite ACE (http://spidr.ngdc.noaa.gov/spidr/).

Period considered: from November 5 to November 15 of 2004.





GPS scintillation data collected with a GSV4004, produced by GPS Silicon Valley, maintained in Tromsø by the University of Bath (UK).



$$\dot{\sigma}_\phi = f\left(\sigma_\phi, Y; \vec{r}, t; \xi\right), \qquad \xi \quad \text{noise}$$

Calculate the causal delay between the Solar Wind dynamical variables and the ionospheric scintillation. This is done via tools from the *information theory* (time delayed mutual information):

$$M\left[Y(t), \sigma_\phi(t+\tau)\right] = I\left[\sigma_\phi(t+\tau)\right] - I\left[\sigma_\phi(t+\tau)\,|Y(t)\right]$$

M. Materassi et al. / Advances in Space Research 47 (2011) 877–885

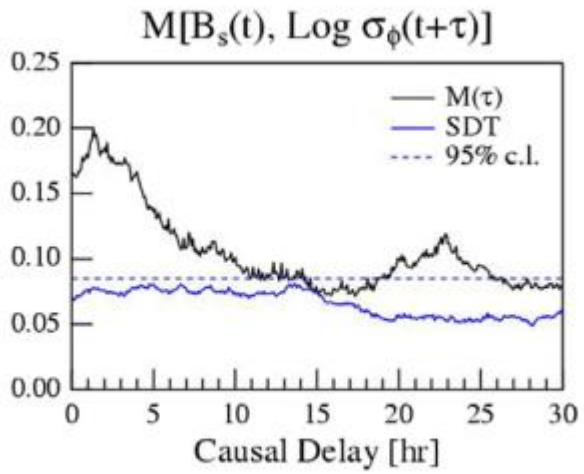


Fig. 1. Time delayed mutual information between solar wind southward IMF and ionospheric phase scintillation. SDT is for surrogate data test.

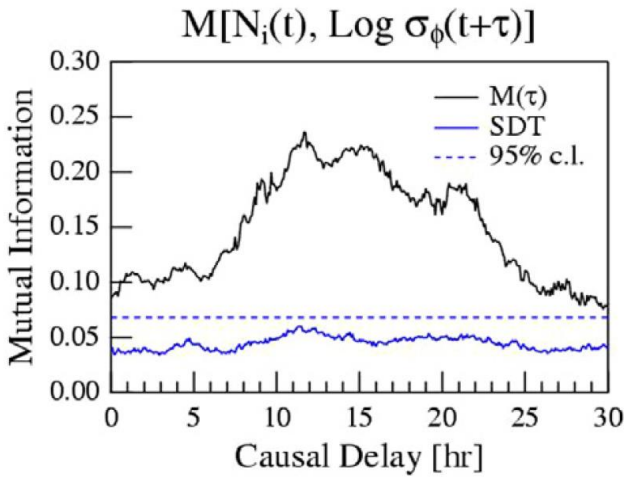


Fig. 2. Time delayed mutual information between solar wind ion density and ionospheric phase scintillation. SDT is for surrogate data test.

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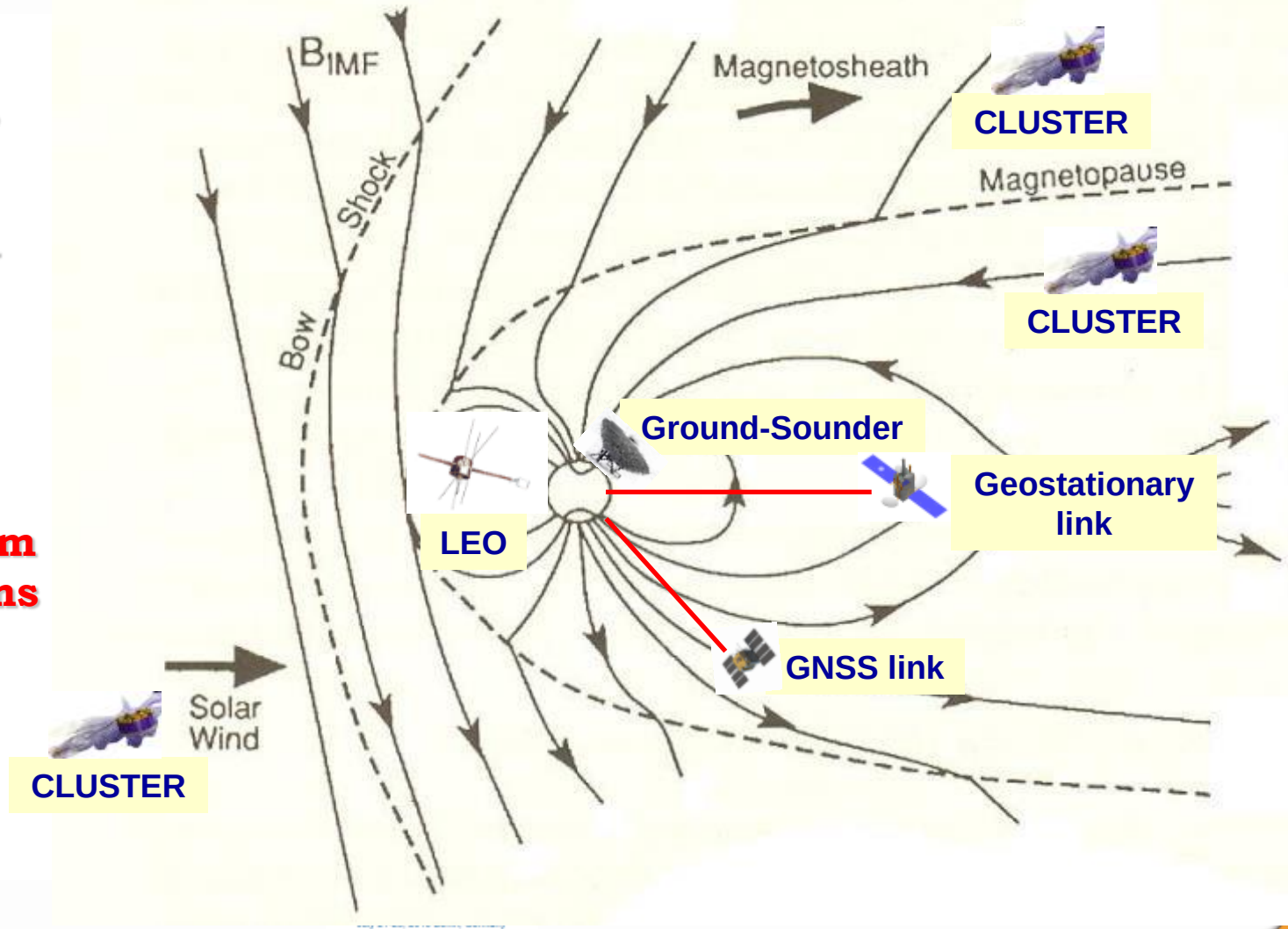
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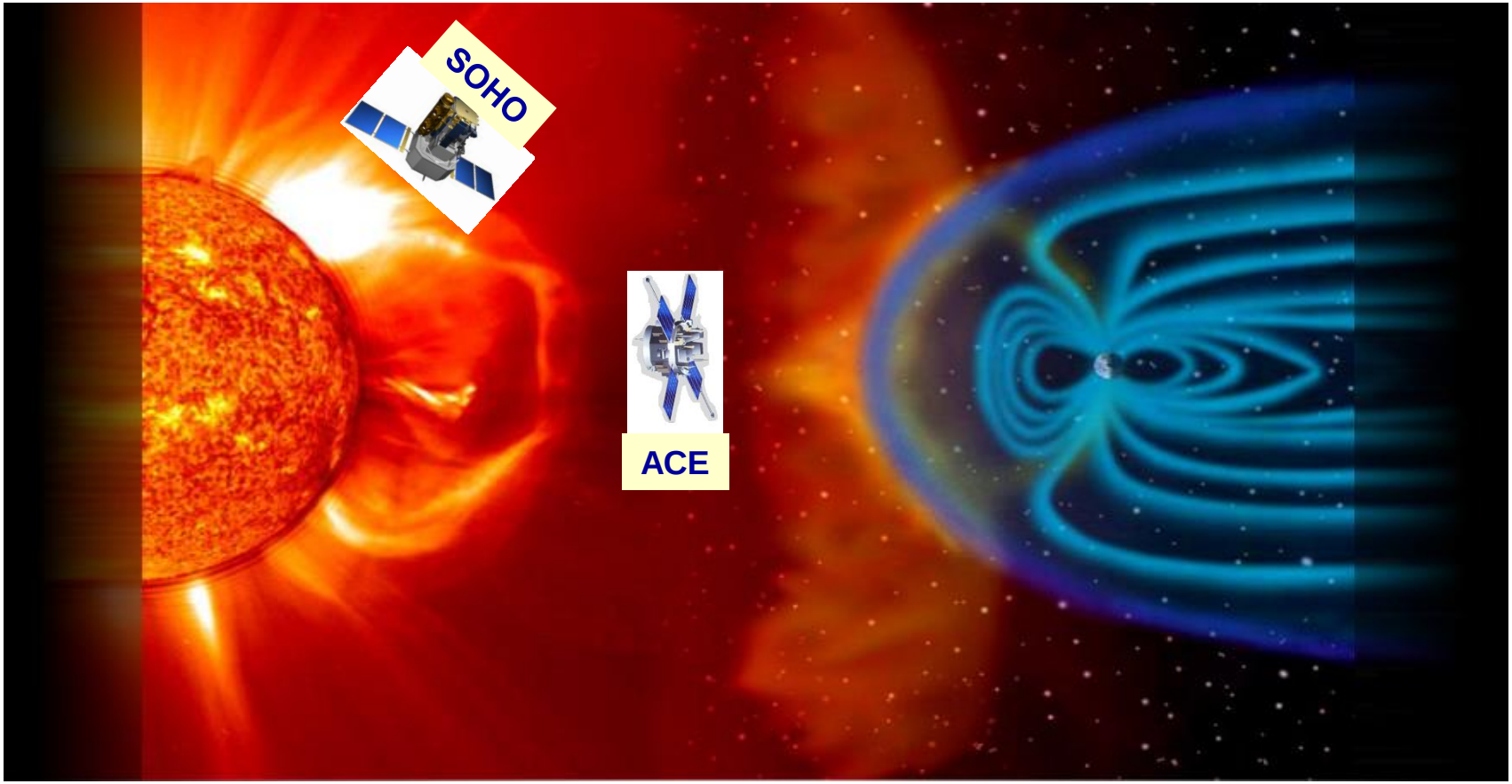
- CONCLUSIONS: WHAT STAKEHOLDERS SHOULD INVEST ON

FEW COMMERCIALS… 1/2

- **Establish wide, strong and open data bases to include as many Sun-Earth-ionosphere data as possible;**
- **Integrate the observations from different missions and commercial systems into a unique multi-instrument approach.**

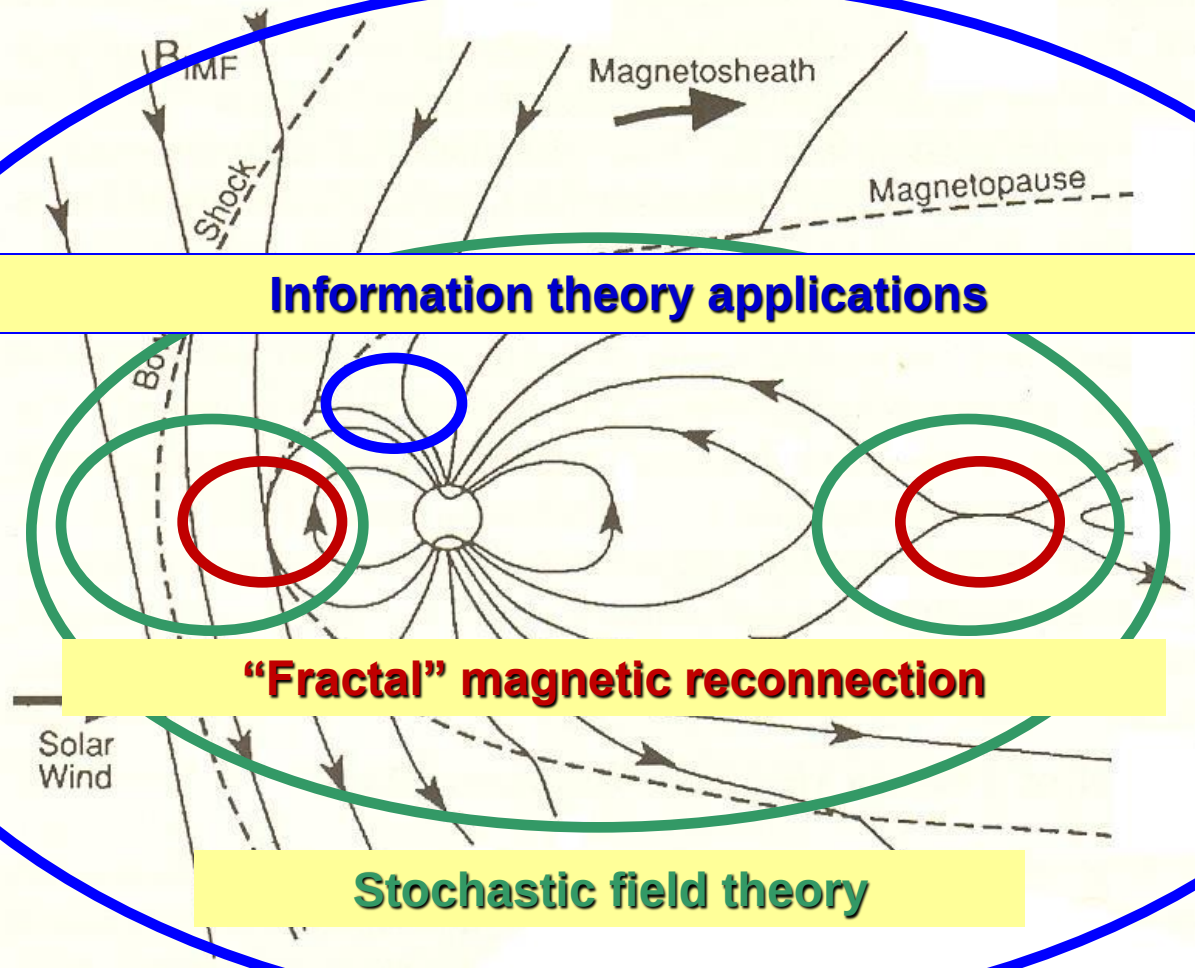


• **Put together different scientific/technical communities: solar and space scientists, ionospheric people, engineers…**



FEW COMMERCIALS… 2/2

• **Promote complexity science:**

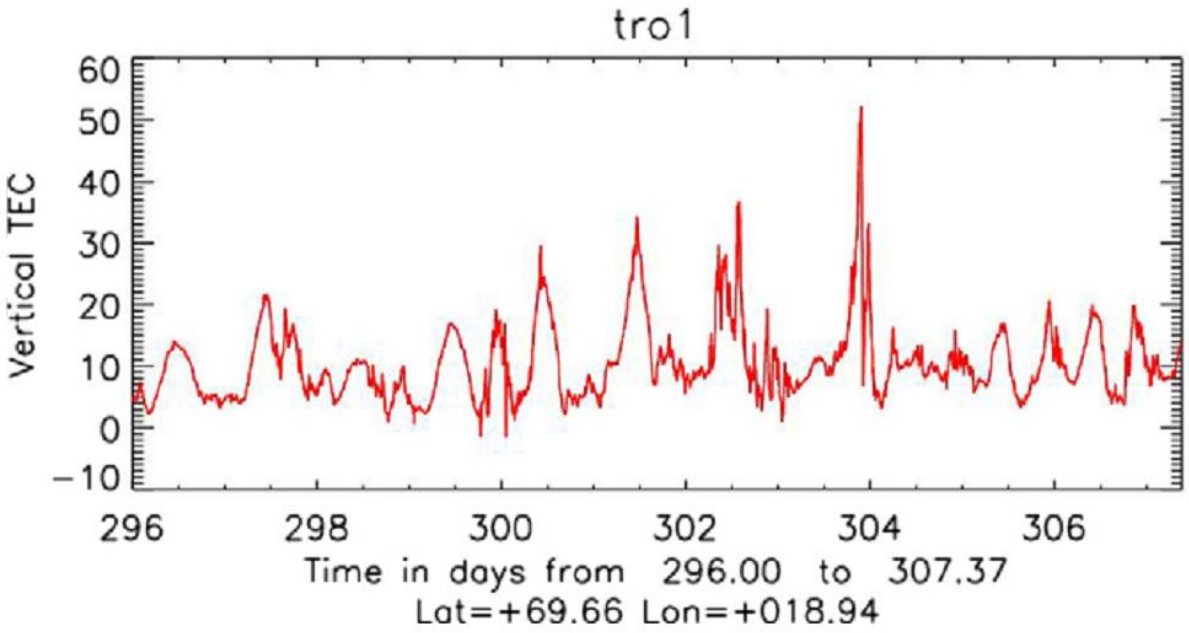


…invest on Universities, public research bodies, private science-oriented fundations!

Thank you for your kind attention!



- **DAY TO DAY (UN)PREDICTABILITY: THE EXTEMPORIZING TEC…**

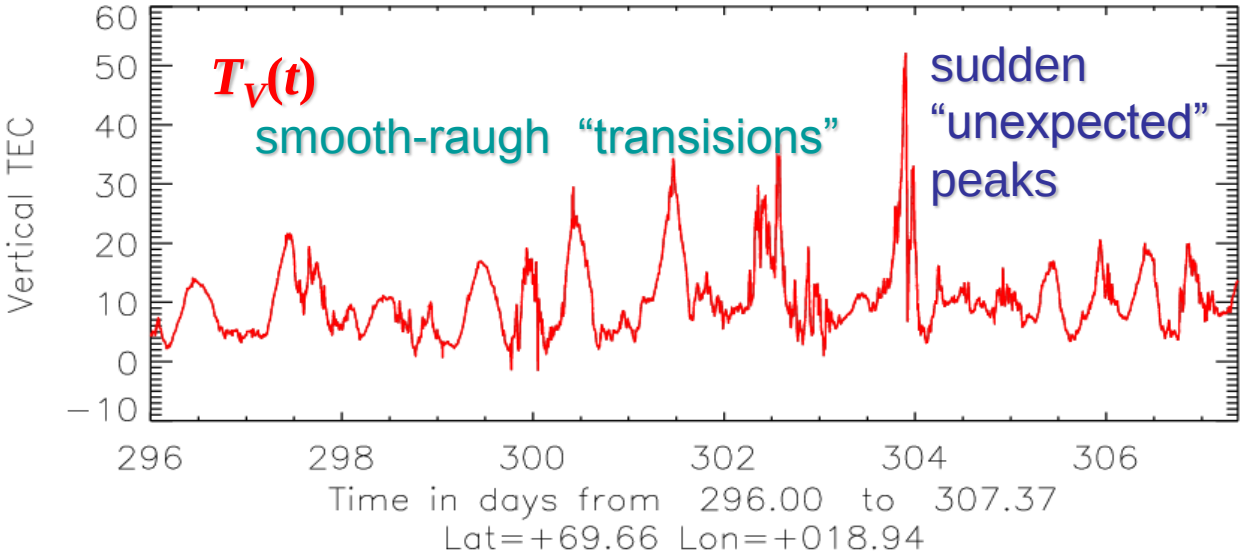


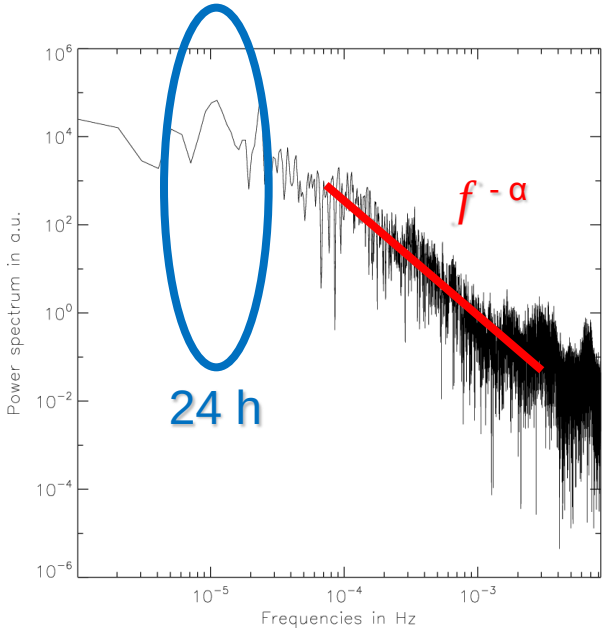
The vertical TEC may be intended as a stochastic process. Each day is a realization of it…

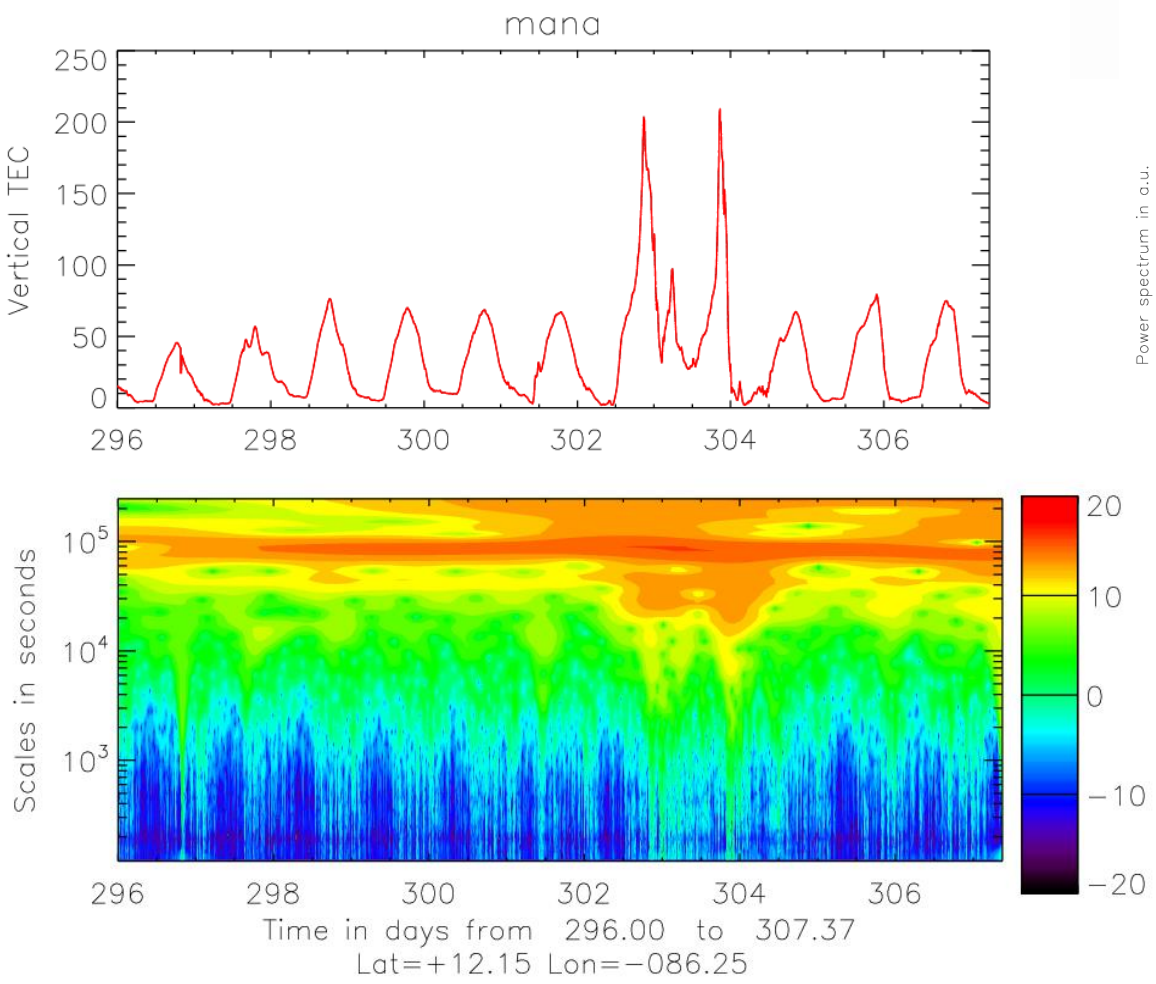
$$\dot{T}_{\mathrm{vert}} = \Upsilon\left(T_{\mathrm{vert}}, Y, \varphi, \vartheta, t_{\mathrm{day}}, \xi\right)$$

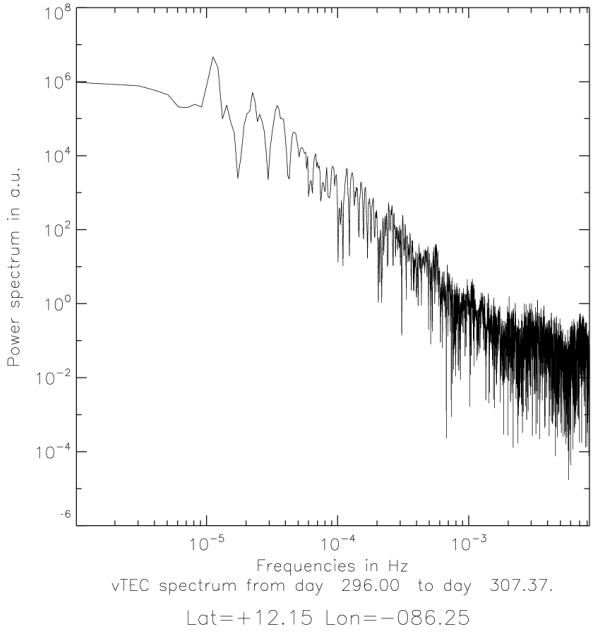
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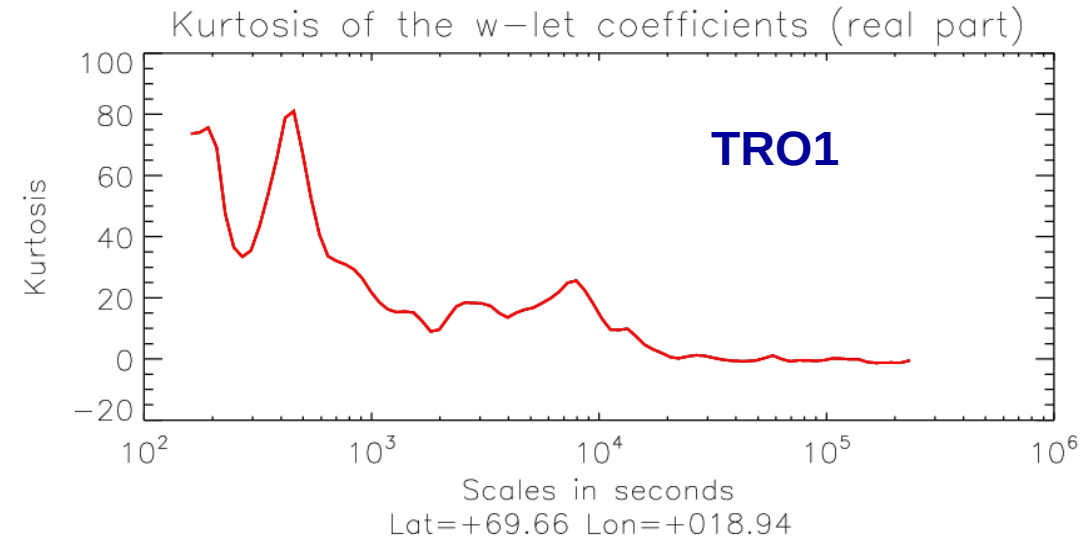


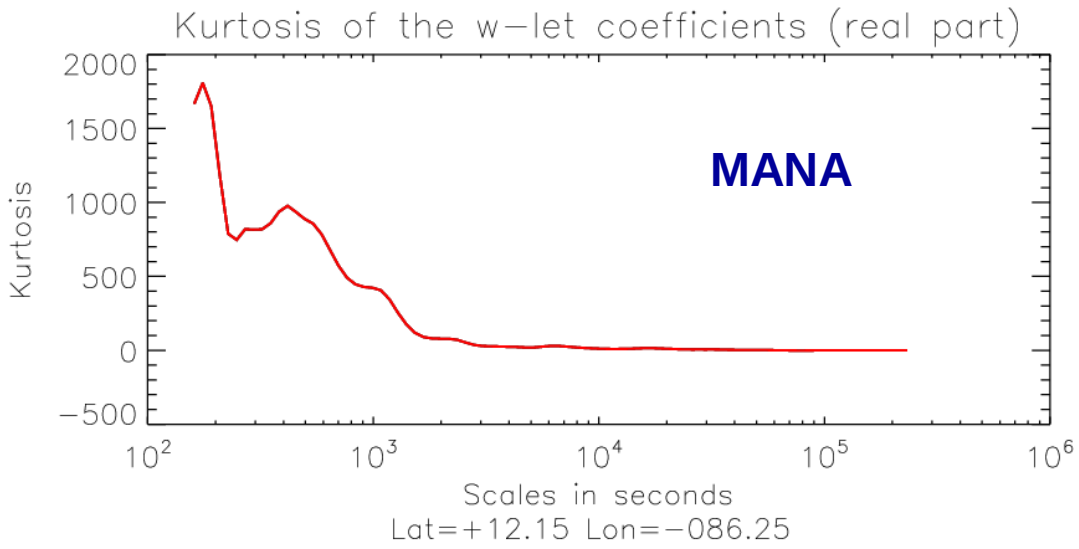






Manaus
(12.15N, 86.25W)





Scale-dependent statistics of the TEC fluctuations

Kurtosis of fluctuations: the TEC is intermittent. Extreme events grow more and more important for smaller and smaller time scales, but this "scale-covariance" depends on location (hence, on local geophysics). Coherent structures.