Doing Space Weather of small scale ionospheric structures via tools from complex system theory

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Chicago, August 7-16, 2008

"...a non negligible feature of the Sun-Earth forcing and of the Geospace response is ***complexity****"*

CONTENTS

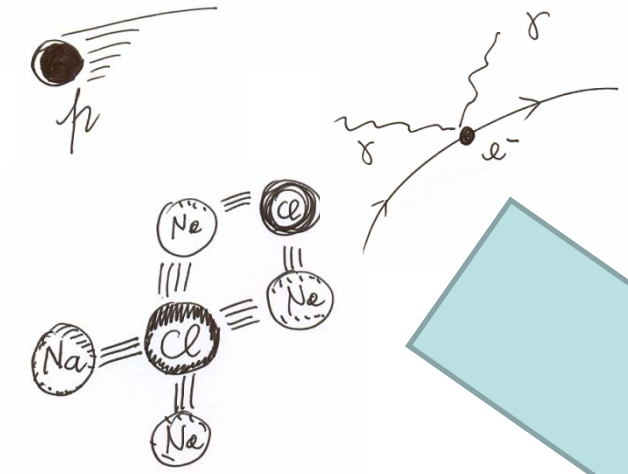
- Complexity and the complex ionosphere.
- The complex evolution of total electron content.
- Information theory and scintillation dynamics.
- Conclusions.

CONTENTS

- **Complexity and the complex ionosphere.**

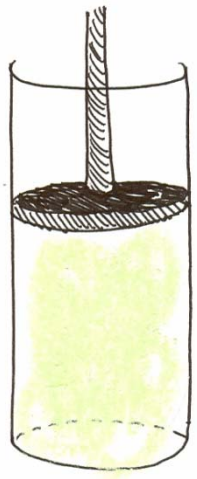
"A ***complex*** *physical system is a* ***classical composite*** *system whose* ***macroscopic*** *quantities* ***do not*** *evolve* ***smoothly*** *and* ***deterministically*** *as the equilibrium statistical physics would predict"*

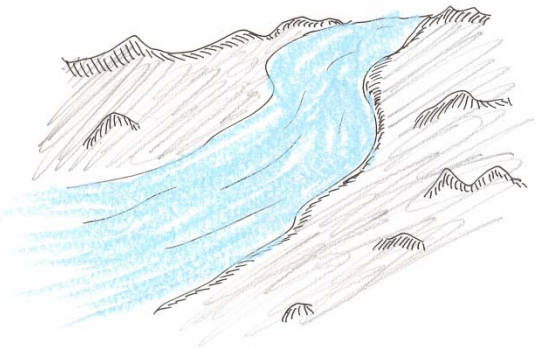
Origin of complexity…



Composite systems can be "non complex" only under very strong hypotheses (equilibrium, weak and local interactions, negligibility of extreme events)…

…widely used in "traditional" statistical mechanics, but very rarely satisfied in nature, and in particular in the helio-geophysical system!

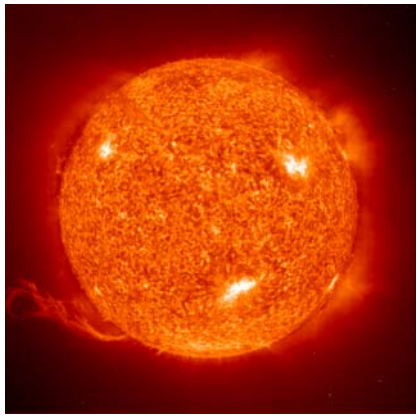


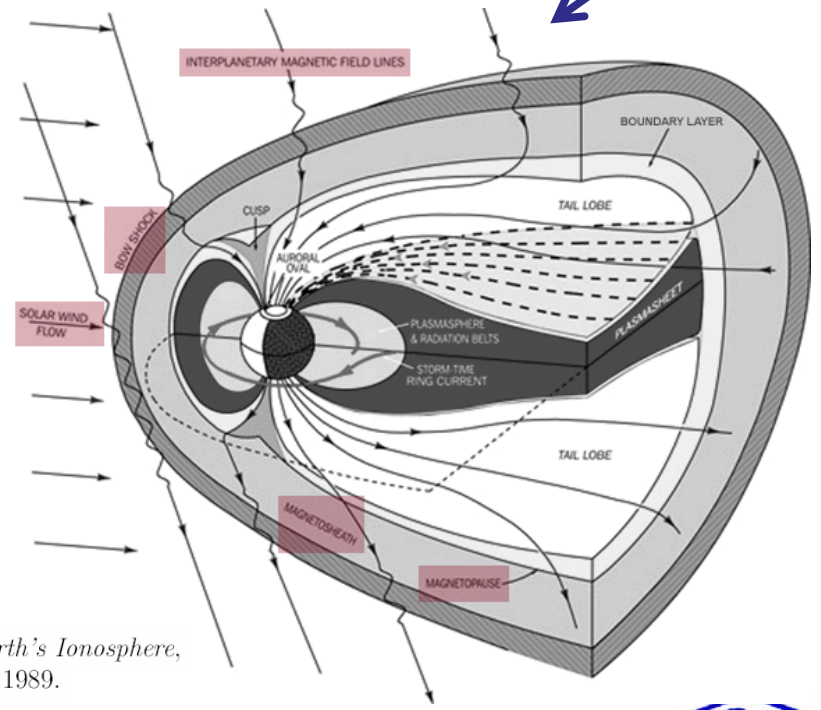


Failure of the "traditional" approach hypotheses yields (macroscopic) stochasticity, formation of hierarchical patterns, multi-scale dynamics

patterns

(macroscopic) stochasticity





multi-scale

M.C. Kelley, *The Earth's Ionosphere*, Academic Press Inc., 1989.

Space Weather deals with
complex systems
that should be treated accordingly!

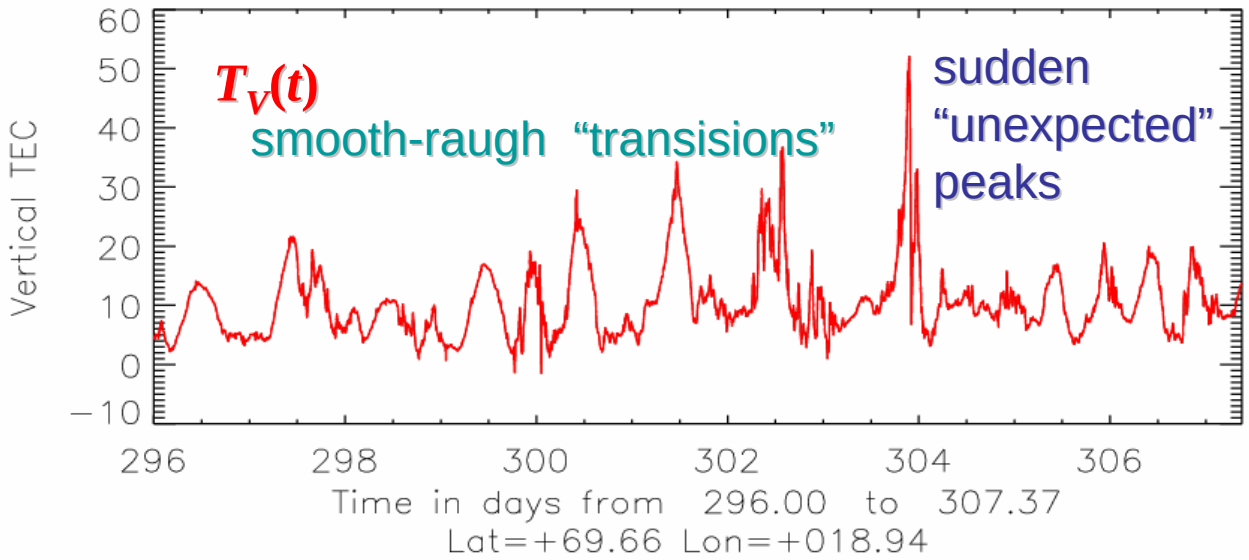
CONTENTS

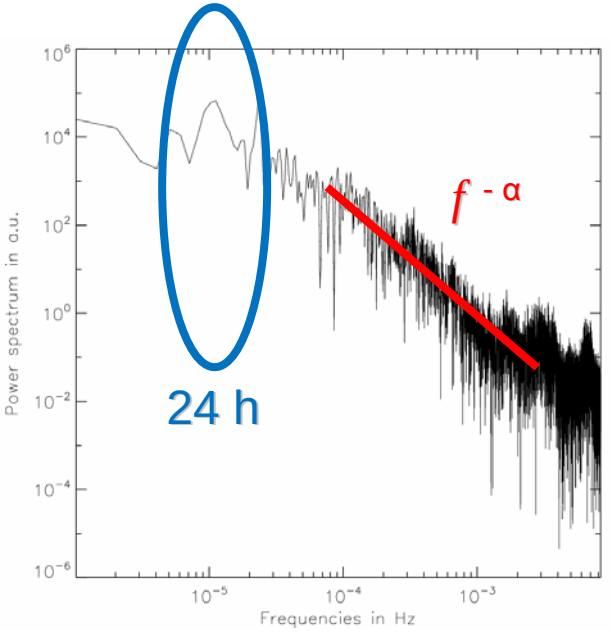
- Complexity and the complex ionosphere.

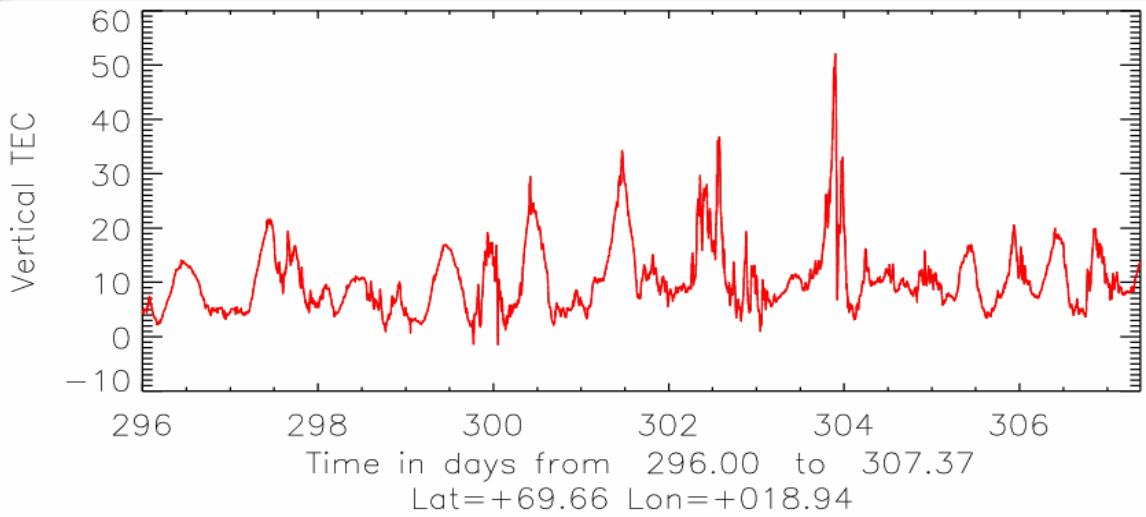
- The complex evolution of total electron content.

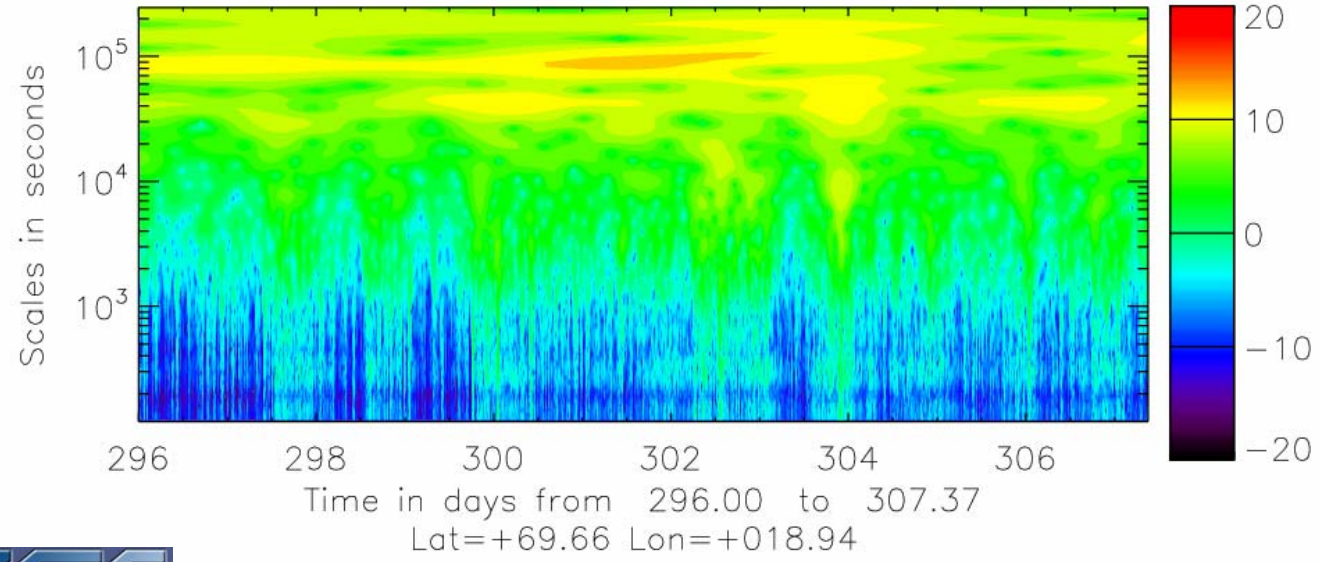
Time evolution of the vertical total electron content (TEC) on the top of GPS ground stations (located in Tromsø, 69.66N, 18.94E and Manaus, 12.15N, 86.25W), days 296 to 308 of year 2003 (from October 23 to November 3), including the days of the "2003 Halloween Storm".

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









- Multi-scale analysis

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

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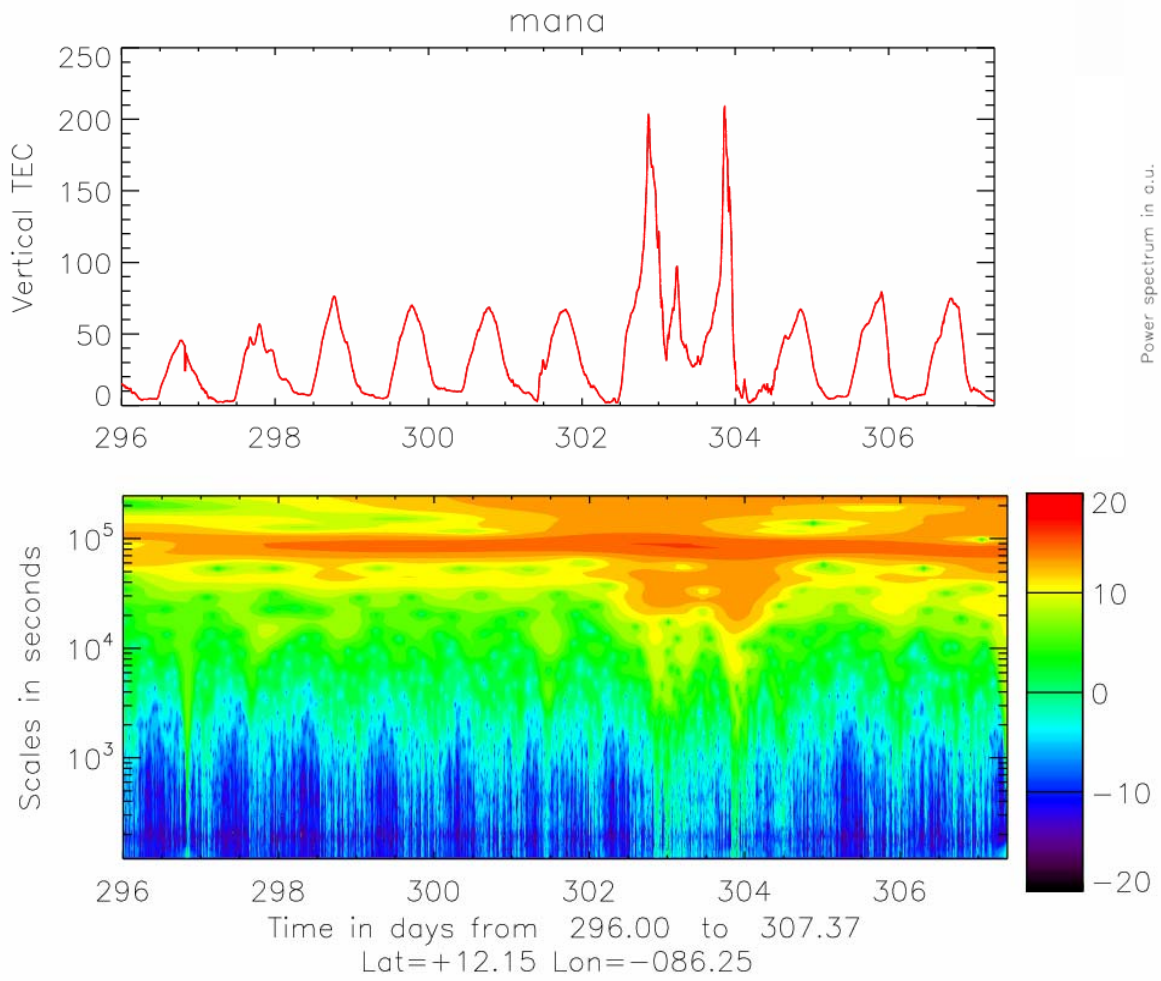

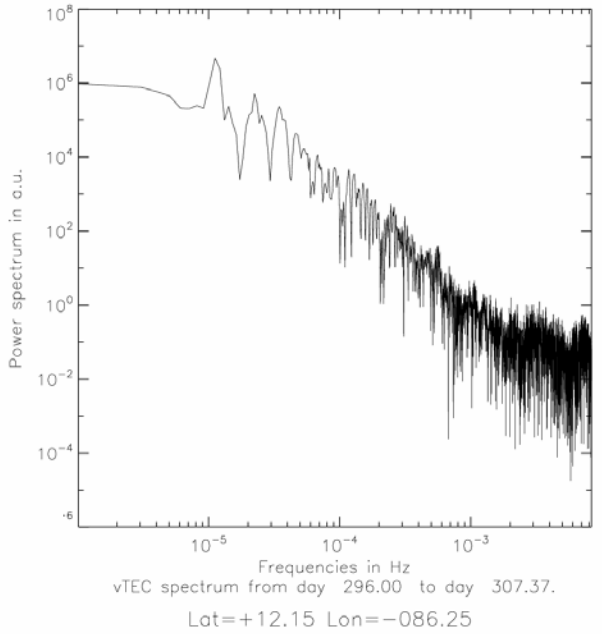

Manaus (12.15N, 86.25W)

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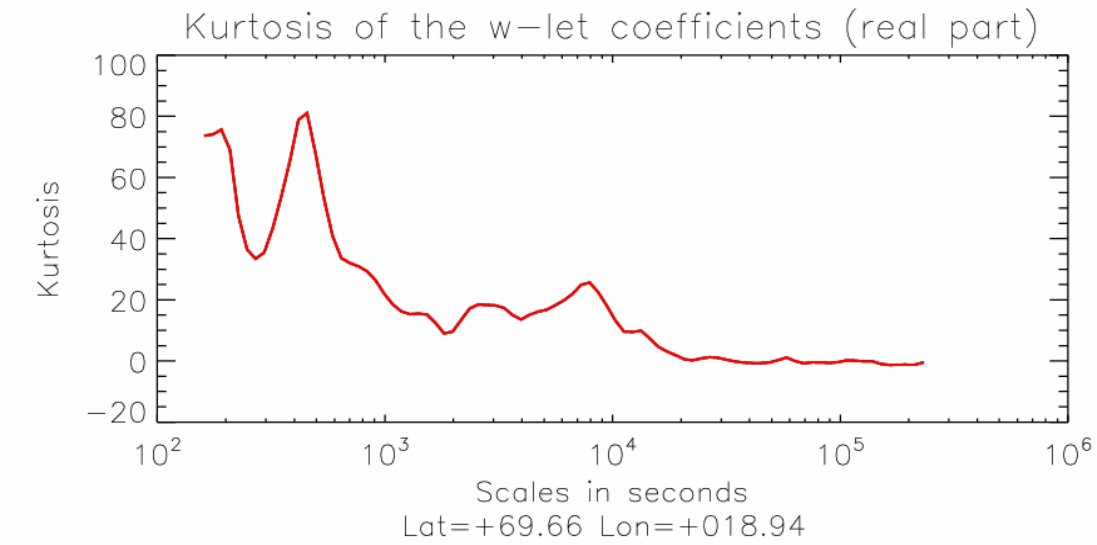

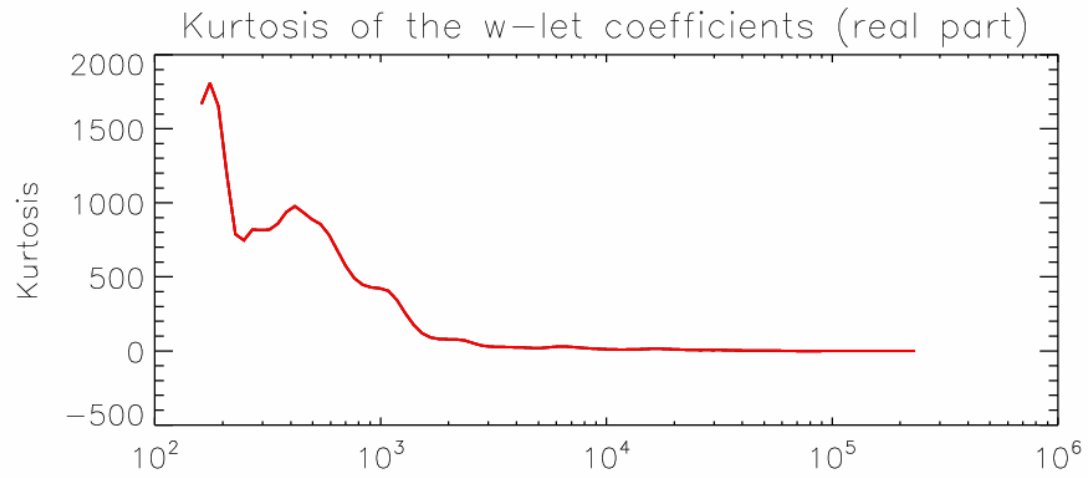

Multi-scale statistics of the TEC evolution: how does the PDF of TEC fluctuations vary with (time) scale?

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).

LIMITATIONS, COMMENTS AND DEVELOPMENTS

- **Strong statistical basis is necessary**: it will be crucial to elaborate systematically TEC data from **all the possible different locations**, for a whole solar cycle and under very **different helio-geophysical conditions.**

- **Verticalization procedure**: the single-station solution *à la Ciraolo* used here could have some **mapping function problems in the Equatorial region**, even if the **fine scale structure** should not be affected by those problems.

- **Multi-scale statistics and Space Weather**: since we are interested in the **most irregular configurations**, we must find the relationship between the appearance of the **intermittency in the TEC** and the helio-geophysical conditions.

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- Complexity and the complex ionosphere.
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- Information theory and scintillation dynamics.

Crucial point: the geospace ***reacts***
with a certain delay *to the S-E forcing,*
which depends on the forcing
and on the geospace conditions...

Dynamical analysis tools are needed!

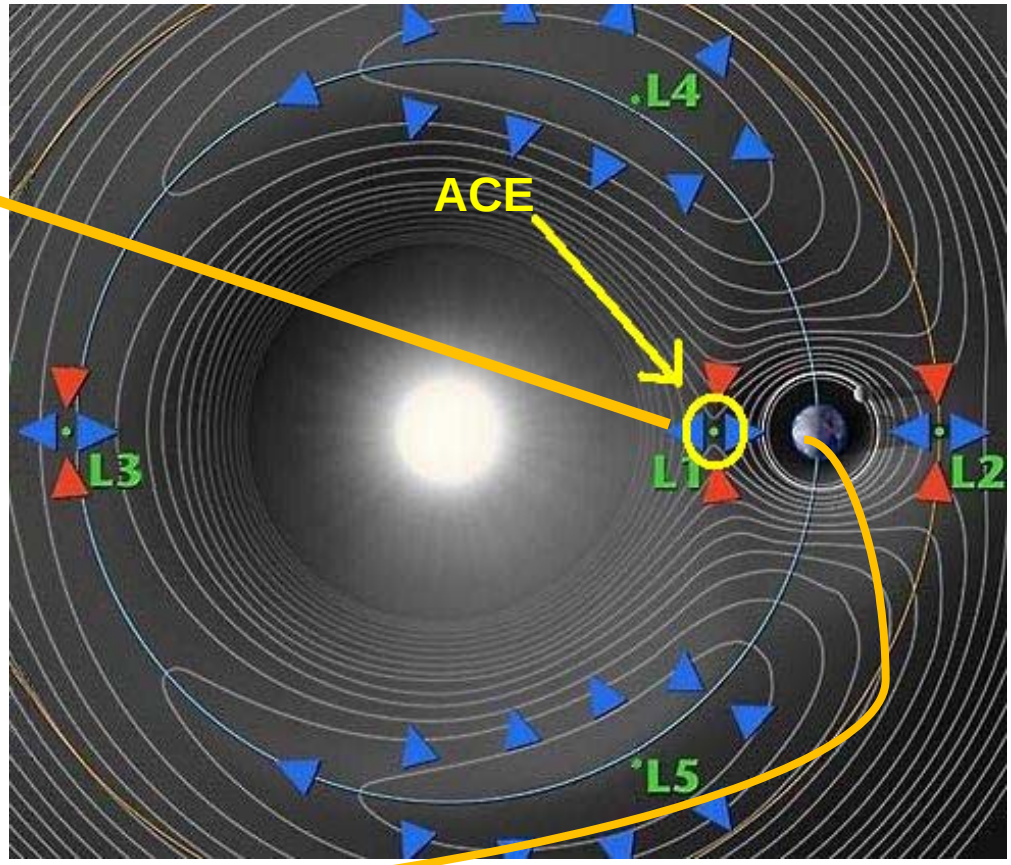
$$B_z(t), \quad N_i(t)$$

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

Putting together Solar-Wind time series…

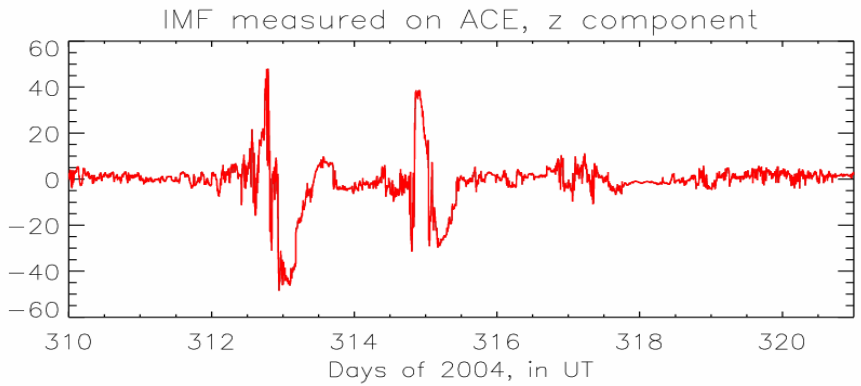
…and a time series describing GPS phase scintillation.

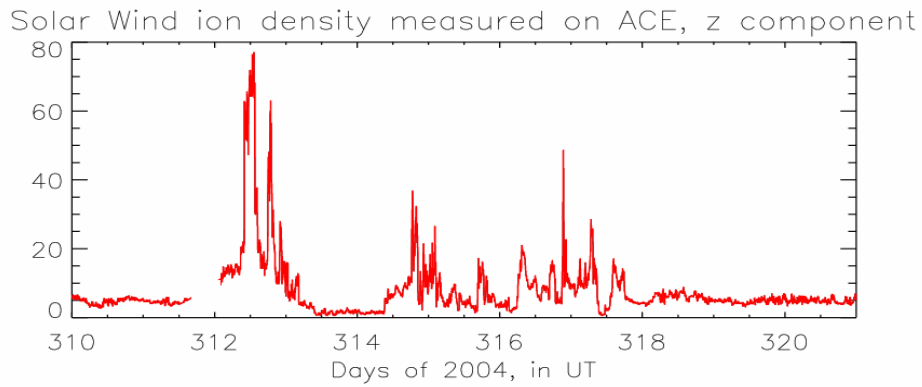
$$\sigma_\phi(t)$$



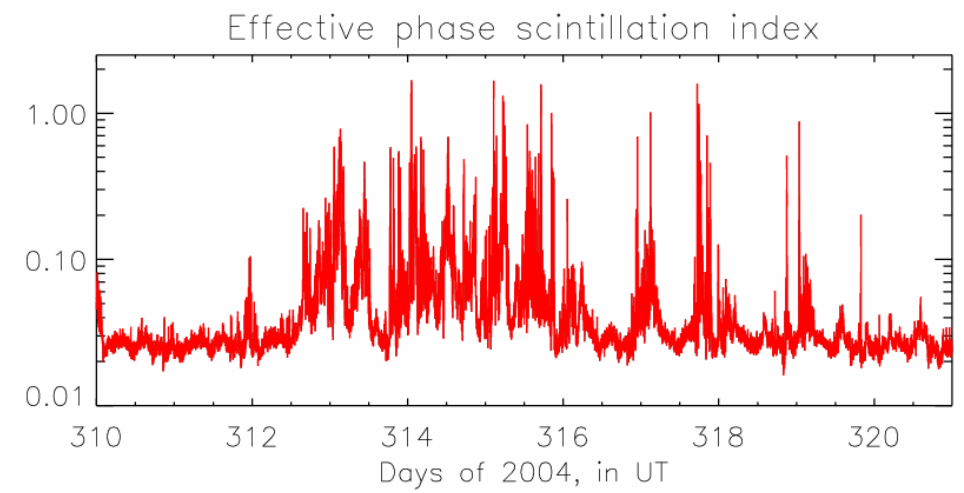
Solar Wind time series: the *z* component of the IMF and the ion density, as measured by the satellite ACE (data source: http://spidr.ngdc.noaa.gov/spidr/).

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).



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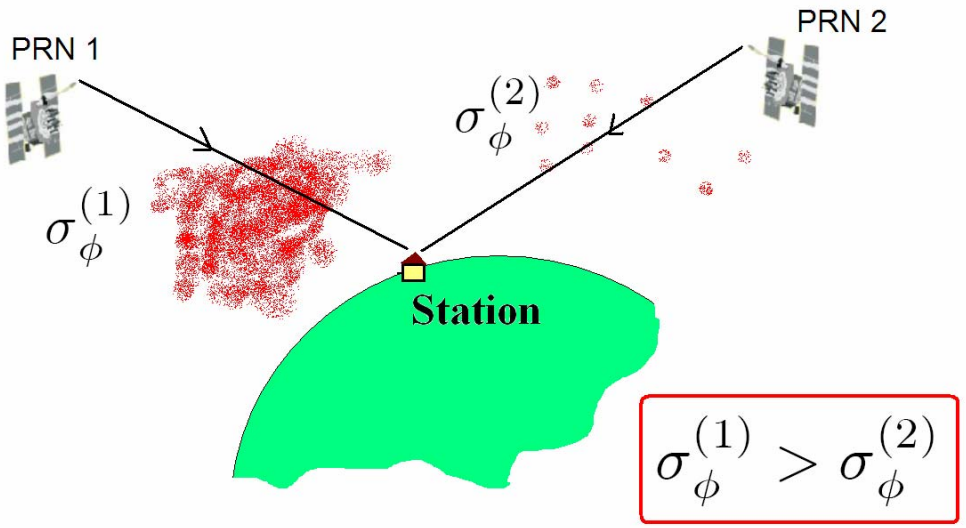
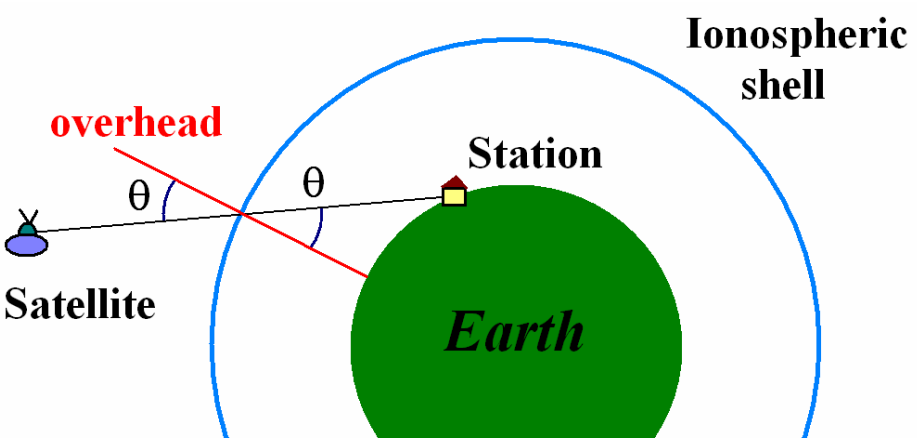


Due to the patchy nature of radio scintillation, scintillation indices do not describe the "state of scintillation" on the top of a location, but just along the radio link raypath.

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

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



What response delay of the effective phase scintillation index should be expected to the evolution of the B_z or of the N_i as measured at the position of ACE?

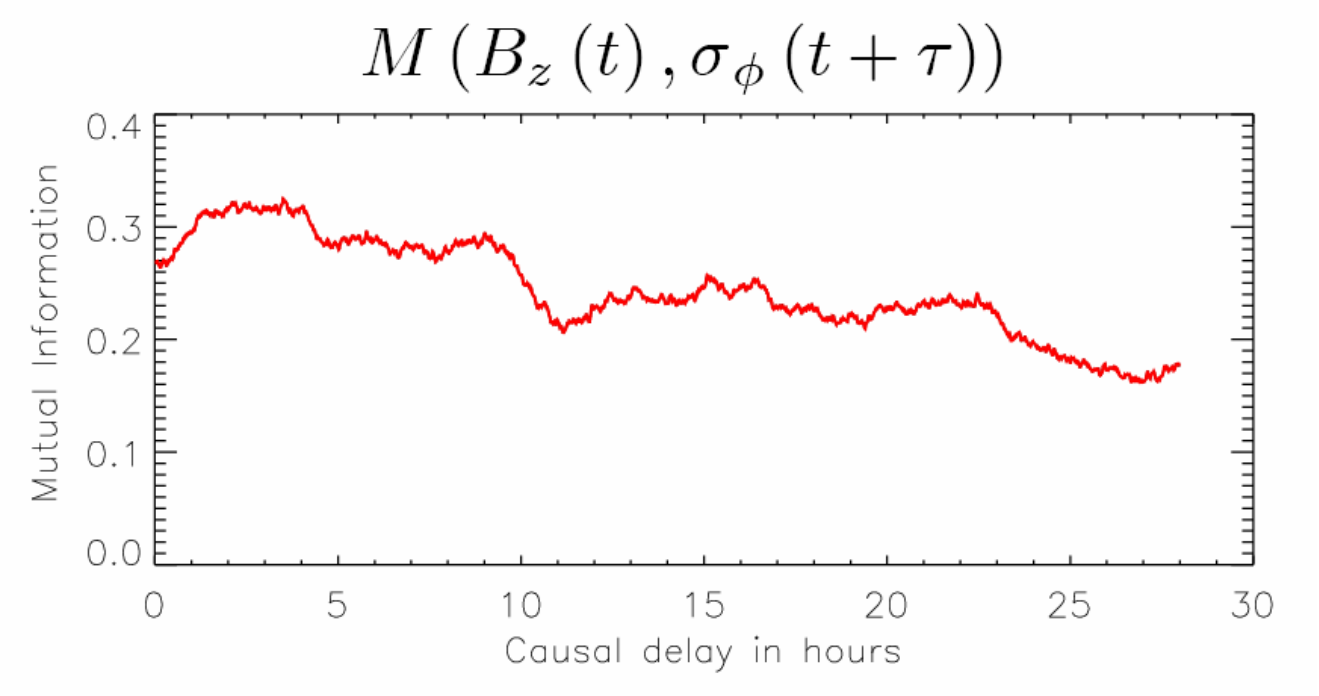
Information theory applied to dynamical systems: given two processes described by the time series $X(t)$ and $Y(t)$, the time-delayed mutual information $M(X,Y;\tau)$ indicates how strongly $Y(t+\tau)$ is "dependent" on the value of $X(t)$:

$$M(X,Y;\tau) = \int_{C_X} dX \int_{C_Y} dY \; p(X(t), Y(t+\tau)) \log \frac{p(X(t), Y(t+\tau))}{p(X(t))\, p(Y(t+\tau))}$$

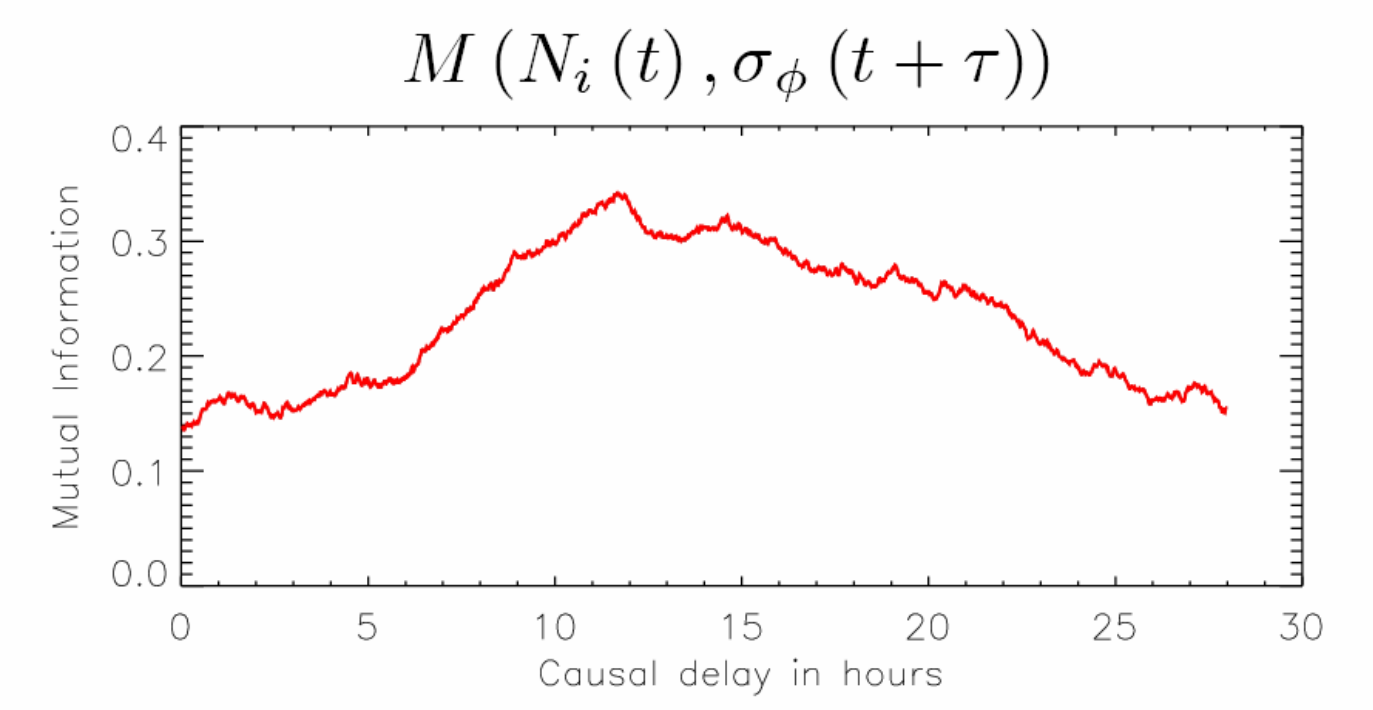
$$M(B_z(t), \sigma_\phi(t+\tau)) \qquad M(N_i(t), \sigma_\phi(t+\tau))$$

$M(X,Y;\tau)$ *may give* ***indications*** *on the* ***interaction times,*** *but* ***not establish the whole nature*** *of the interaction*

B_z delayed mutual information with phase scintillation: the maximum response of σ_ϕ to the IMF z-component takes place between 1 and 5 hours, with another peak at 8 hours delay.



N_i delayed mutual information with phase scintillation: the maximum response of σ_ϕ to the Solar Wind ion density takes place with a delay of 11-12 hours, while a smaller maximum appears after 15 hours.



LIMITATIONS, COMMENTS AND DEVELOPMENTS

- **Mutual information may give an indication of the delay between processes, but consistent theoretical models of the forcing are necessary to make predictions: what really happens to σ_ϕ at $t + \tau$ after what happens at t in the solar wind?**

- **Probabilities are all calculated by "histogramming", hence assuming the time statistics to coincide with the ensemble statistics. This is correct only for stationary time series, which is not the case in stormy situations.**

- **Strong statistical basis is necessary: it will be crucial to collect and elaborate scintillation data from many different locations, for a whole solar cycle and under very different helio-geophysical conditions.**

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- Conclusions.

- **Space Weather could take great advantage from complexity scince tools: the geospace is an intrinsically complex structure forced by a turbulent agent (the Sun) via an intrinsically complex chain of mechanisms.**

- **Multi-scale analysis, phase space exploration, information theory are all well based tools, theoretically, but need giant well assorted collections of data, which is the real challange.**

- **Dynamical interpretation: this mathematics gives lots of "values", that remain speechless if one does not interpret them dyanically.**

- **Galileo's approach: learn how to disentangle different effects of different causes asking the right question to Nature, avoiding confusing mix up of things.**

A special thanks goes to Dr Nathan Smith (University of Bath) for very useful discussions!

THANK YOU ALL

FOR YOUR KIND ATTENTION!