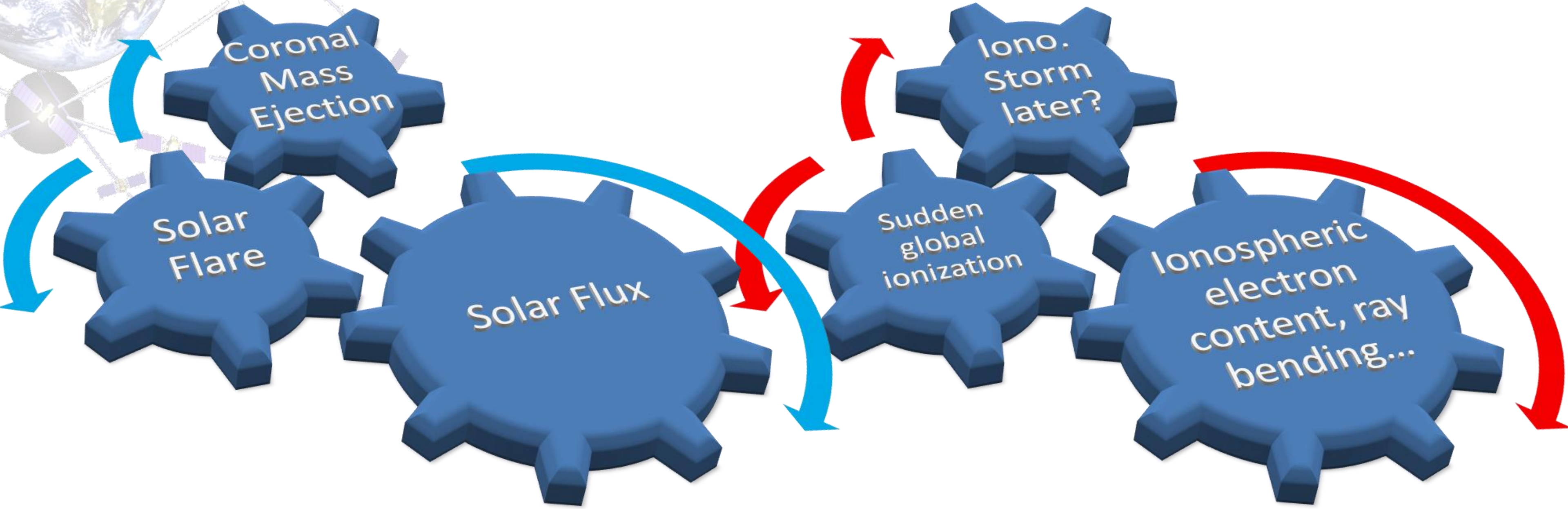
GPS as a Solar Flare EUV flux-meter



Manuel Hernández-Pajares[1], **Alberto García-Rigo**[1], Enric Monte-Moreno[2], Talwinder Singh[3] and David Martínez-Cid[1]

1 *UPC-IonSAT, Departament de Matemàtiques, Mod. C3 Campus Nord UPC, Jordi Girona 1-3, 08034-Barcelona, SPAIN* (E-mail: manuel.hernandez@upc.edu , alberto.garcia.rigo@upc.edu , david.martinez.cid@alu-etsetb.upc.edu)

2 *Departament de Teoria del Senyal i Comunicacions, TALP res. group, Universitat Politècnica de Catalunya, Jordi Girona 1-3, 08034-Barcelona, SPAIN*
(E-mail: enric.monte@upc.edu)

3 *Departament of Physics, Indian Institute of Technology (BHU), Varanasi, INDIA*
(E-mail: talwinder.singh.app11@iitbhu.ac.in)

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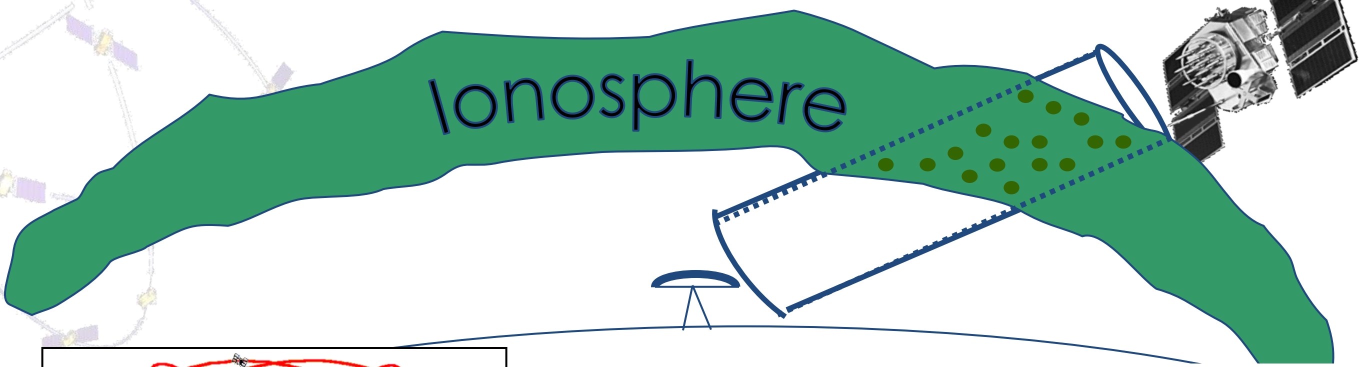
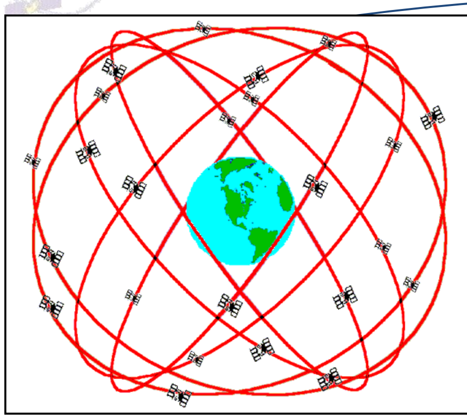
Outline

1. Introduction
2. Sudden global daylight overionization
3. GSFLAI
    3.a) EUV flux rate proxy during Solar Flares
    3.b) Inmunity vs. events of relativistic electrons.
    3.c) Correlation with X-ray flux rate
4. "Fractality": fractional Brownian model proposed (GSFLAI probability and length of a given burst of flares).
5. SISTED: Solar flare indicator index.
6. Conclusions

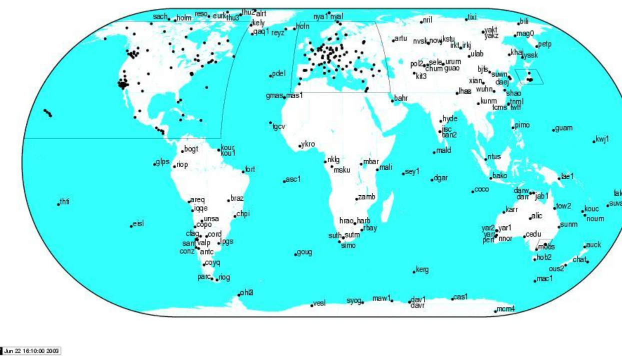
1. Introduction

Introduction: from GNSS to "GISS"





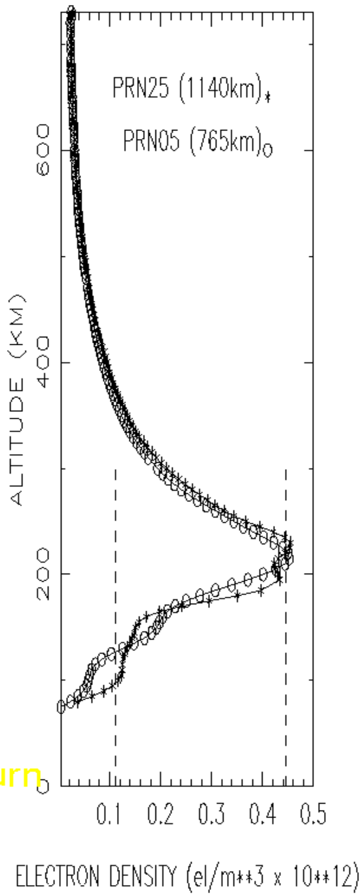
GNSS
Sat. + Rec.

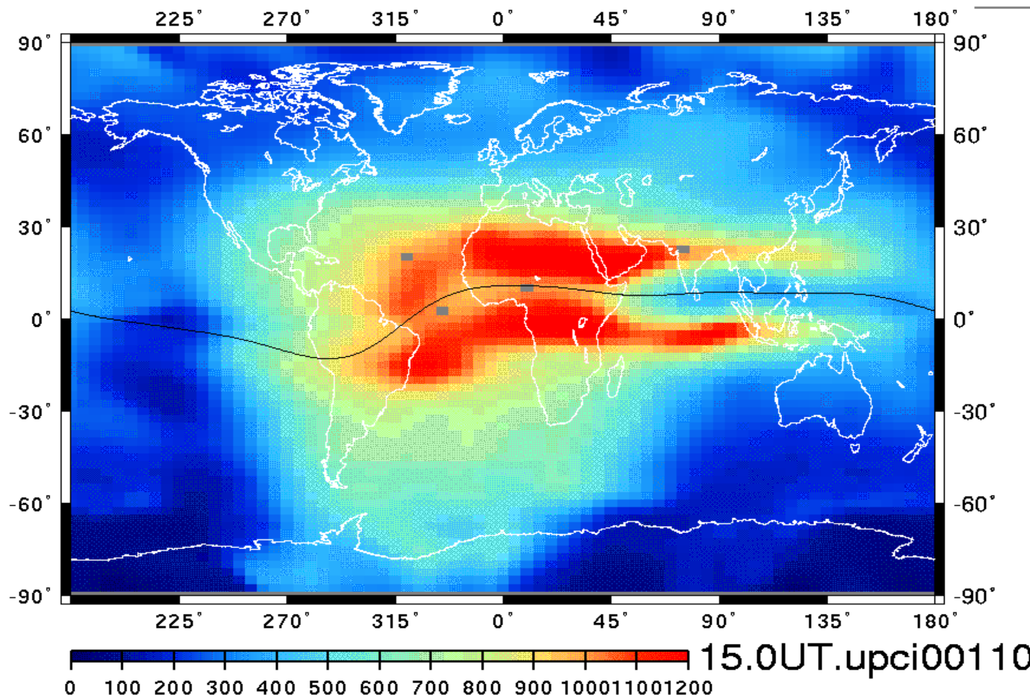


Global Ionospheric Sounding System (GISS)

GPS, and in general Global Navigation Satellite Systems (GNSS), have become a well founded *Global Ionospheric Sounding System* (GISS) after an intensive development during the last 25 years.

Introduction: Examples of Ne & VTEC spatial dist. from GPS (COSMIC & IGS) data





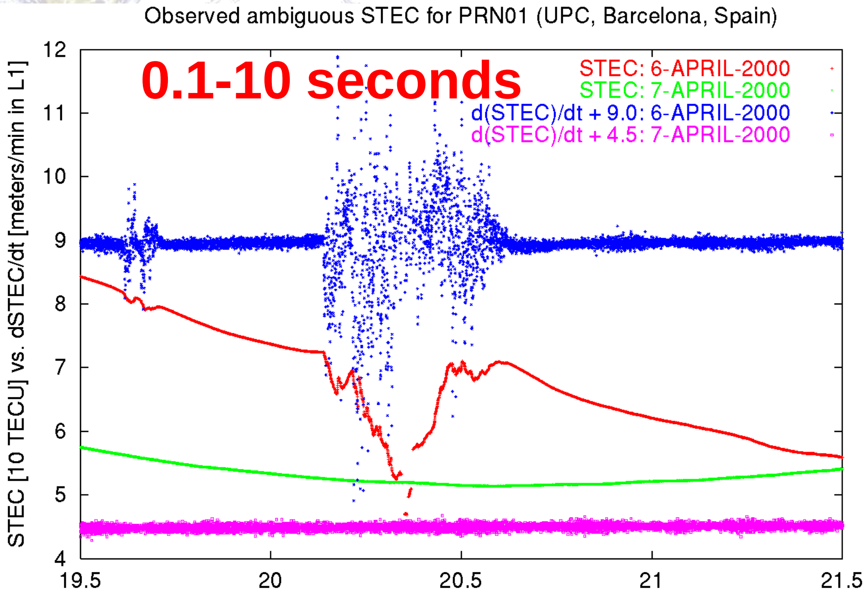
Global Vertical Total Electron Content (VTEC) map computed from ~100 GPS dual-freq CORS (units: 0.1 TECU). [*]

Electron density (Ne) profile computed from LEO GPS data (units: Te-/m**3).[*]

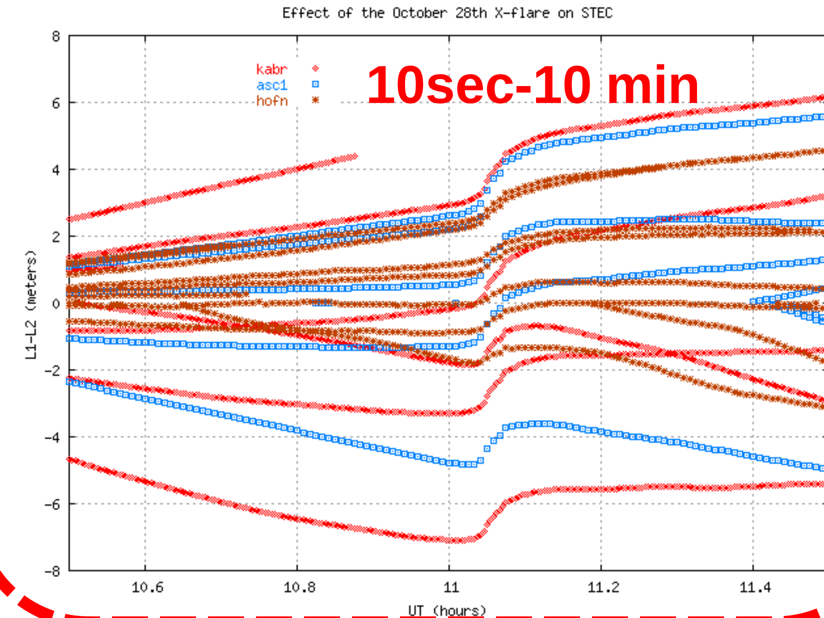
[*] Computed with UPC-TOMION soft

Introduction: iono. time variability

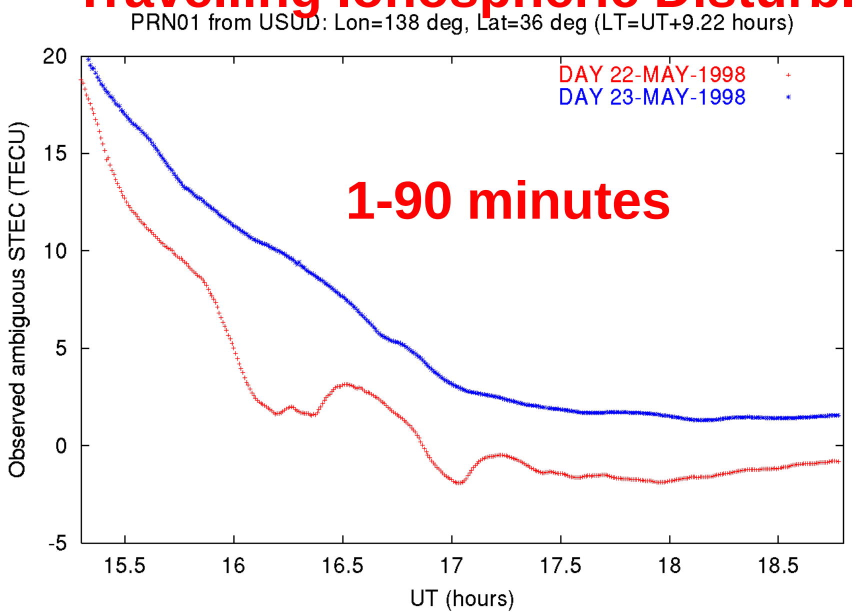
Scintillation



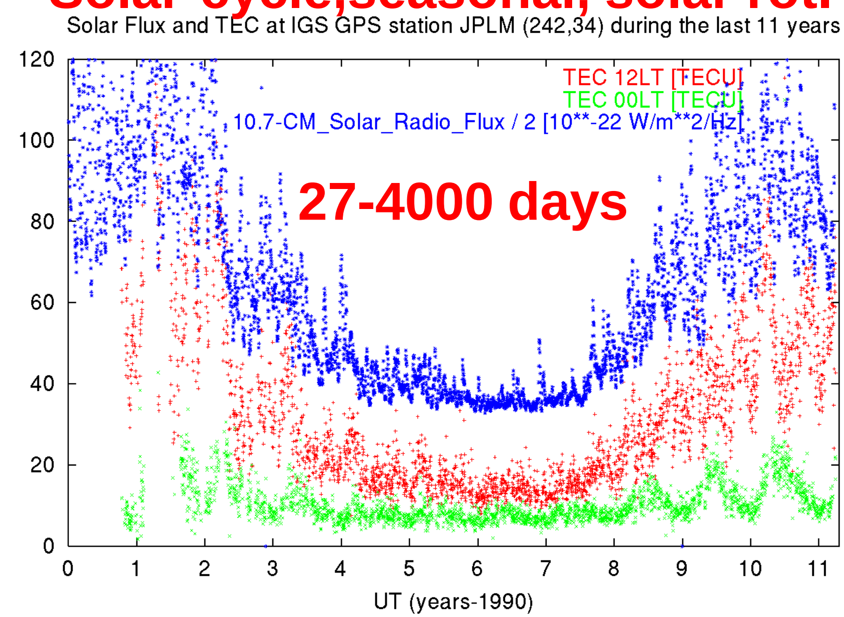
Solar Flare sudden overioniz.



Travelling Ionospheric Disturb.

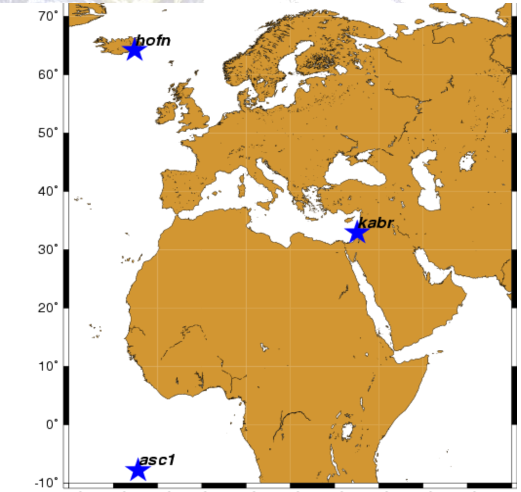


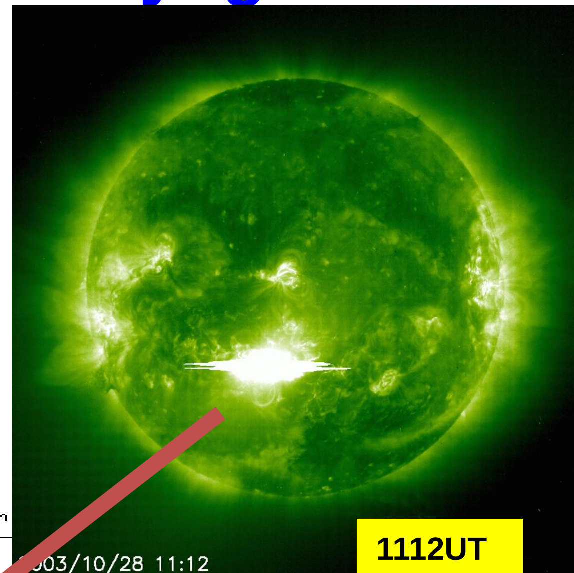
Solar-cycle,seasonal, solar rot.

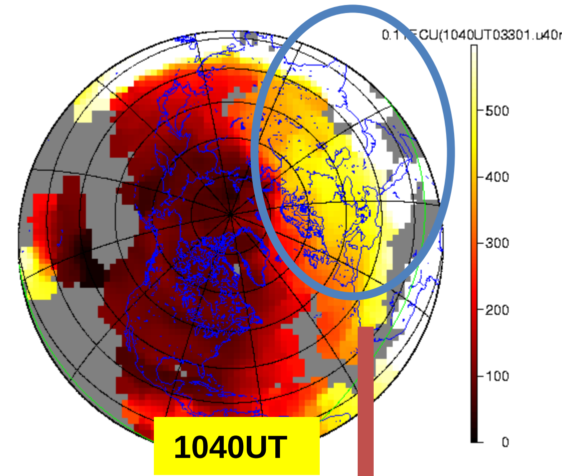


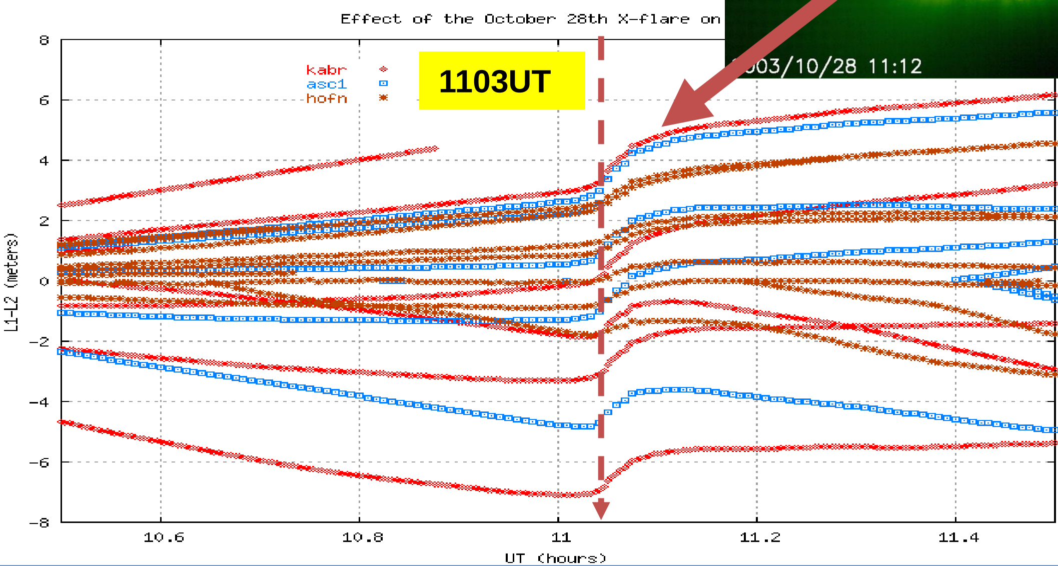
2. Sudden global daylight overionization

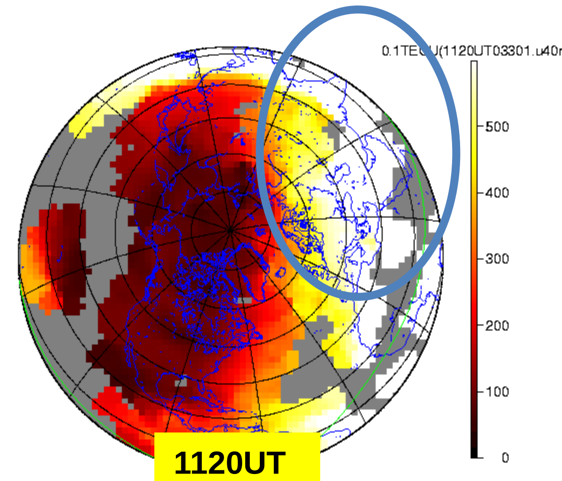
Solar X-class flare producing a global and sudden TEC increase in the daylight hemisphere (28Oct03)







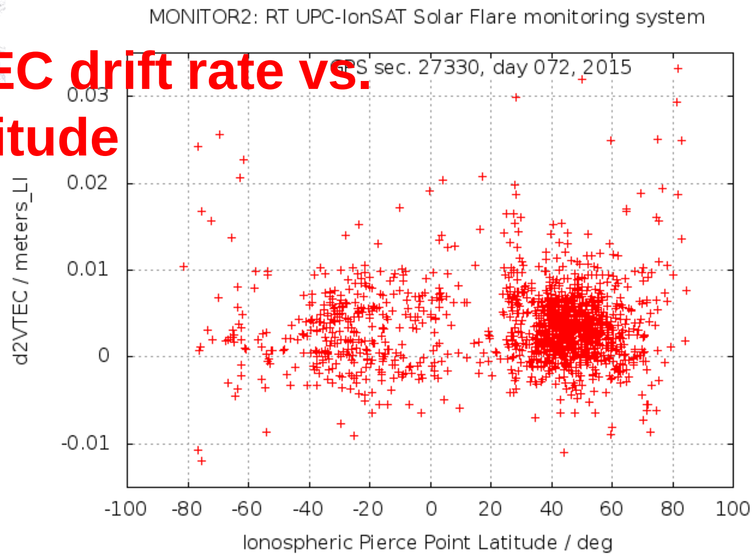




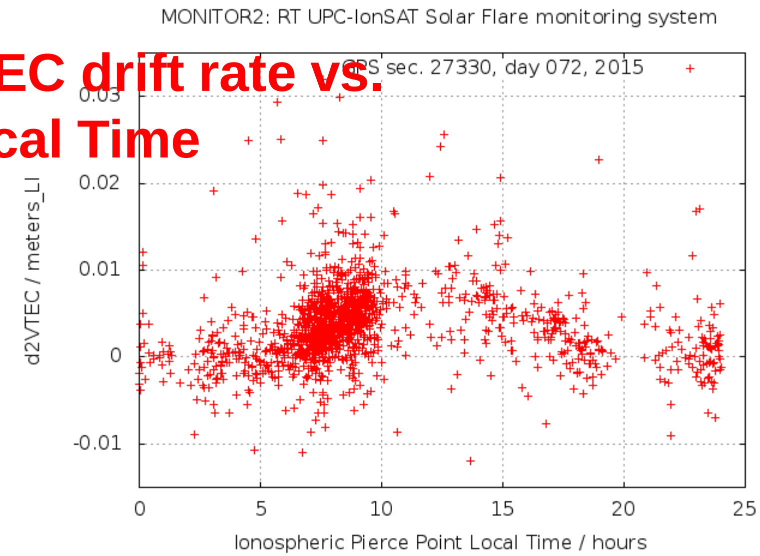
Sudden TEC increase of 10+ TECU experienced in the daytime hemisphere due to the arrival of a Solar X-flare X-rays/UV extra radiation (event during 28th Oct. 2003, 11UT approx, preceding superstorms) clearly seen by GPS rec.

Looking for main dependence of TEC increase: (example: M-class Solar Flare during day 072, 2015, preceeding St. Patrick's geom. storm)

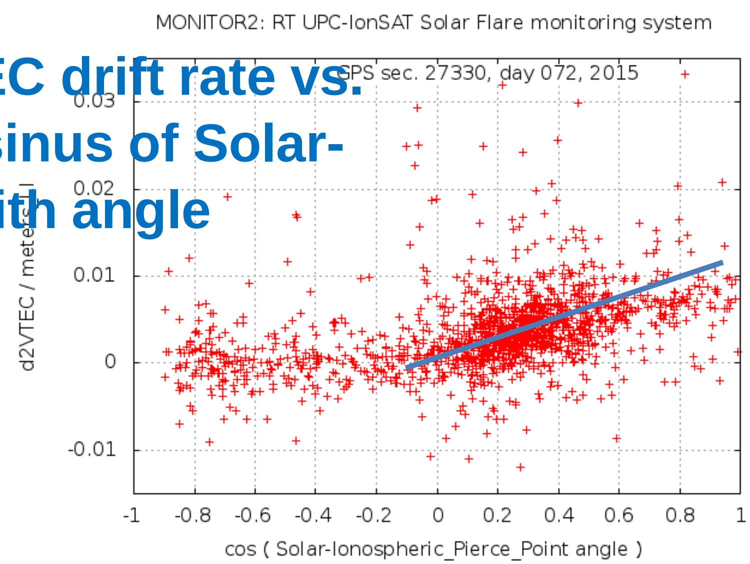
VTEC drift rate vs. Latitude



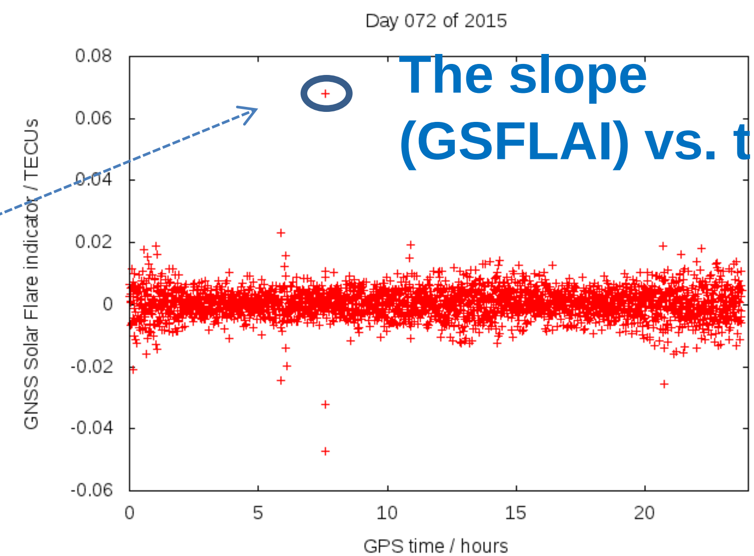
VTEC drift rate vs. Local Time



VTEC drift rate vs. Cosinus of Solar-zenith angle

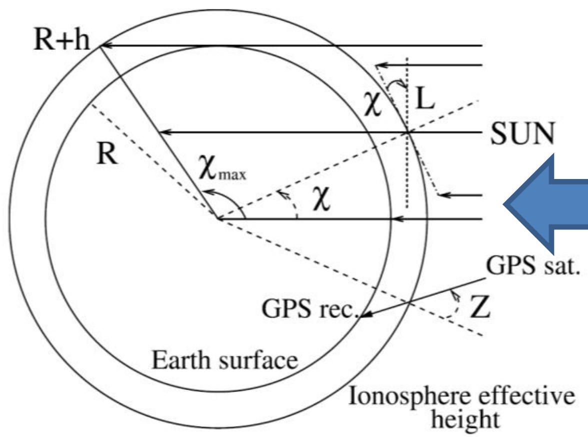


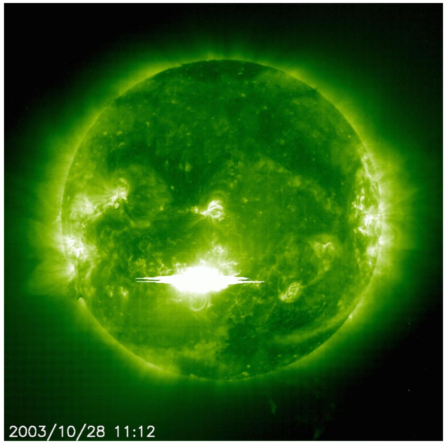
The slope (GSFLAI) vs. time



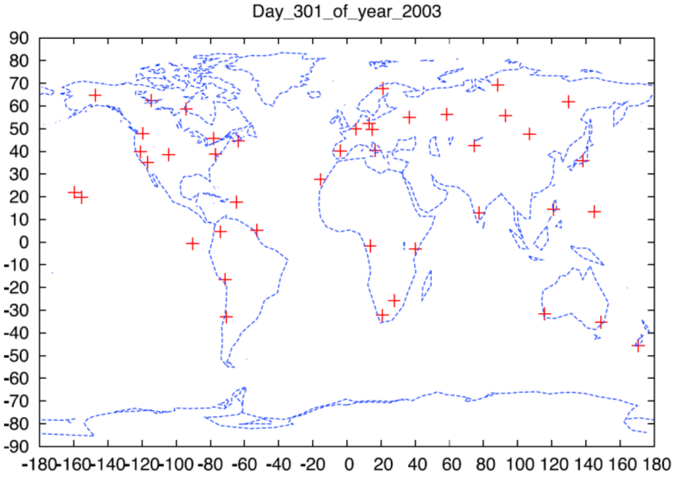
3. GSFLAI

Overionization model: First principles, GPS… and GSFLAI



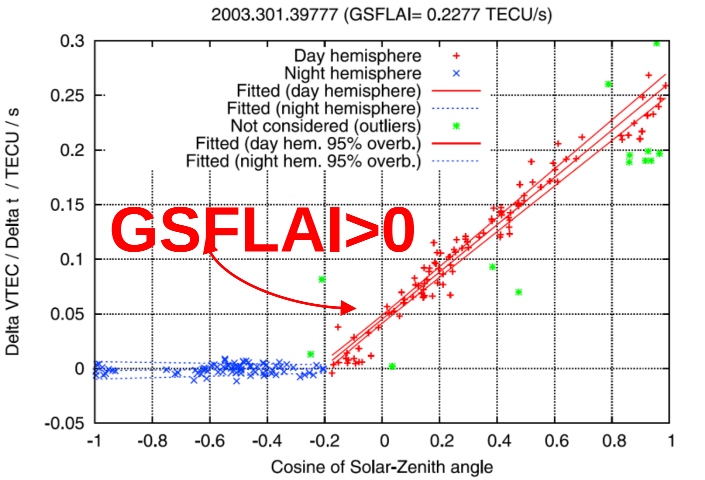


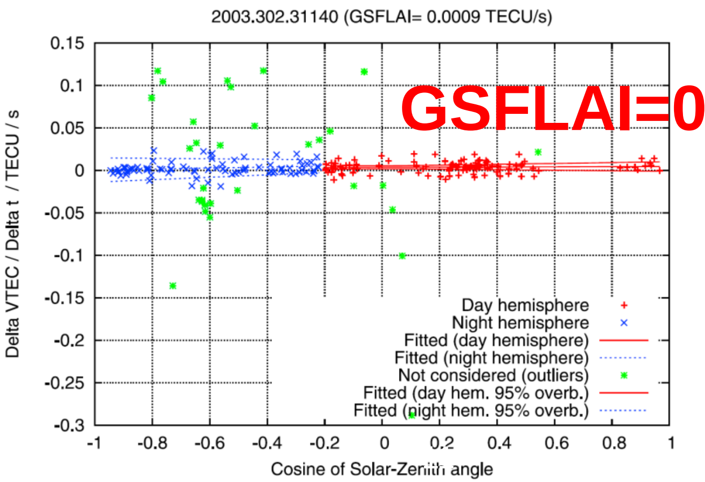
$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I}$$



Halloween **X-class** SF snapshot: **the regression line slope (GSFLAI)** reacts well.

$$\dot{V} = a_1 \cos\chi + a_2$$

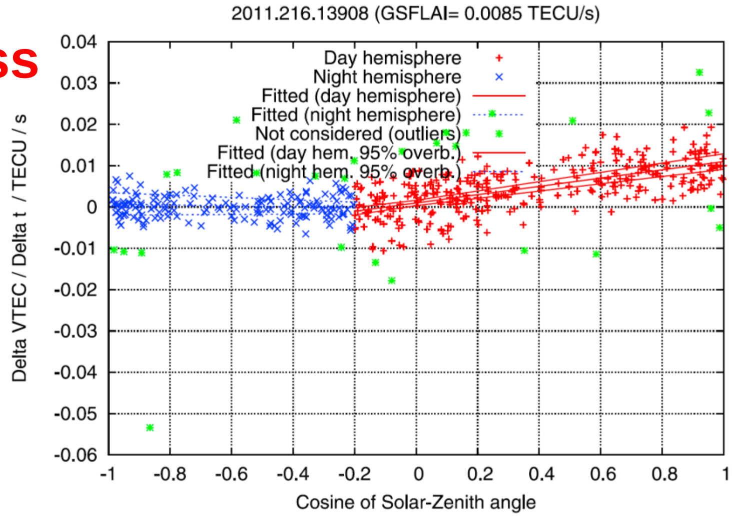


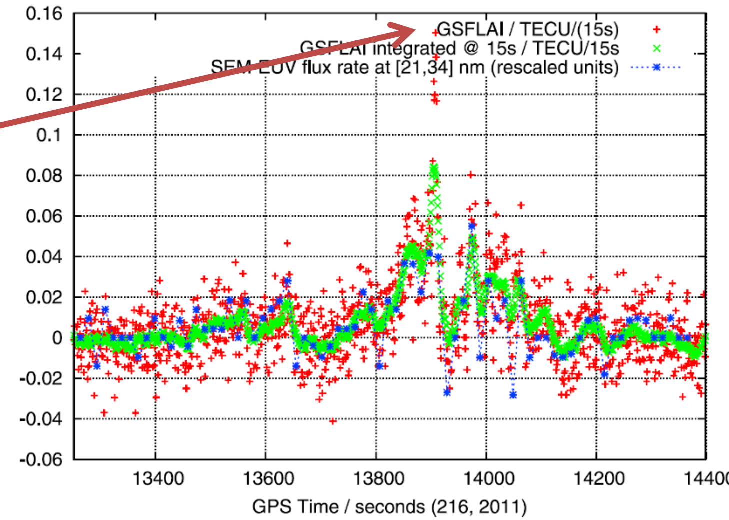


During the next day **major geomagnetic storm peak**, the higher **variations do not follow the SF spatial pattern**, and GSFLAI (=0) performs again well.

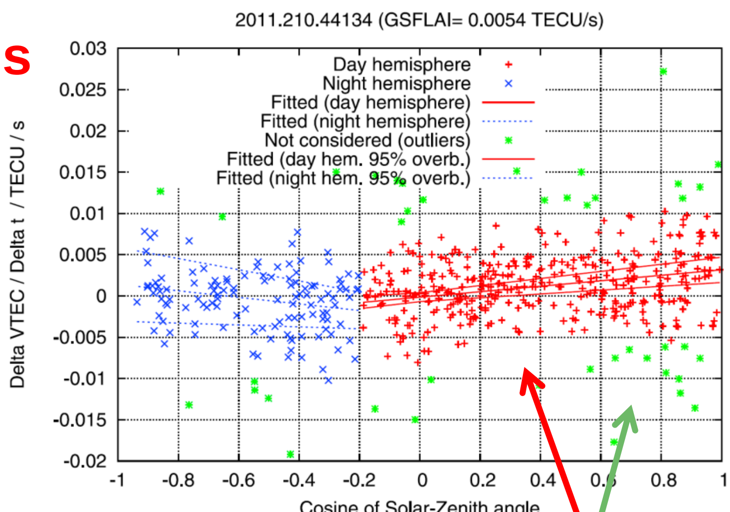
GSFLAI is a good proxy of direct EUV rate meas., also for M- and C-class Solar Flares

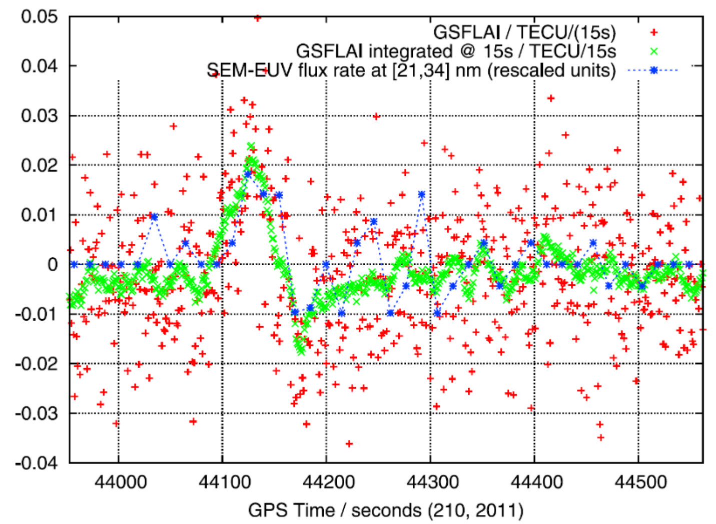
M-class





C-class

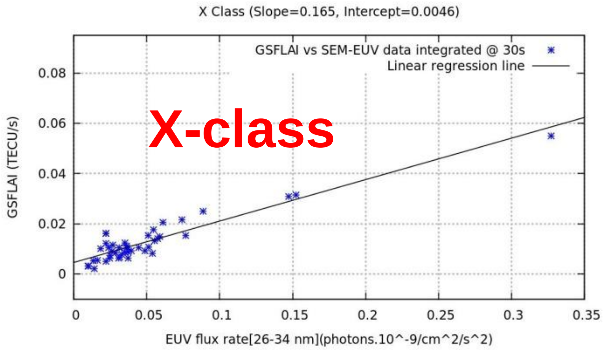


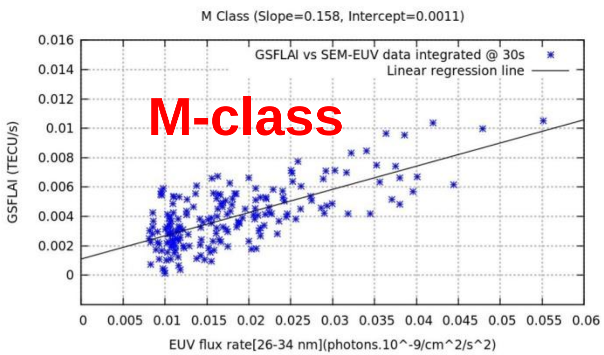


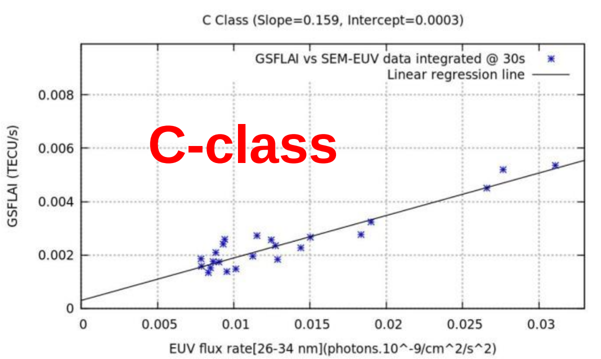
Iterative voting scheme to find the optimal fitting result (outlier detection method similar to RANSAC)

More details can be found in ***Hernández-Pajares, M., A. García-Rigo, J. M. Juan, J. Sanz, E. Monte, and A. Aragón-Àngel (2012), GNSS measurement of EUV photons flux rate during strong and mid solar flares, Space Weather, 10, S12001, doi:10.1029/2012SW000826.***

The GSFLAI, a proxy of EUV flux rate for X, M & C-class S. Flares







- **GSFLAI** (point with fastest increase per flare, if above the GNSS measurement error) **vs. EUV flux rate data** (from SOHO-SEM in 26-34 nm range).

- From top to bottom: X, M and C-class Solar Flares meeting the criteria since **2001** until **2014**.

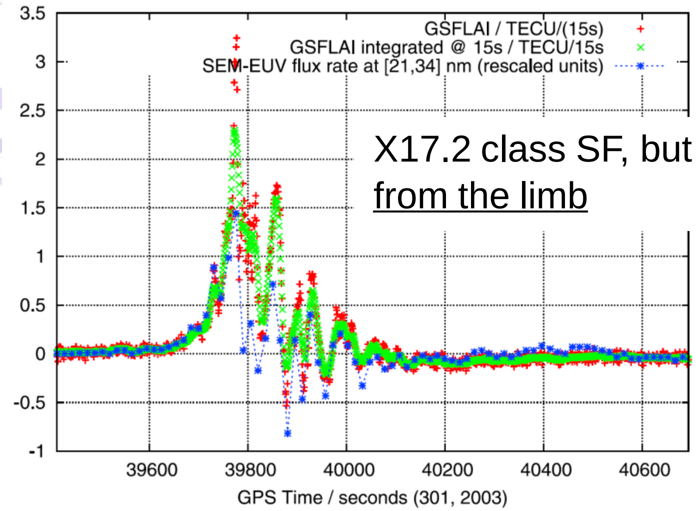
- Regression lines, with **slopes 0.165, 0.157 and 0.159 for X, M & C-class** => high consistency of the simple physical model & technique.

More details in ***Singh, T., M. Hernandez-Pajares, E. Monte, A. Garcia-Rigo, and G. Olivares-Pulido (2015), GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares, J. Geophys. Res. Space Physics, 120, doi:10.1002/2015JA021824.***

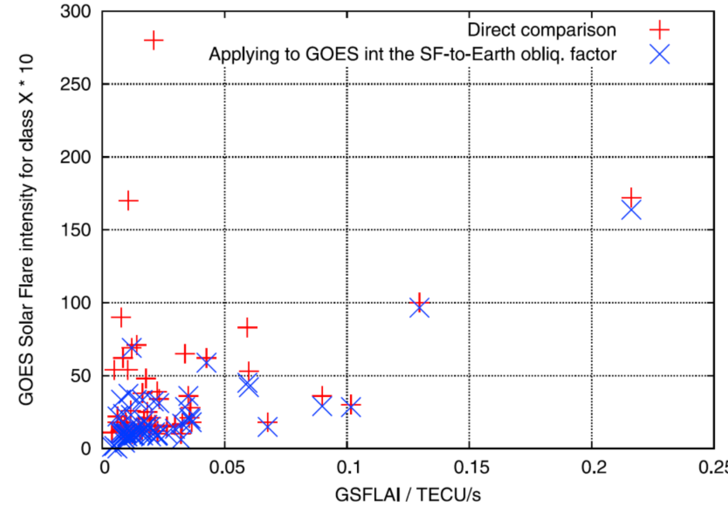
Flares		Slope		Intercept		Corr. Factor	
Class	Number	All	Peaks	All	Peaks	All	Peaks
X	60	0.184	0.165	0.0022	0.0046	0.83	0.94
M	320	0.127	0.157	0.0012	0.0012	0.63	0.70
C	300	0.111	0.159	0.0008	0.0003	0.46	0.94

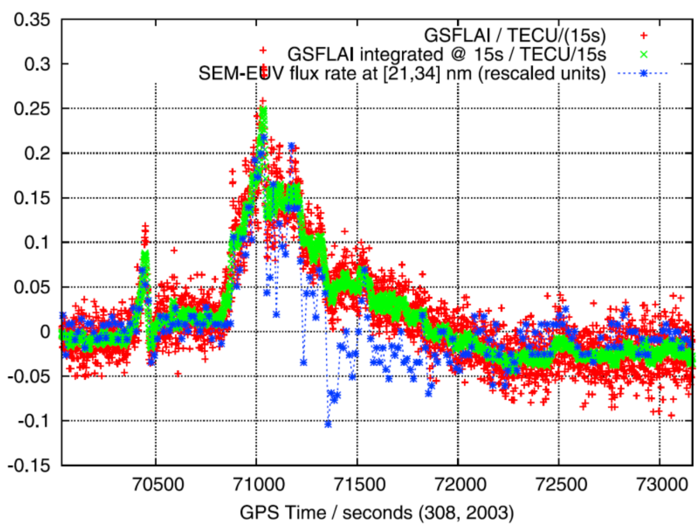
[a] The units are $TECU/s$ for GSFLAI and $photons.10^-9/cm^2/s^2$ for EUV flux rate.

The Solar Flare location distance to the disc center (proximity to limb) matters....



X17.2 class SF, but far from the limb

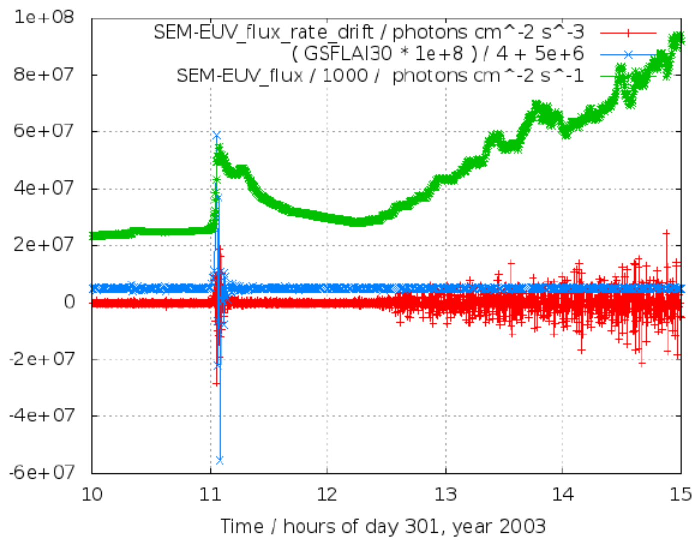


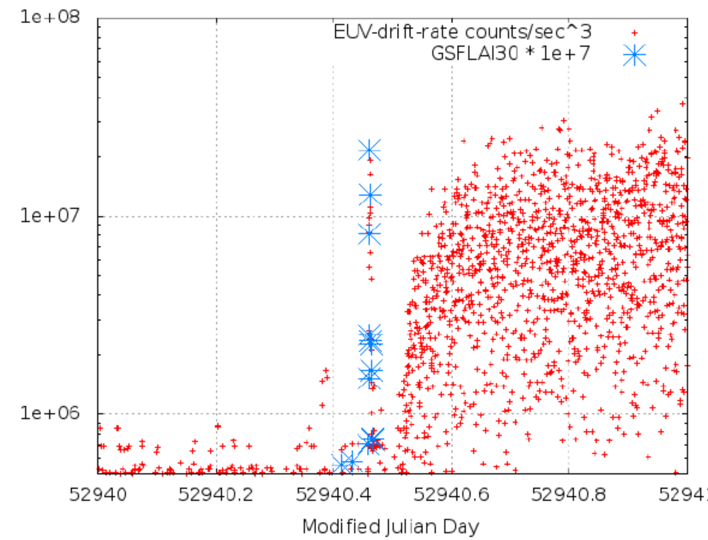


X28.0 class SF, but far from the Solar Disc, i.e. **close to the limb.**

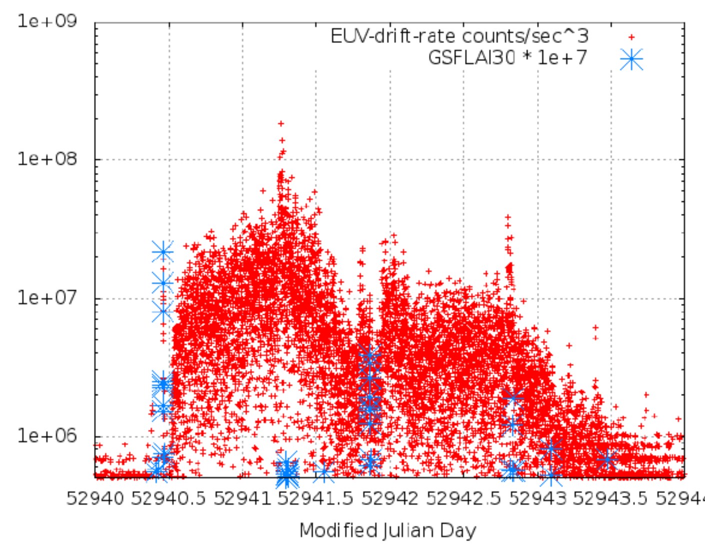
After applying a **simple extinction law from Solar disc distance**, **a relationship of GSFLAI with GOES X-ray based classification is disclosed**, making feasible its usage as geophysical index (a potential proxy of GOES classification...).

GSFLAI is immune to prompt particle contamination like relativistic electrons, affecting direct space-based measurements...



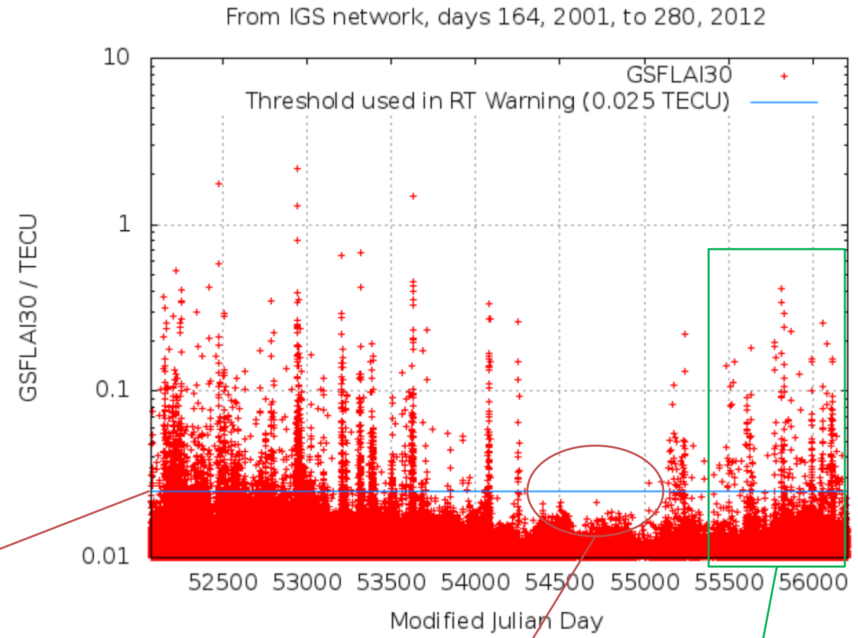


The **particle contamination** in the direct EUV flux readings (**SEM** measurements in green and its rate in red) can make difficult the detection of consecutive Solar Flares.

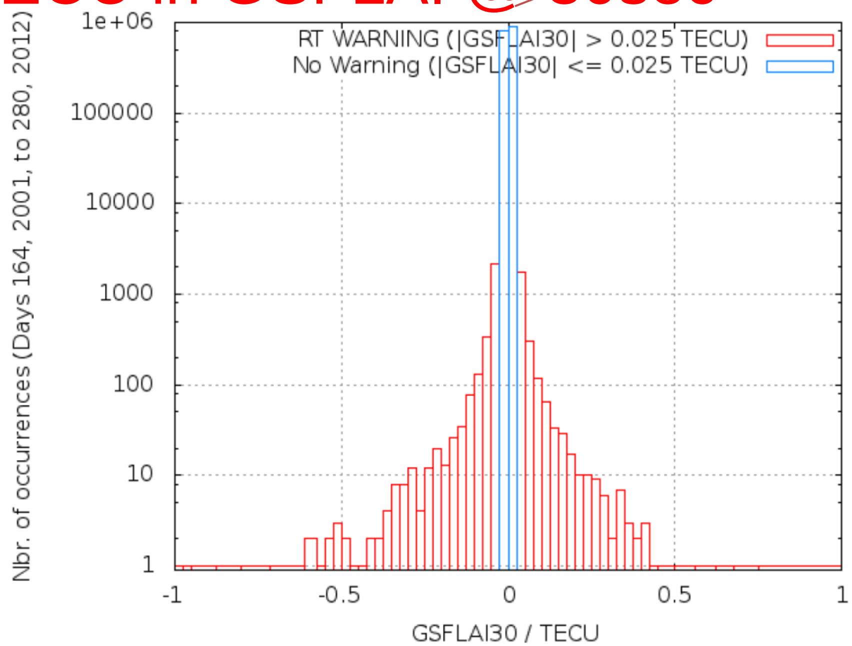


This does not happen by using **GSFLAI** (at 30 seconds in this case), due to **the requirement of the fulfillment of a solar-zenithal angle dependence** for any perturbation to be considered as a solar related one.

Distribution of GSFLAI @ 30 sec. during a whole Solar Cycle: day 164, 2001 to 280, 2012.



Adopted threshold of 0.025 TECU in GSFLAI @ 30sec



Solar Cycle minimum: No important Solar Flares during ~ 1000 days, between 2008 and 2010.

In this period the GSFLAI @ 30 sec has been computed in **real-time** in the context of the UPC contribution to **MONITOR ESA funded project.**

Other recent findings on Solar Flares by analyzing GSFLAI time series since 2001

- The solar flare time series have **extreme properties regarding amplitude and time correlation.**

- The **fractional Brownian model** proposed in

Monte E., Hernández-Pajares, M. (2014). Occurrence of solar flares viewed with GPS: Statistics and fractal nature, Journal of Geophysical Research: Space Physics, 119, 11, 9216-9227.

accounts for the **probability of the observed extremely high values of the time series, and also with the fact that the flares appear in bursts**.

- Another practical consequence is that the statistical characterization done in this paper allows for the estimation of the probability of a given GNSS solar flare indicator value and also the length of a given burst of flares.

- The probability of observing a GNSS solar flare indicator threshold value 2 times greater than the maximum observed one in last solar cycle (Solar flare preceeding the Halloween geomagnetic storm), is once every 44 years approximately.

SISTED: The Solar Flare indicator based in similar principles than GSFLAI

GSFLAI has a counterpart associated detection algorithm, the Sunlit Ionosphere Sudden TEC Enhancement Detector (SISTED), based on the same physical foundations. It shows reliable detection performance of 94% of X-class solar flares during more than half solar cycle (and 65% for M-class flares).

All the non-detected 6% of X-class solar flares, with solar disc location information, fall on the solar limb, in a consistent way with the associated dimming of the geoeffective solar EUV flux.

Table 1.7: *Validated/Total SISTED detections and the corresponding percentage comparing with GOES X-ray events (XRA) and Optical flares observed in H-alpha (FLA) from the Edited Solar Events Lists. Results are obtained for the test dataset considering* $\Delta^2 V|_{thres} = 0.74$. *Remember that SISTED results from years 2001 and 2005 were already used as training set to adjust the detector parameters.*

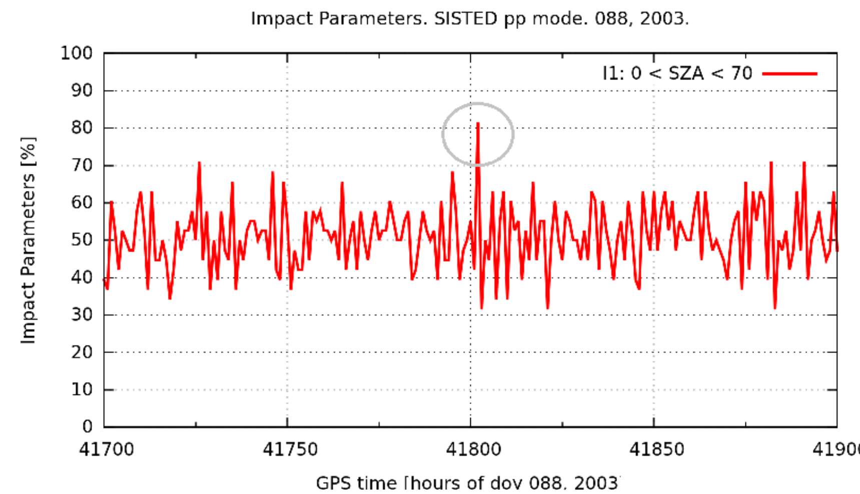
	Year	SISTEDvsXRA||FLA	GOES XRA		
			X-class	M-class	C-class
val./det.	1999	883/982	4/4	115/170	330/1854
	2000	1222/1309	16/17	137/215	426/2262
	2002	970/1032	11/12	129/219	375/2319
	2003	693/742	18/20	91/160	170/1316
	2004	569/590	12/12	78/122	145/913
	2006	111/114	4/4	9/10	24/150
	2007	48/49	0/0	6/10	9/73
	TEST	4496/4818	65/69	565/906	1479/8887
percent.%	TEST	**93.4%**	**94.2%**	62.4%	16.6%

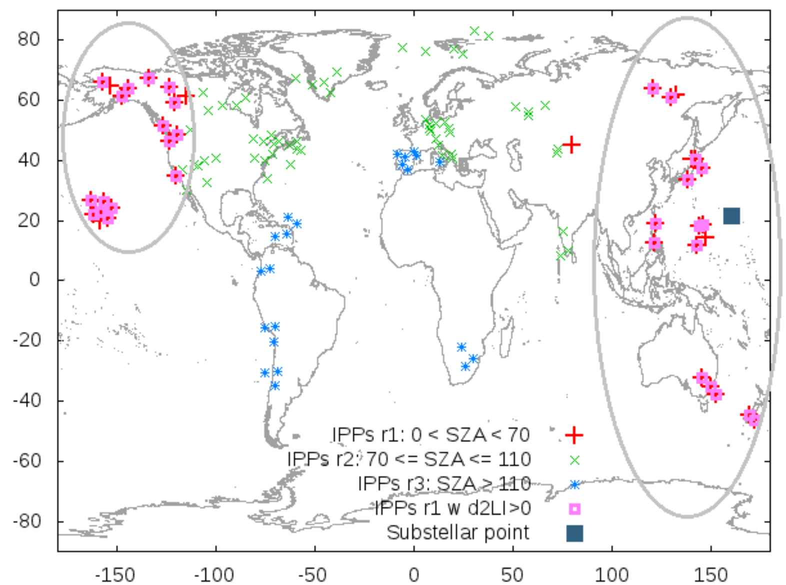
First GPS signatures of stellar bursts?

Launching **SISTED** @ 1 Hz to **GRB030329**.
GRB_Time: 11:37:14.67 UT (SOD: 41834.67)

Could it be a coincidence or a detection?

Ref. http://gcn.gsfc.nasa.gov/other/030329.gcn3





Day 88, 2003 IPPs distribution.

At the time of the event the **substellar point was at the Pacific Ocean** and the IPPs in the sunlit región were at West North America to East Asia.

A total of **31 illuminated IPPs out of 38 during the stellar burst.**

Conclusion

- GNSS proves again its versatility and power in order to become not only an extremely sensitive and accurate global ionospheric sounder but a calibrated solar observational instrument as well, able to provide reliable estimates of the **Solar EUV flux rate during Solar Flares**.

Thank you

This work has been partially funded by European Space Agency's MONITOR & MONITOR2 projects (ESA/ESTEC TEC-EEP)