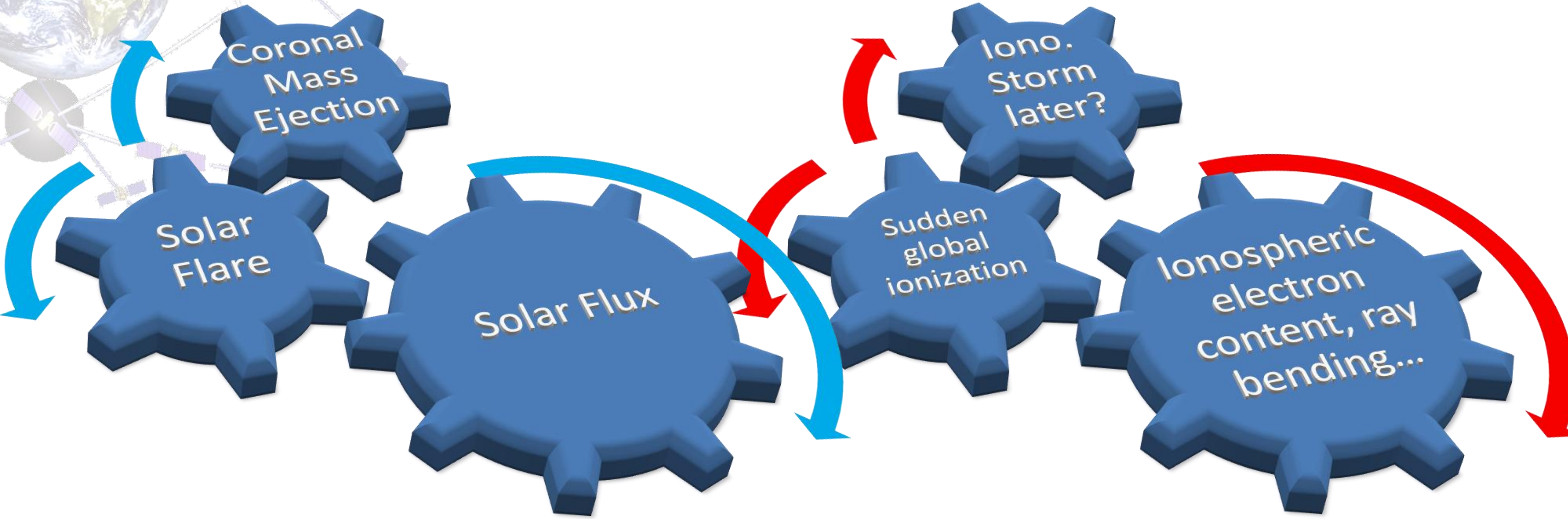
GPS as a Solar Flare EUV flux-meter



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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

3.d) “Fractality”: fractional Brownian model proposed (GSFLAI probability and length of a given burst of flares).

3.e) SISTED: Solar flare indicator index.

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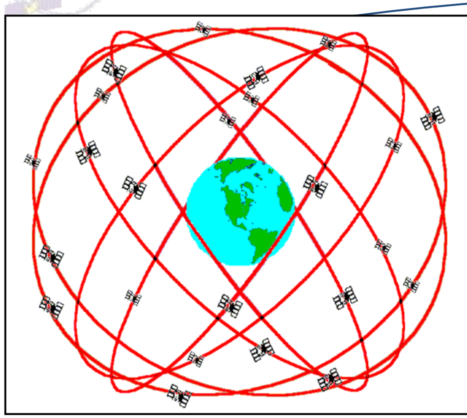
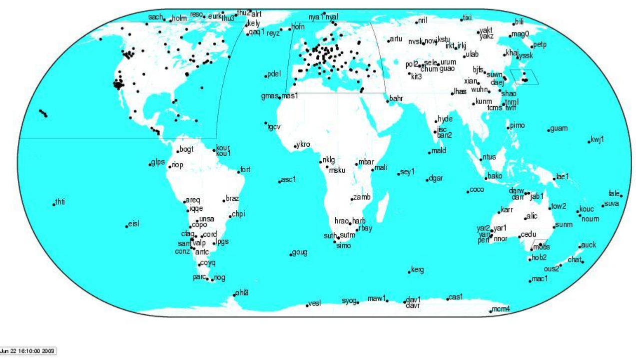
1. Introduction

Introduction: from GNSS to “GISS”



GNSS

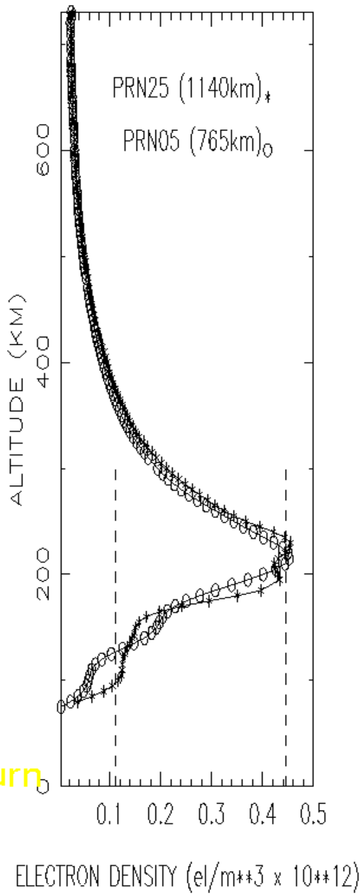
Sat. + Rec.

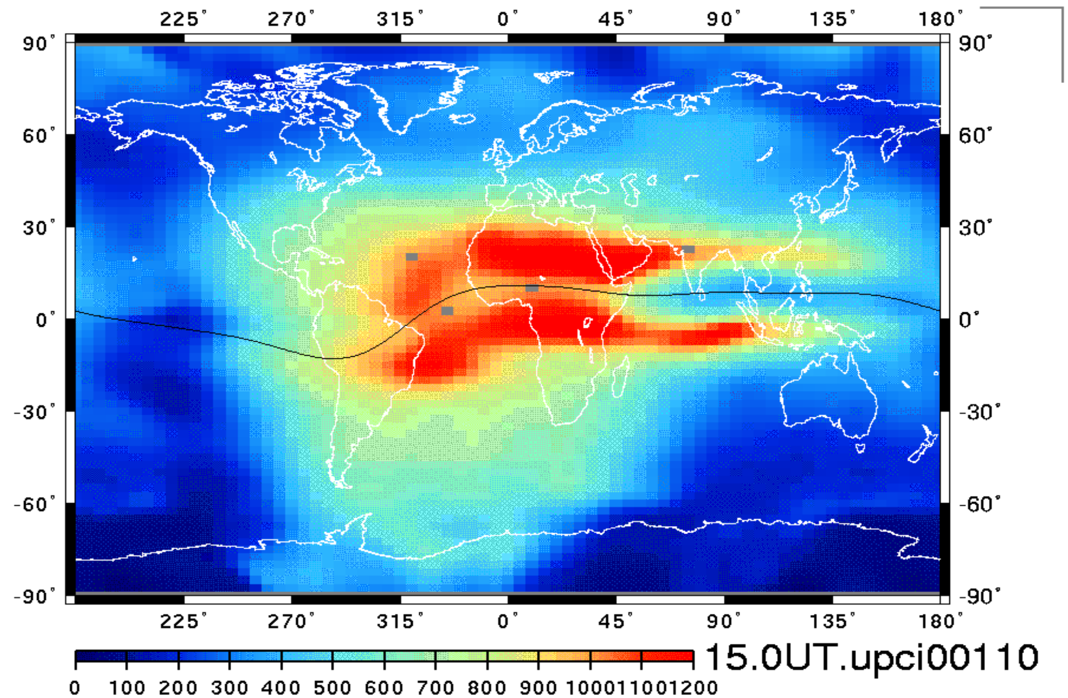


Global Ionospheric Sounding System (GISS)

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





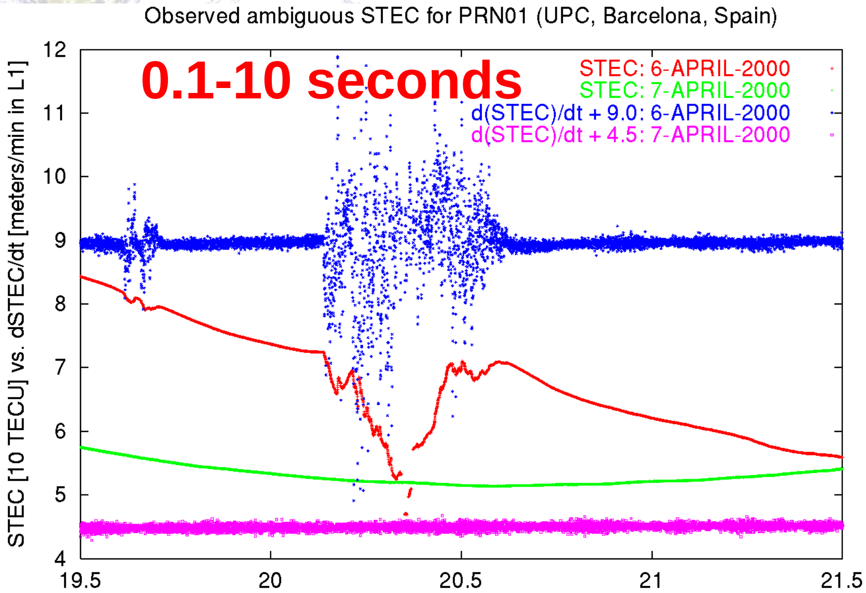
Global Vertical Total Electron Content (VTEC) map computed from ~100 GPS dual-freq CORS (units: 0.1 TECU). [*]

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

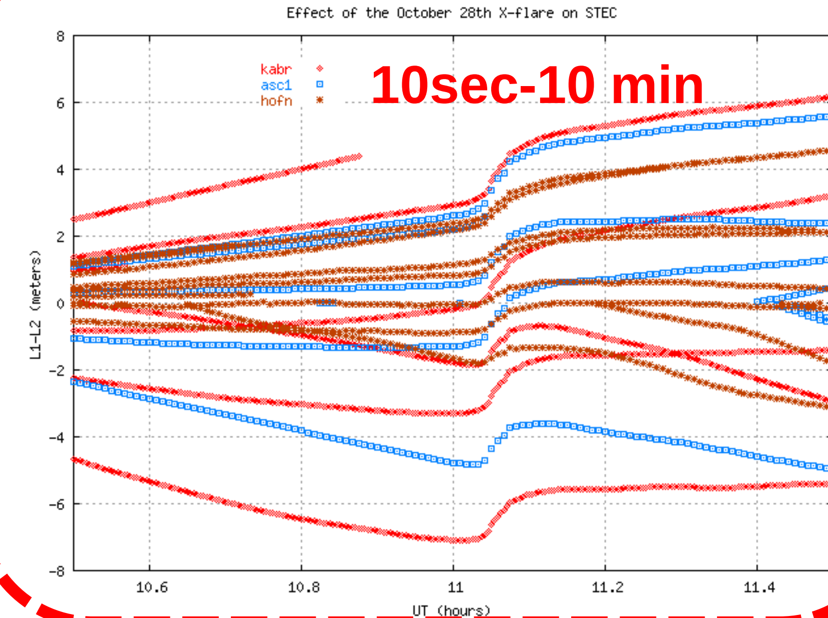
[*] Computed with UPC-TOMION soft

Introduction: iono. time variability

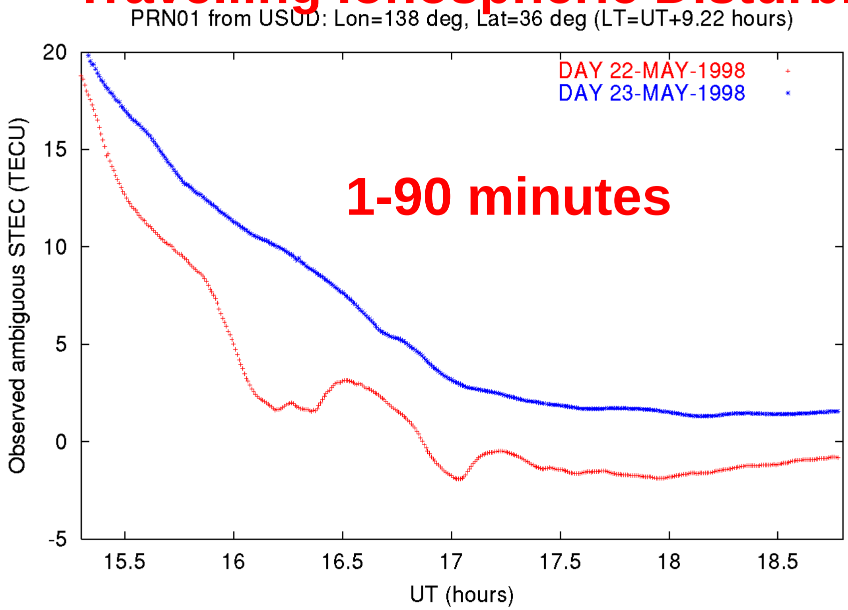
Scintillation



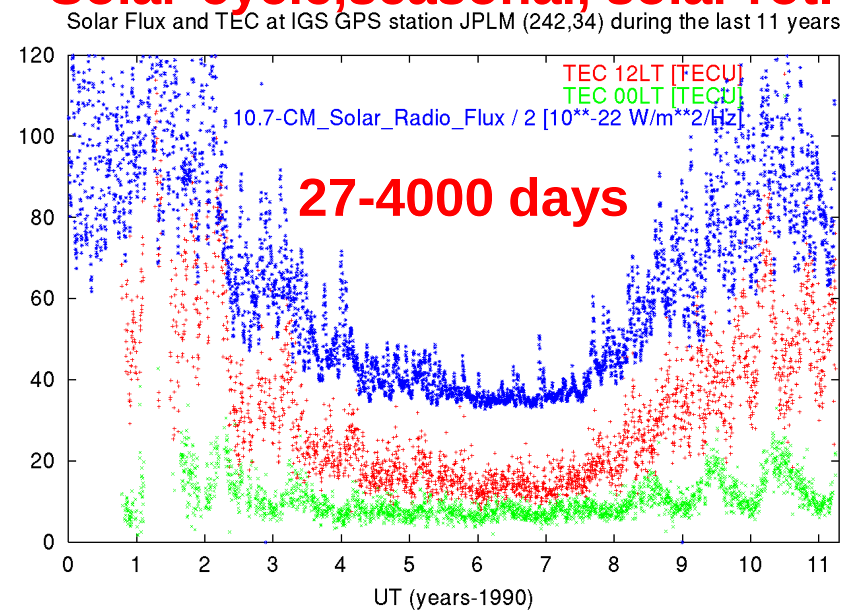
Solar Flare sudden overioniz.



Travelling Ionospheric Disturb.

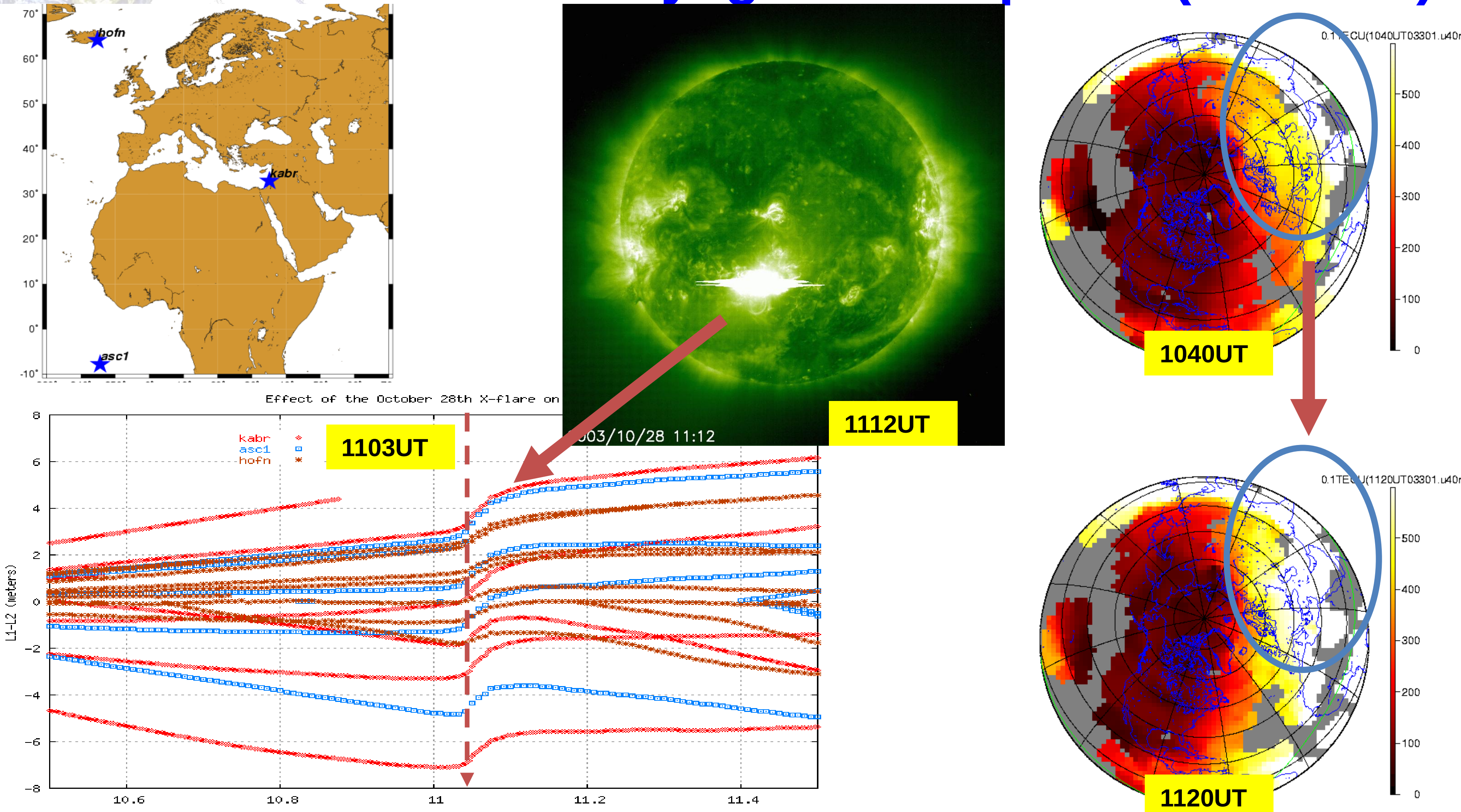


Solar-cycle,seasonal, solar rot.



2. Sudden global daylight overionization

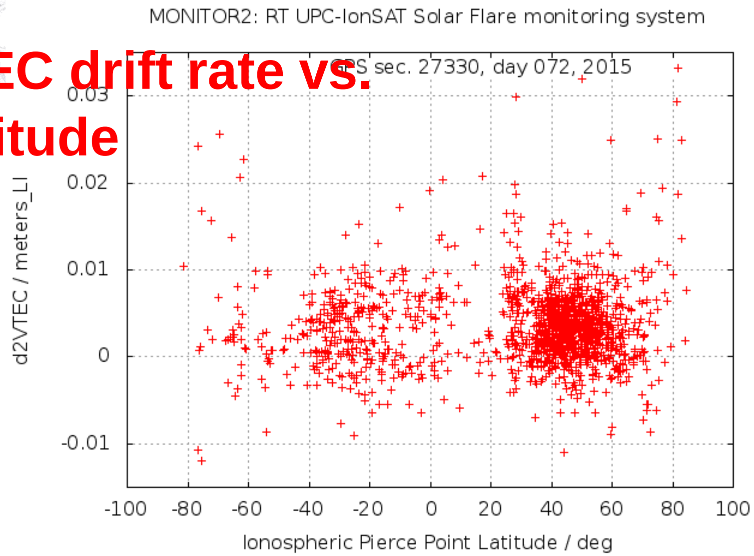
Solar X-class flare producing a global and sudden TEC increase in the daylight hemisphere (28Oct03)



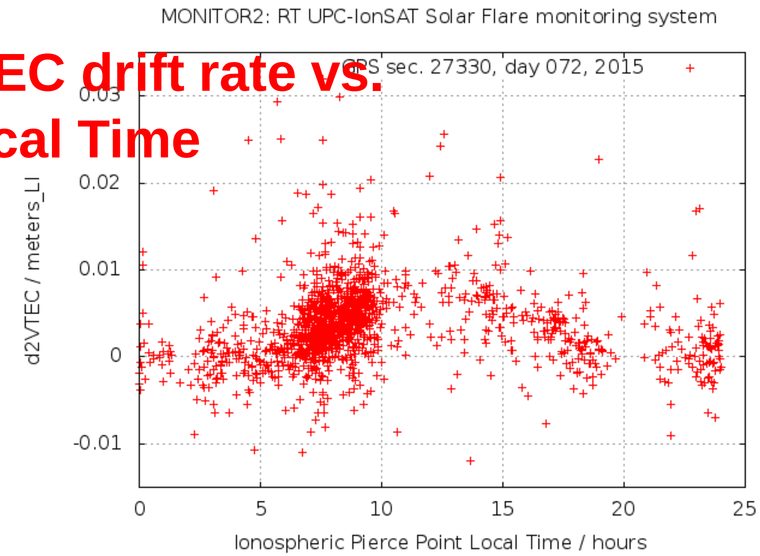
Sudden TEC increase of 10+ TECU experienced in the daytime hemisphere due to the arrival of a Solar X-flare X-rays/UV extra radiation (event during 28th Oct. 2003, 11UT approx, preceding superstorms) clearly seen by GPS rec.

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

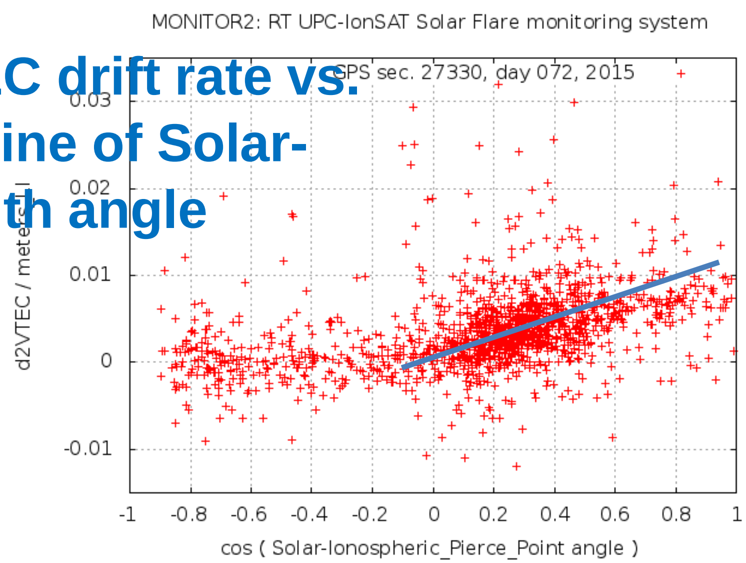
VTEC drift rate vs. Latitude



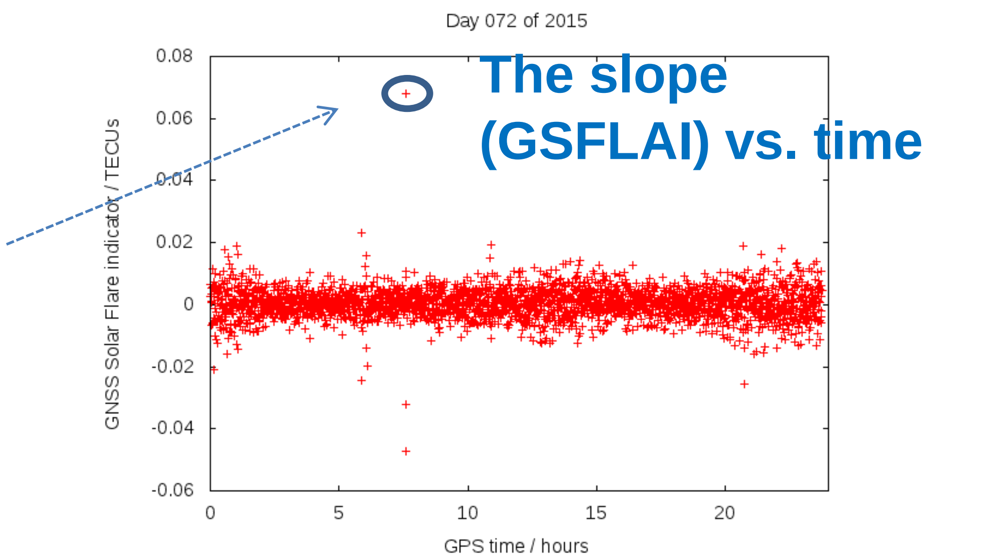
VTEC drift rate vs. Local Time



VTEC drift rate vs. Cosine of Solar-zenith angle

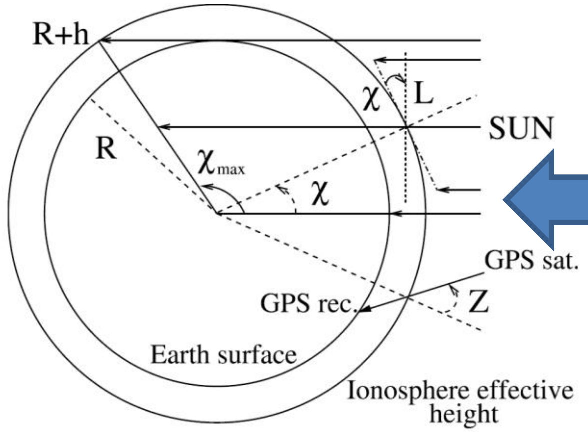


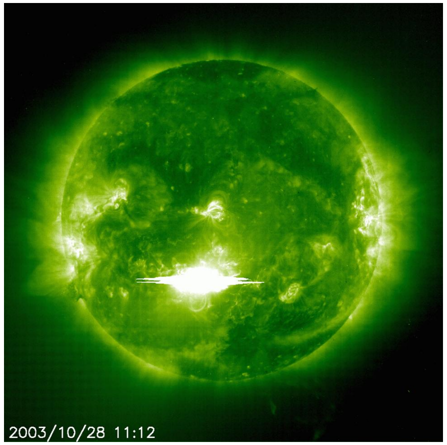
The slope (GSFLAI) vs. time



3. GSFLAI

Overionization model: First principles, GPS… and GSFLAI

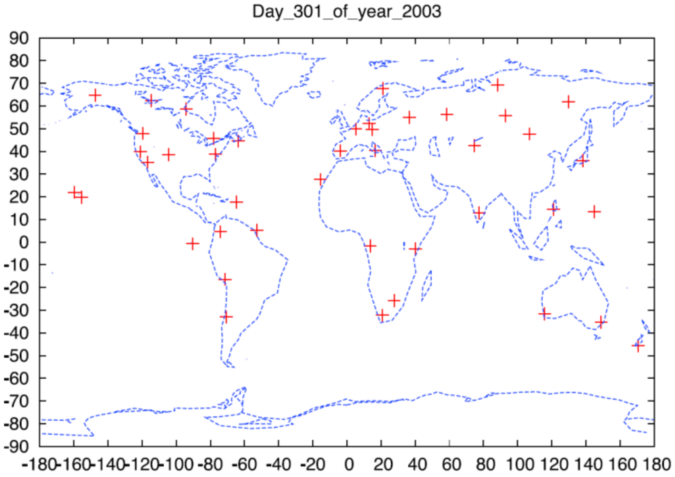


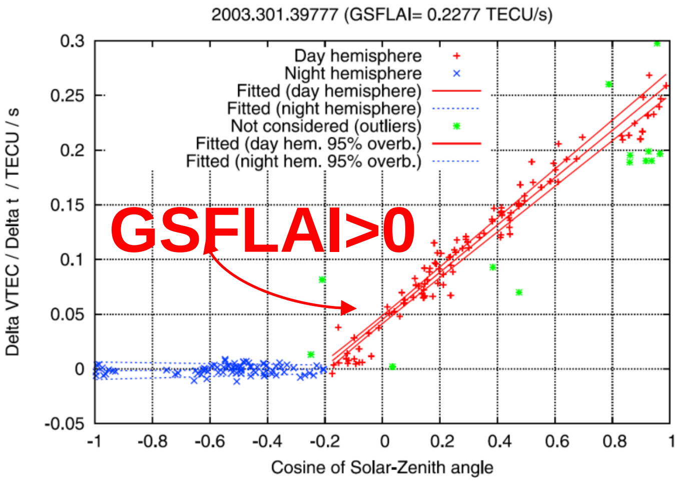


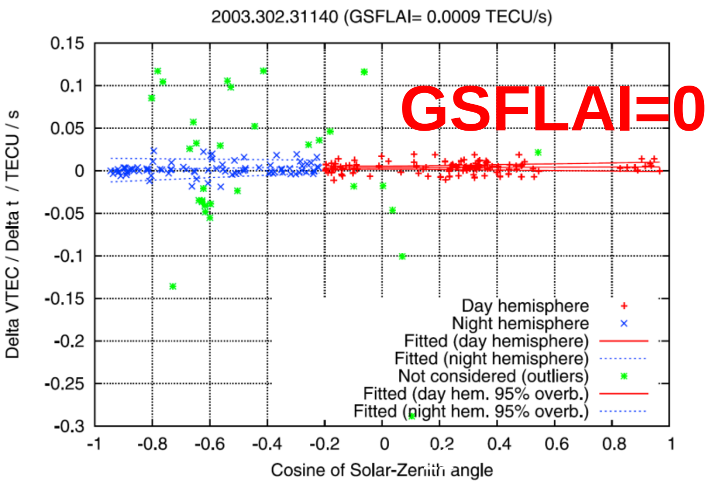
$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I}$$

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

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



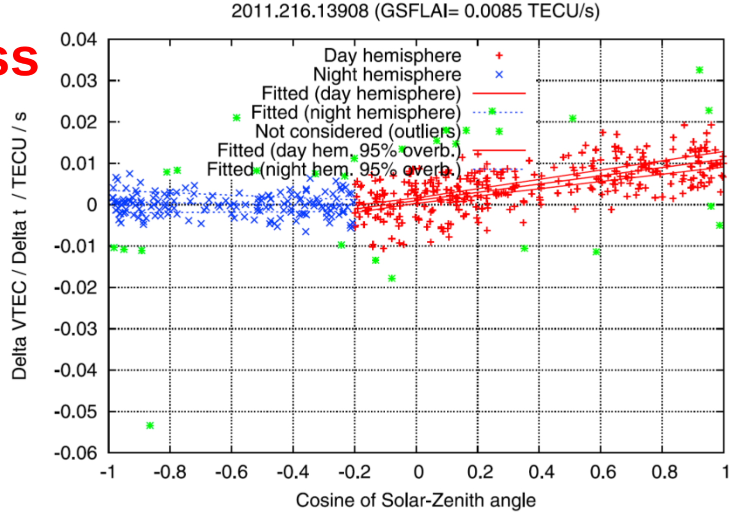


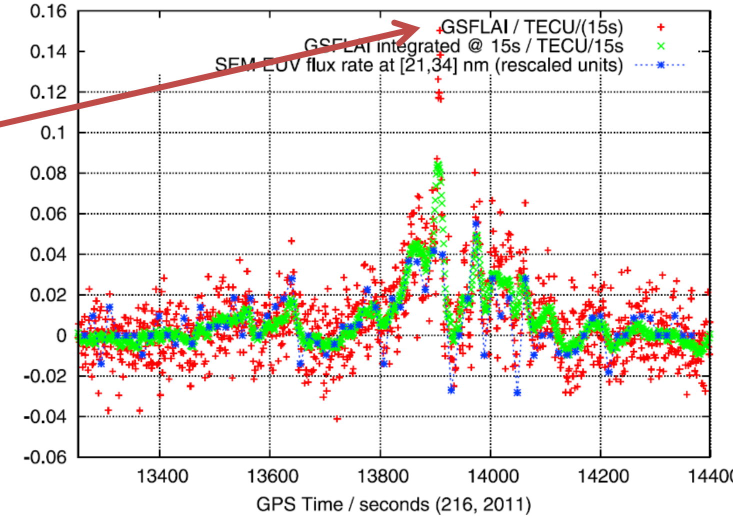


During the next day **major geomagnetic storm peak**, the higher **variations do not follow the SF spatial pattern**, and GSFLAI (=0) performs again well.

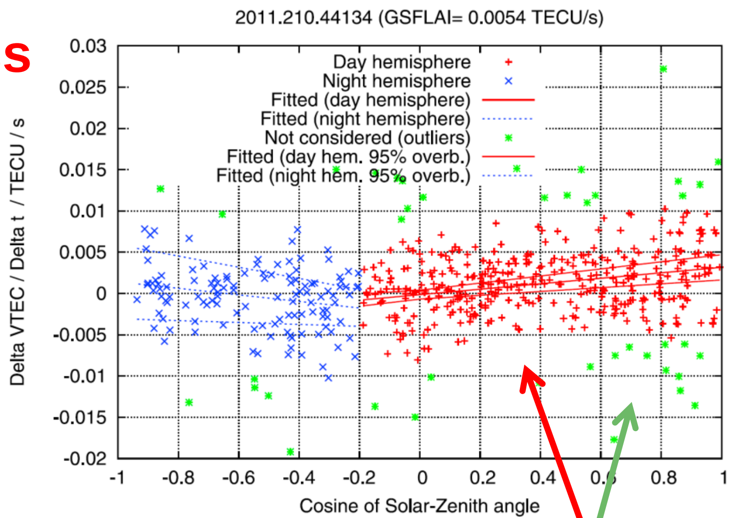
GSFLAI is a good proxy of direct EUV rate meas., also for M- and C-class Solar Flares

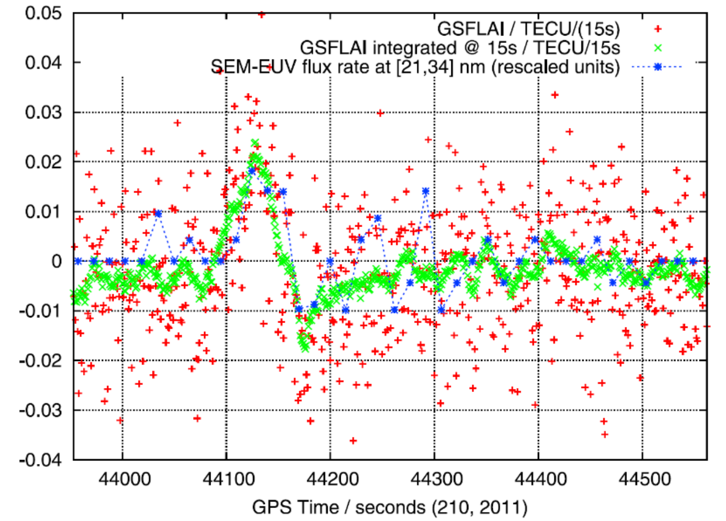
M-class





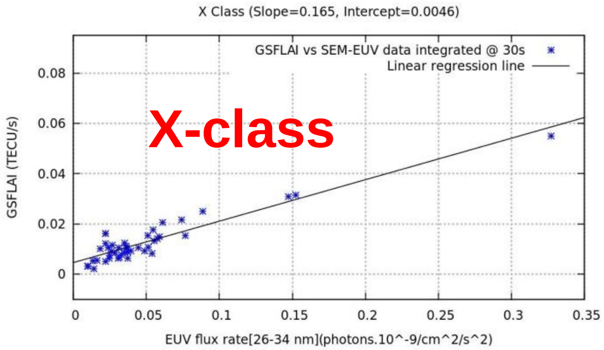
C-class

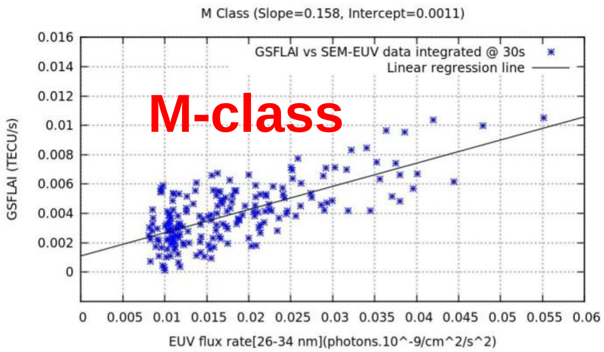


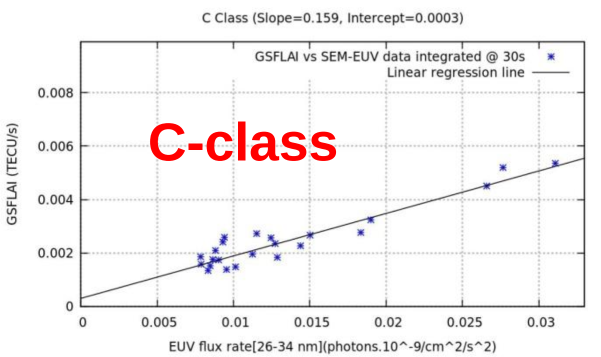


Iterative voting scheme to find the optimal fitting result (outlier detection method similar to RANSAC)

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.

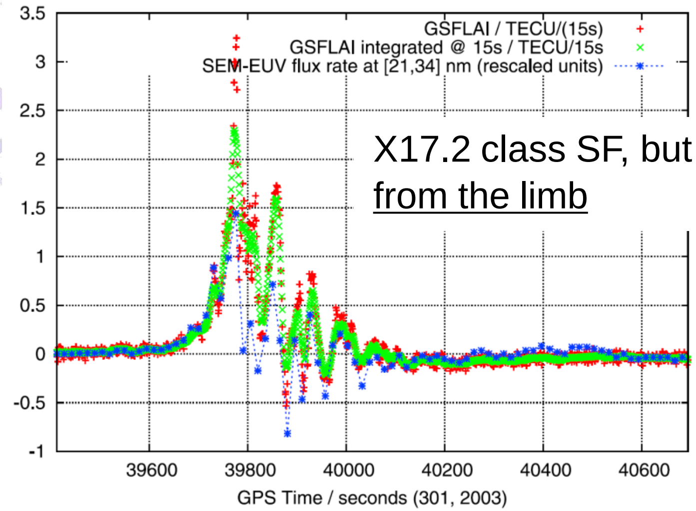
More details in ***Singh, T., M. Hernandez-Pajares, E. Monte, A. Garcia-Rigo, and G. Olivares-Pulido (2015), GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares, J. Geophys. Res. Space Physics, 120, doi:10.1002/2015JA021824.***

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

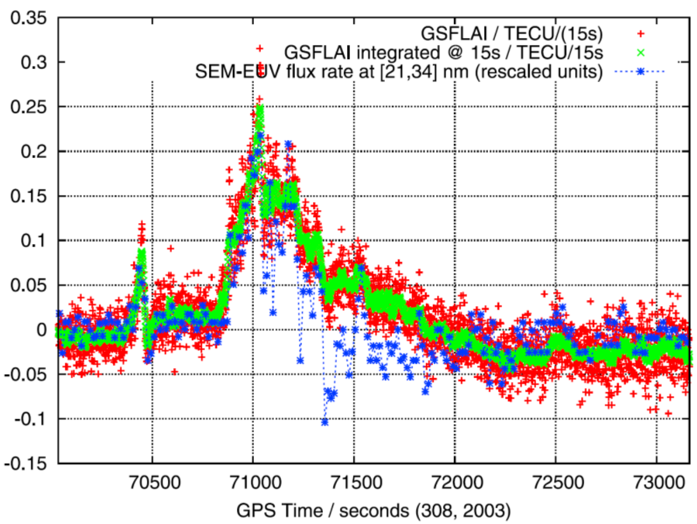
[a] The units are $TECU/s$ for GSFLAI and $photons.10^-9/cm^2/s^2$ for EUV flux rate.

UPC

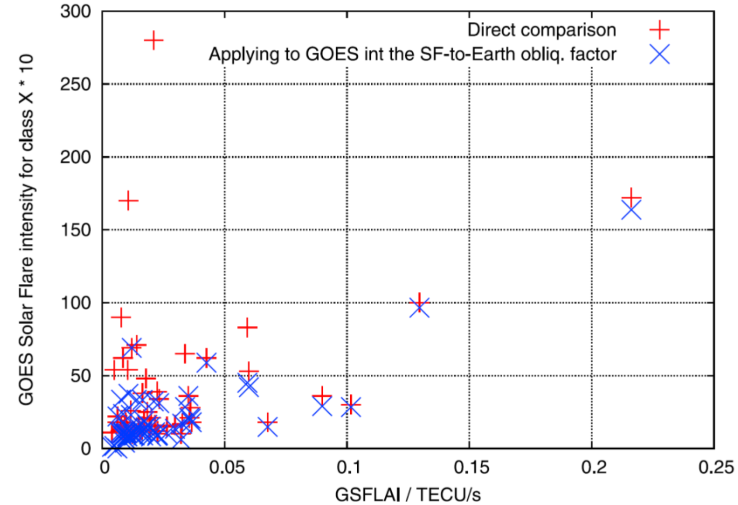
The Solar Flare location distance to the disc center (proximity to limb) matters....



X17.2 class SF, but <u>far from the limb</u>

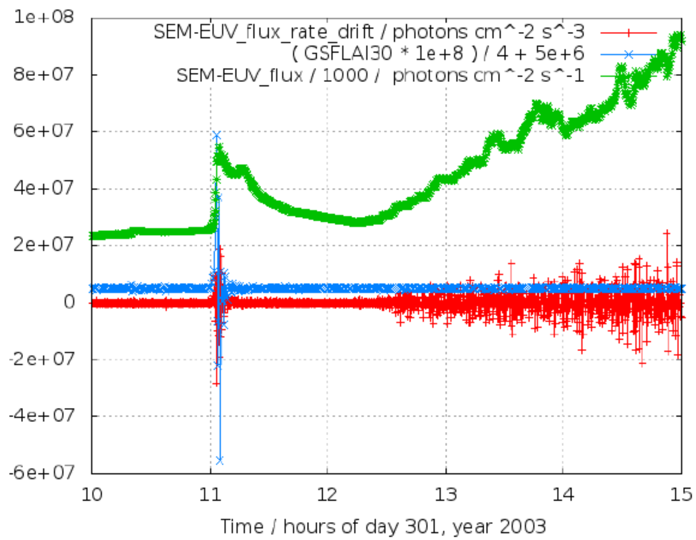


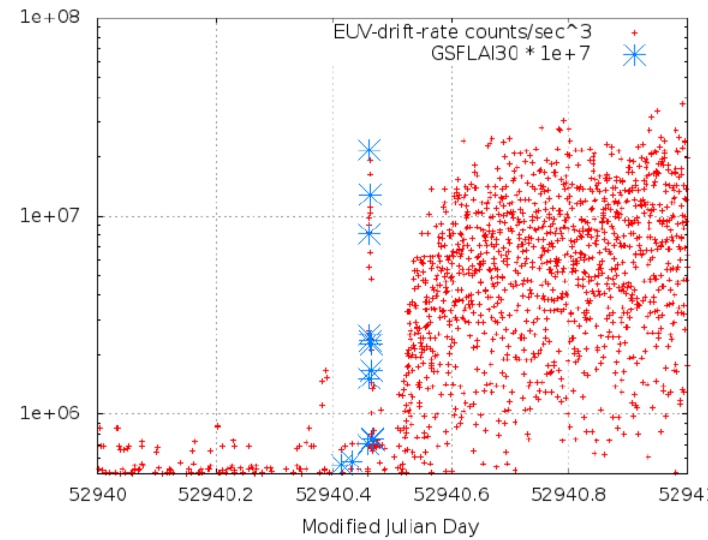
X28.0 class SF, but far from the Solar Disc, i.e. **close to the limb.**



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...).

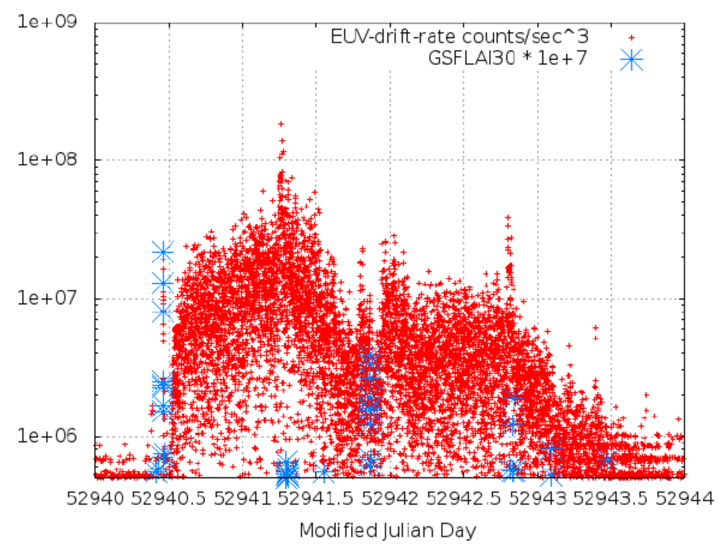
GSFLAI is immune to prompt particle contamination like relativistic electrons, affecting direct space-based measurements...



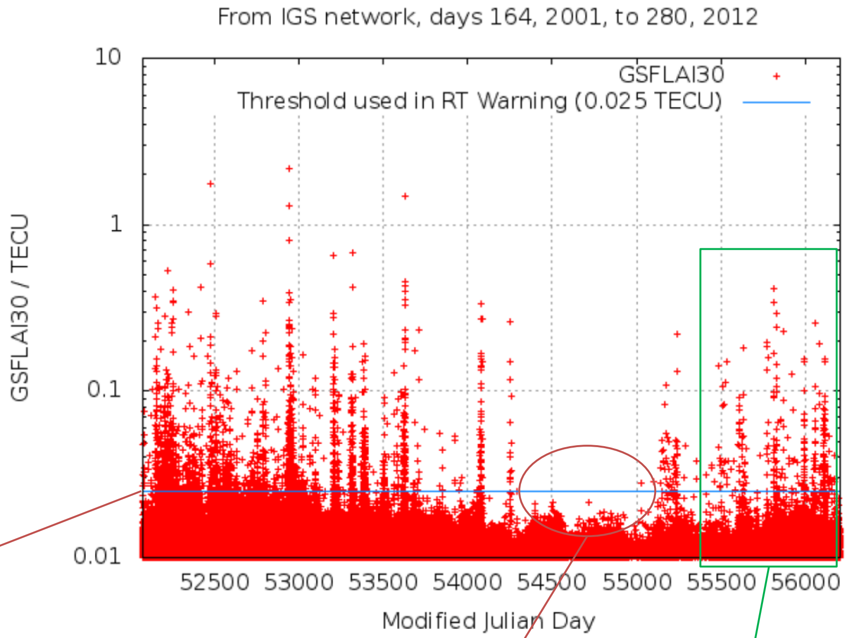


The **particle contamination** in the direct EUV flux readings (**SEM** measurements in green and its rate in red) can make difficult the detection of consecutive Solar Flares.

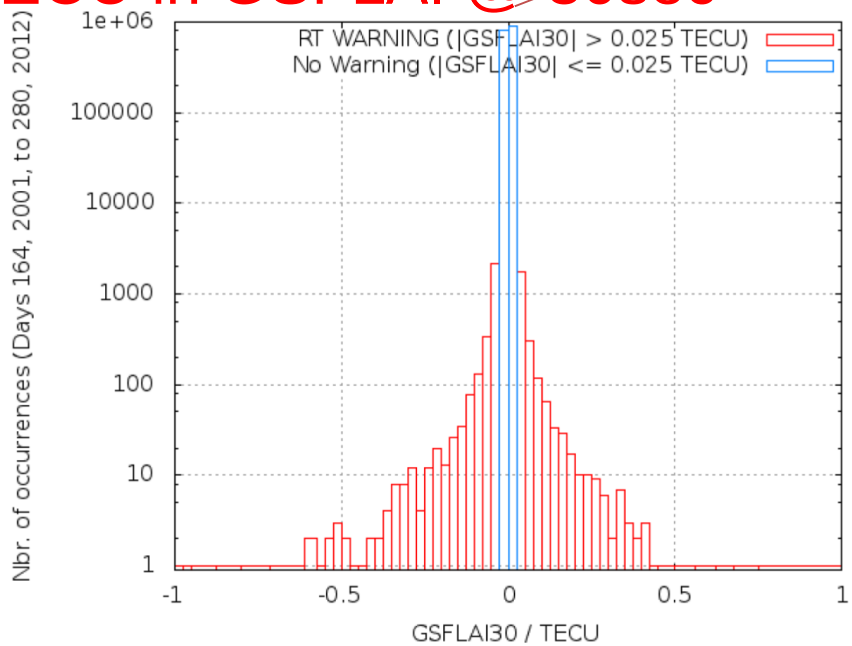
This does not happen by using **GSFLAI** (at 30 seconds in this case), due to **the requirement of the fulfillment of a solar-zenithal angle dependence** for any perturbation to be considered as a solar related one.



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**.

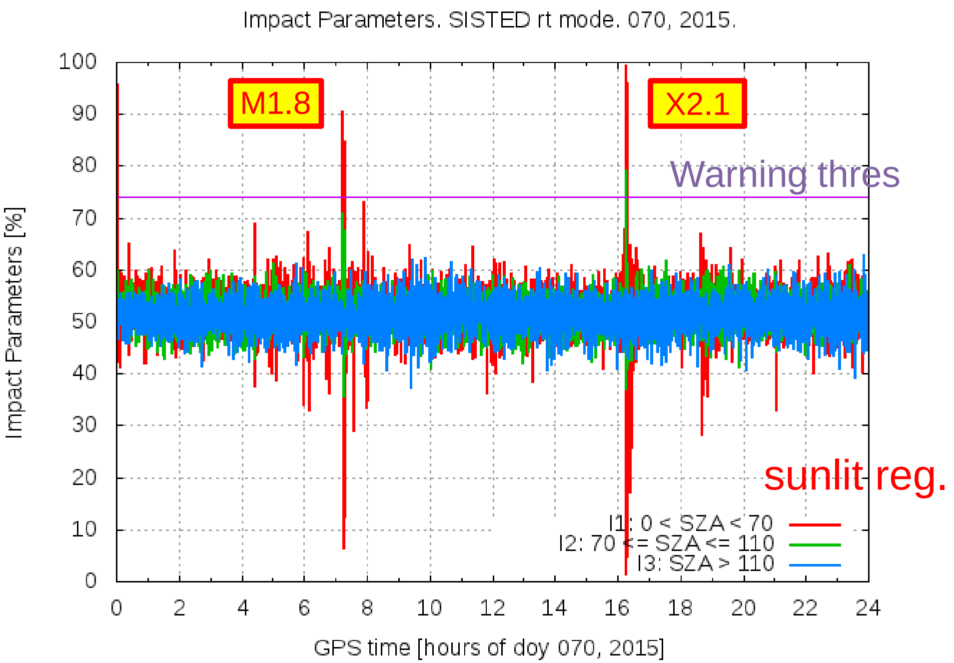
- Another practical consequence is that the statistical characterization done in this paper allows for the estimation of the probability of a given GNSS solar flare indicator value and also the length of a given burst of flares.

- 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**.



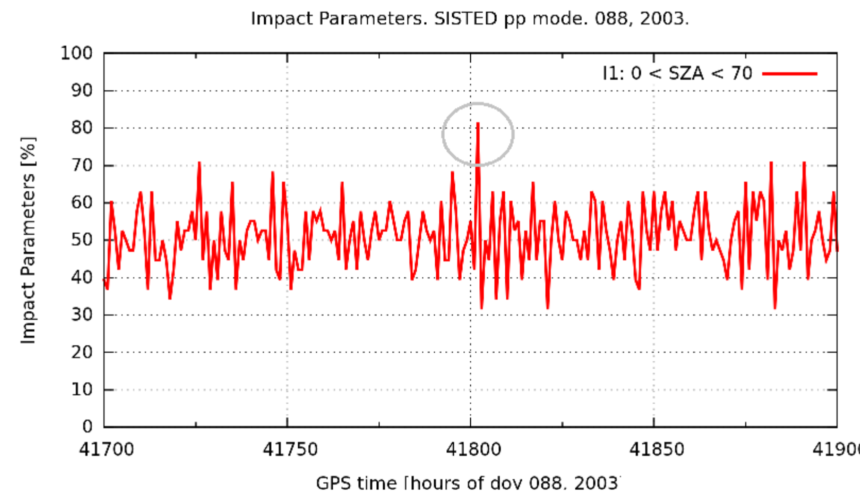
	Year	SISTEDvsXRA‖FLA	GOES XRA		
			X-class	M-class	C-class
	1999	883/982	4/4	115/170	330/1854
	2000	1222/1309	16/17	137/215	426/2262
	2002	970/1032	11/12	129/219	375/2319
val./det.	2003	693/742	18/20	91/160	170/1316
	2004	569/590	12/12	78/122	145/913
	2006	111/114	4/4	9/10	24/150
	2007	48/49	0/0	6/10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

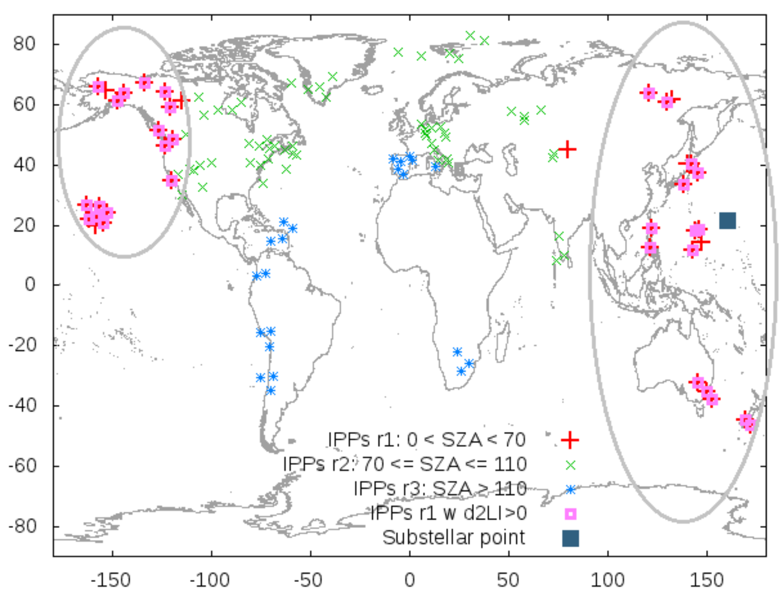
First GPS signatures of stellar bursts?

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)