IGS WORKSHOP 2017 PARIS JULY 3-7

SISTED & GSFLAI solar flare nowcasting products based on GNSS ionospheric monitoring, part of SSA's Ionospheric Weather ESC and ESA's MONITOR service

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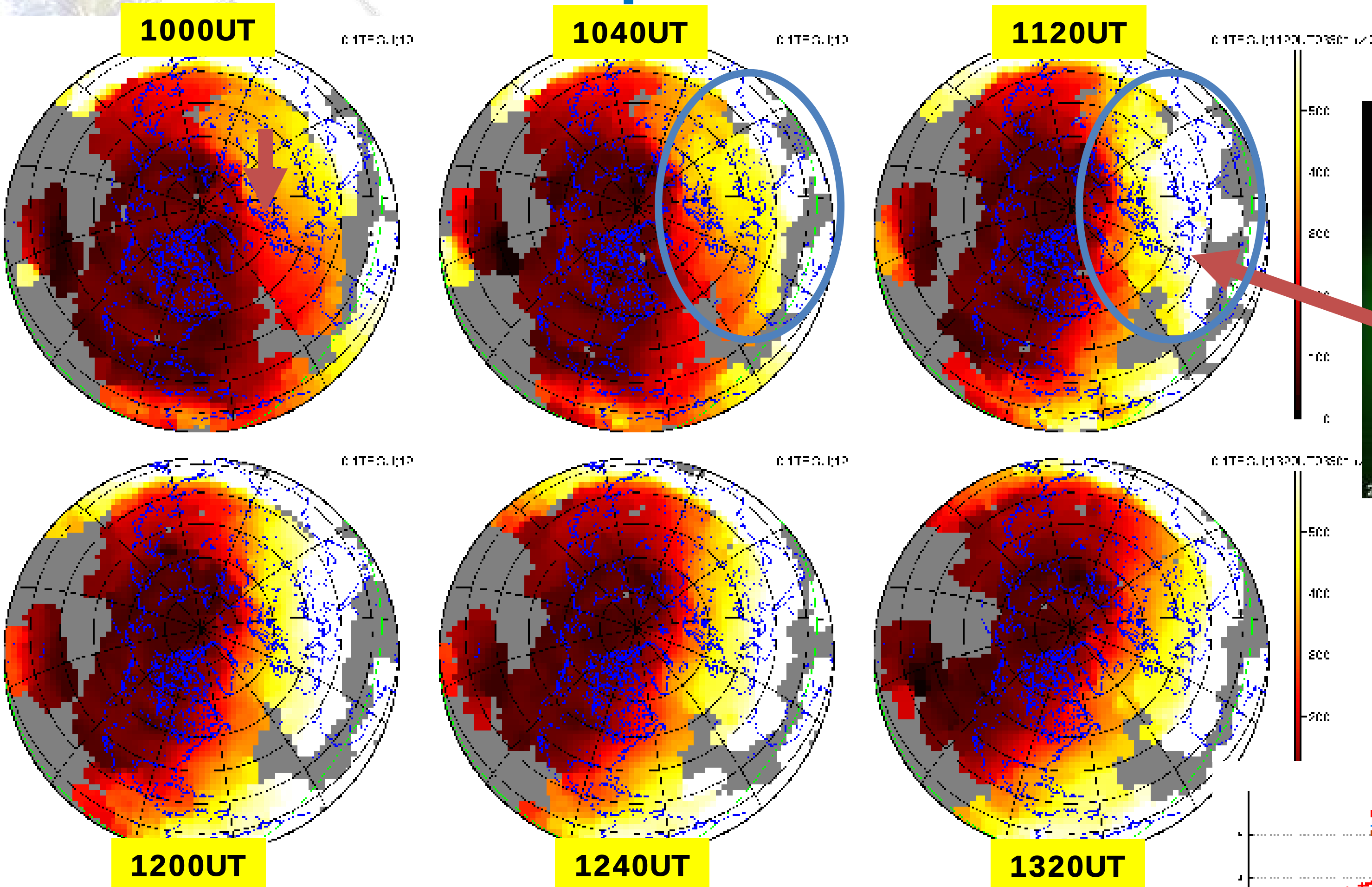
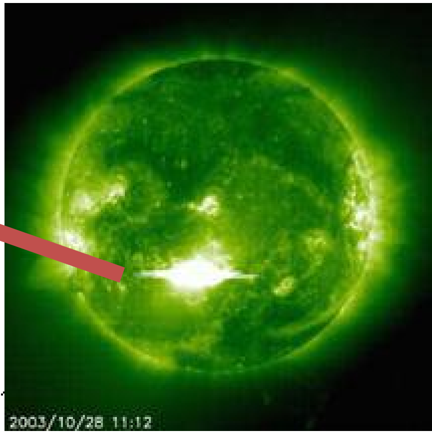
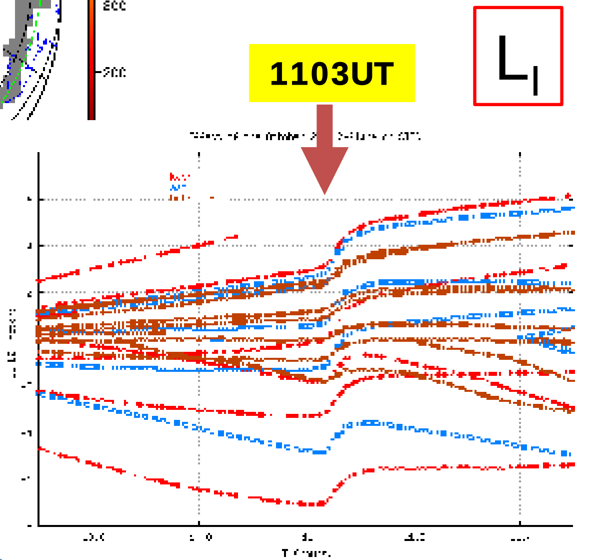
Sudden STEC increase in the day-side hemisphere due to Solar Flares



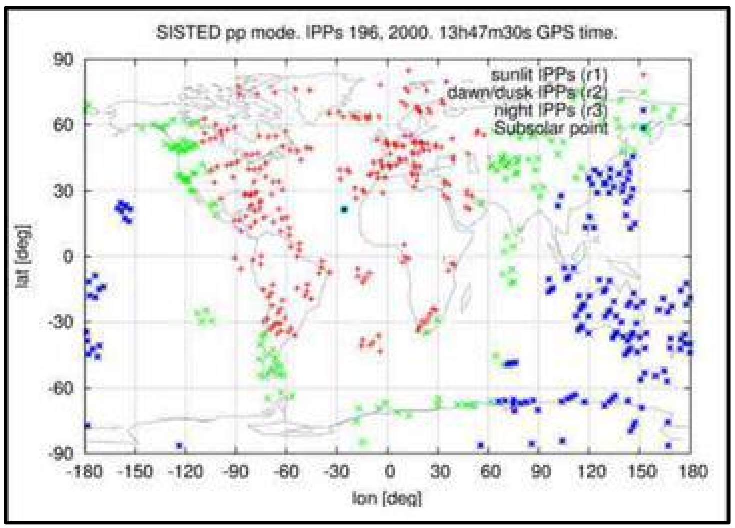




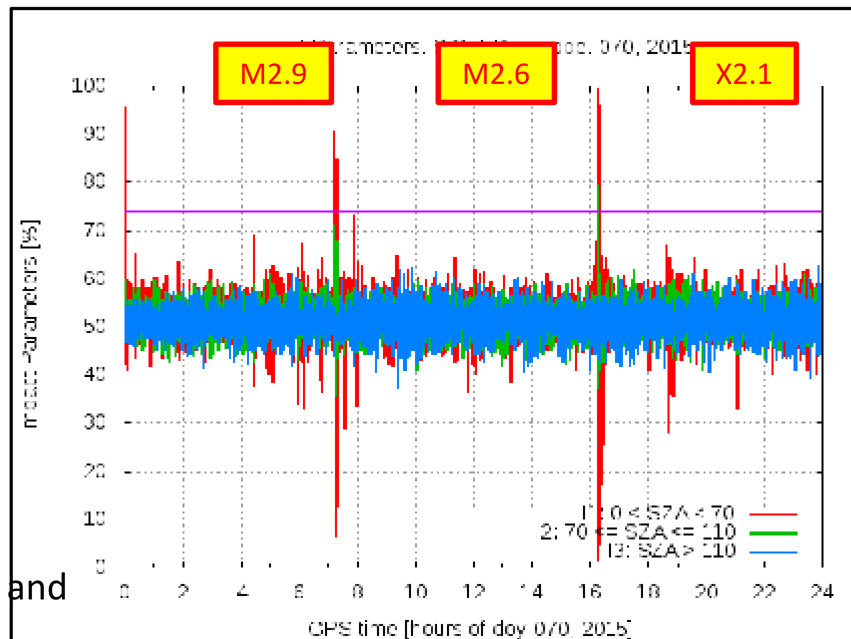
Huge and sudden STEC/LI variations are experienced in the daylight hemisphere GPS receivers due to the **overionization** associated to **solar flares increase of radiation** (e.g. Halloween event, 28 Oct. 2003, 11UT).

SISTED – Sunlit Ionosphere Sudden TEC Enhancement Detector

- **SISTED** is **monitoring simultaneous sudden enhancements in the ionospheric Total Electron Content (TEC) using the drift rate** (second difference in time) **of the carrier phase ionospheric combination (L_I),** linearly related to the Slant TEC (STEC).
- L_I are derived from GNSS signals gathered in **real time** by NTRIP datastreams world-wide.
- **Impact Parameters (IP)** account for **the percentage of Ionospheric Pierce Points** (IPPs) **affected by an abrupt overionisation** (positive drift rate) simultaneously in a certain region.
- A solar flare warning is triggered if the sunlit **IP** exceeds the threshold of 74%.



Distribution of IPPs in SZA regions (sunlit, dawn/dusk and night)



SISTED Impact Parameters obtained on 11th March, 2015

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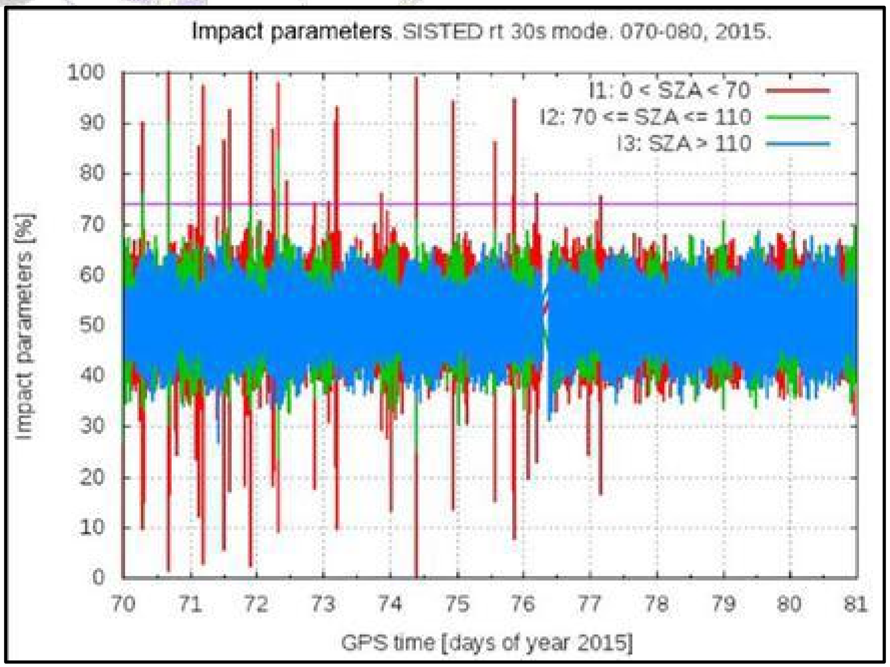
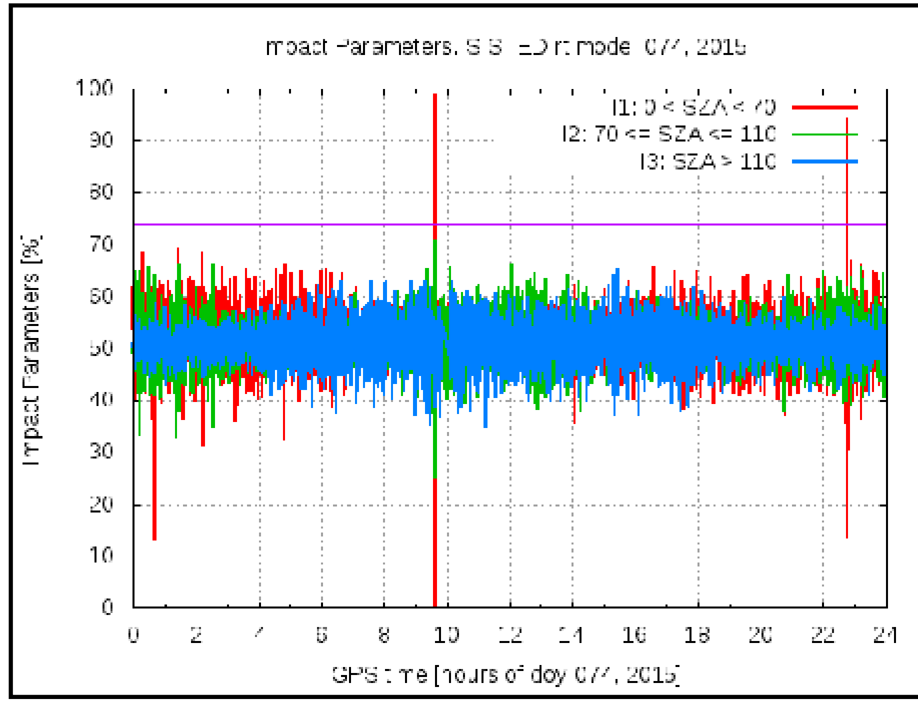
SISTED Impact Parameters





SISTED impact parameters evolution on days 70–80, 2015 (left) and zoom at 74, 2015 (right). The sunlit ionospheric region values are marked in red, the dawn and dusk values in green and the nighttime ones in blue (source: Béniguel et al. 2017).

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SISTED performance

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
	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%

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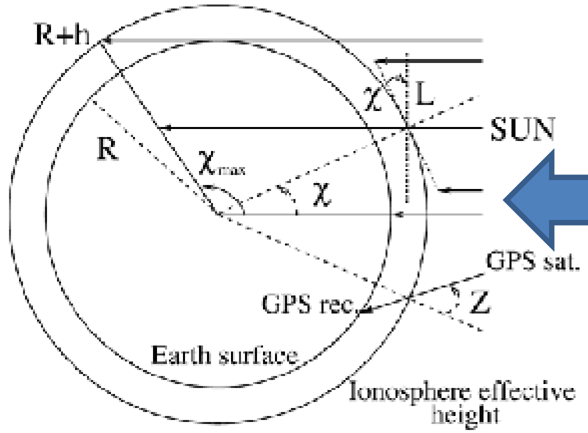
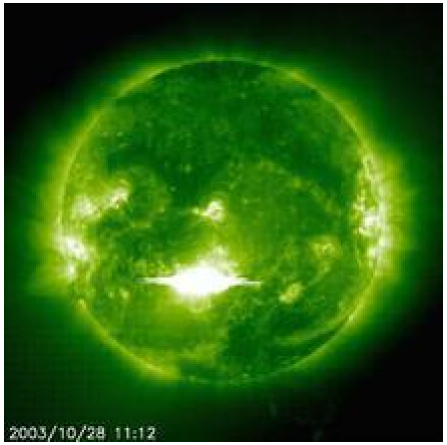
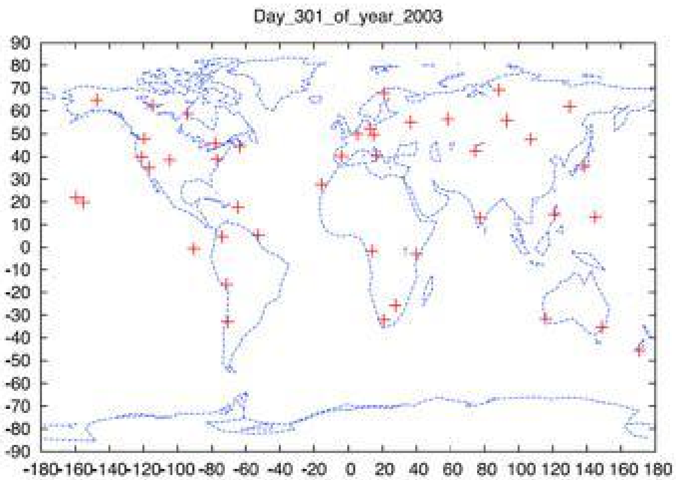
Overionization model: First principles, GPS… and GSFLAI



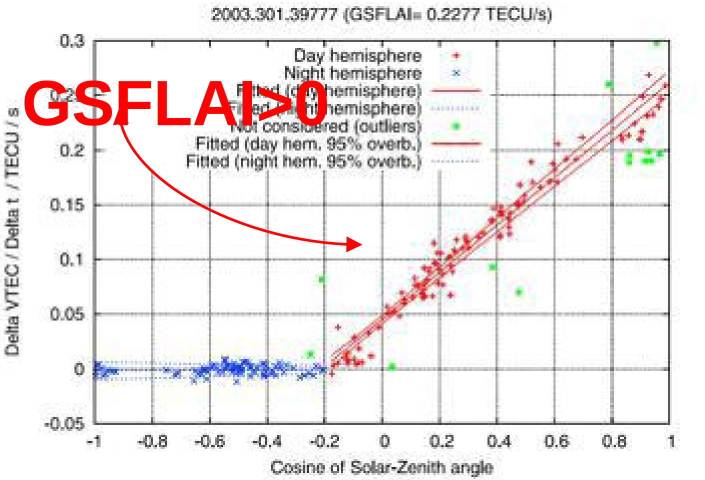


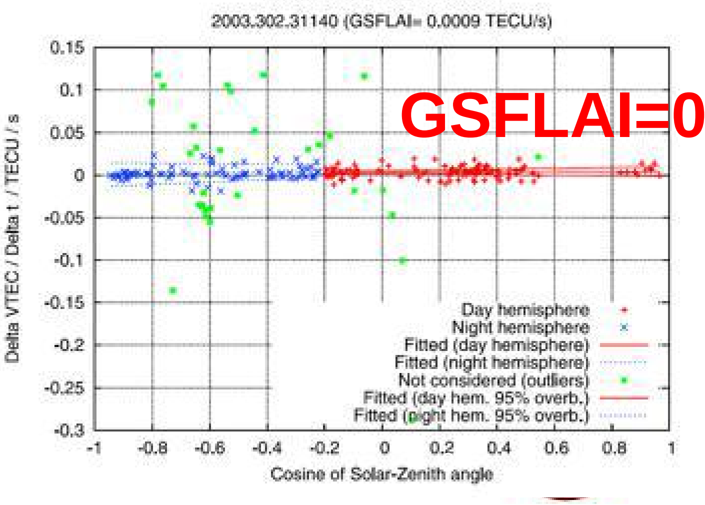
$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I}$$

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



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

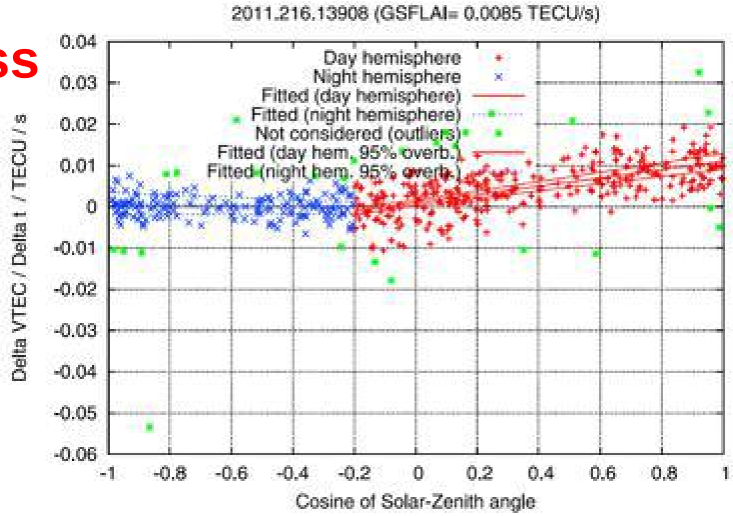


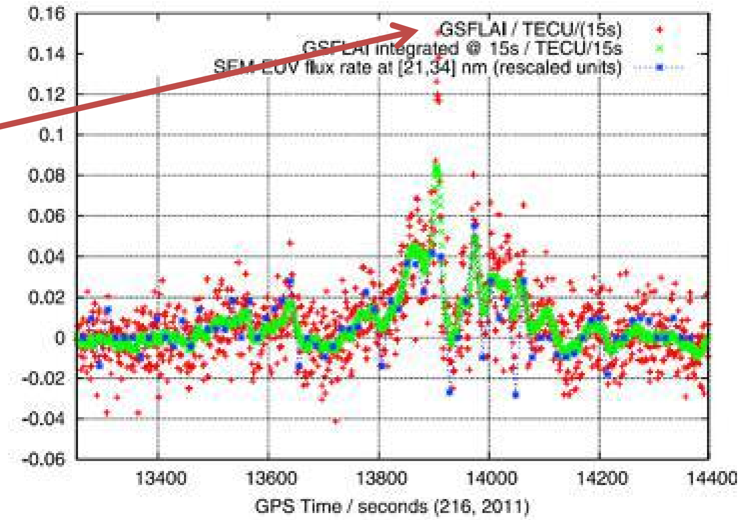


During the next day major geomagnetic storm peak, the higher variations doesn't follow the SF spatial pattern, and GSFLAI (=0) performs again well.

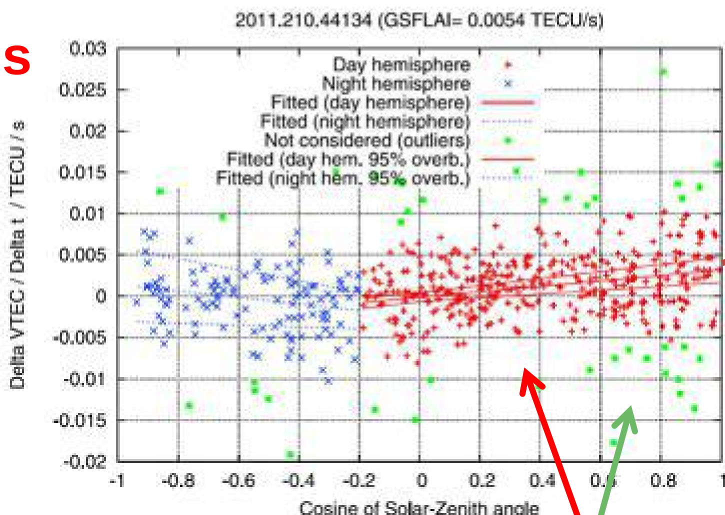
GSFLAI is a good proxy of direct EUV rate meas., also for M- and C-class Solar Flares

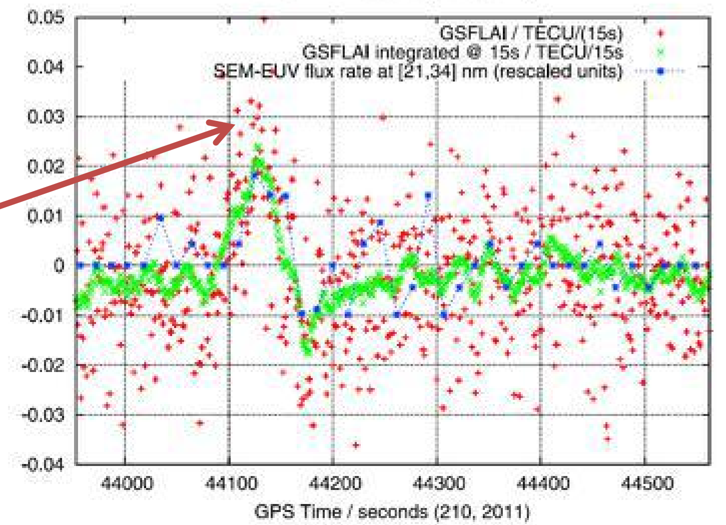
M-class





C-class





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

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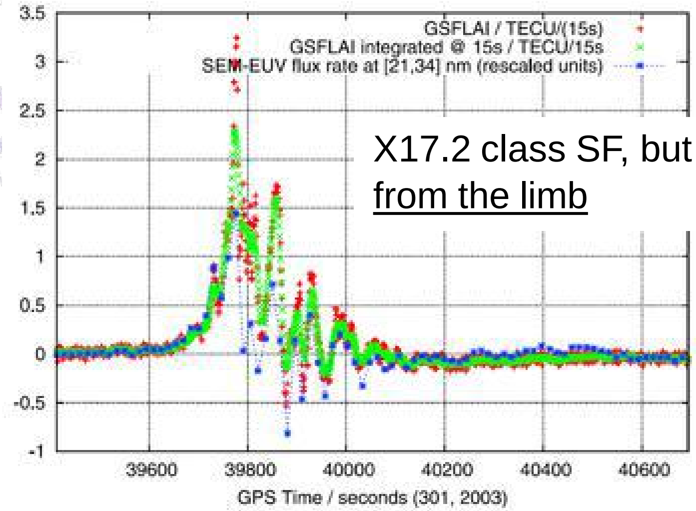
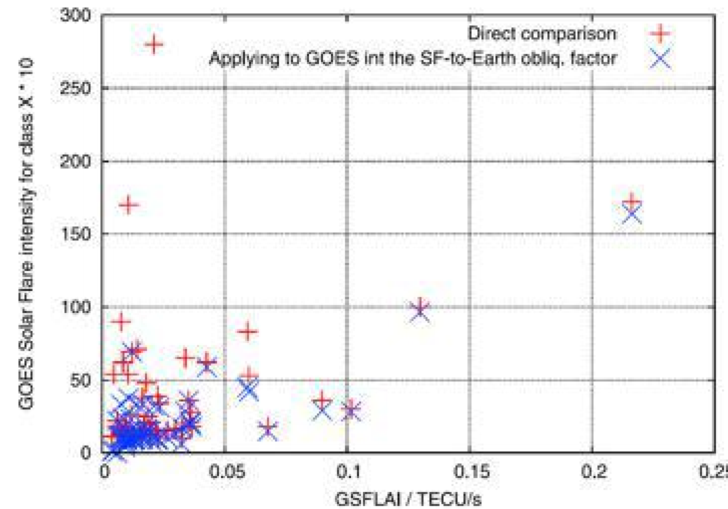
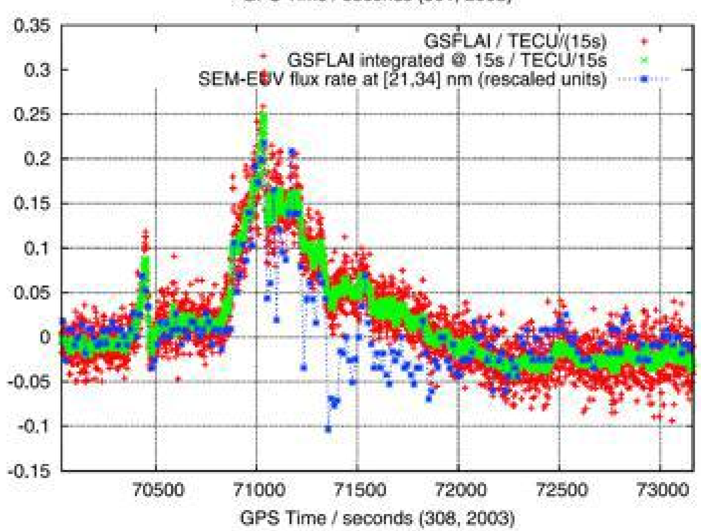
The Solar Flare location distance to the disc center (proximity to limb) matters....



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.**

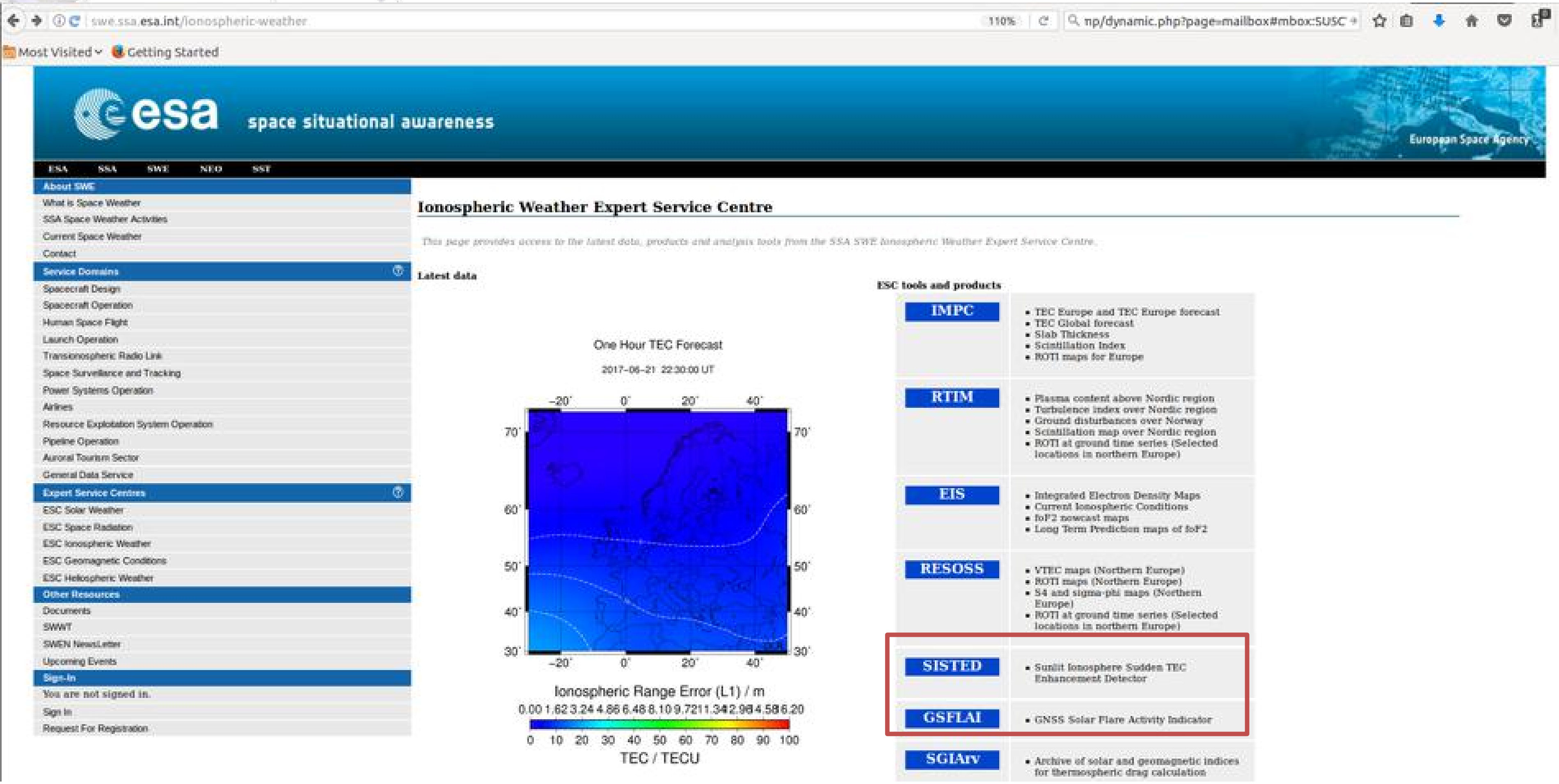
After applying a **simple extinction law from Solar disc distance**, **a relationship of GSFLAI with GOES X-ray based classification is disclosed**, making feasible its usage as geophysical index (a potential proxy of GOES classification...).

MONITOR – SISTED/GSFLAI

http://monitor.estec.esa.int

Space Weather I-ESC products

http://swe.ssa.esa.int/ionospheric-weather



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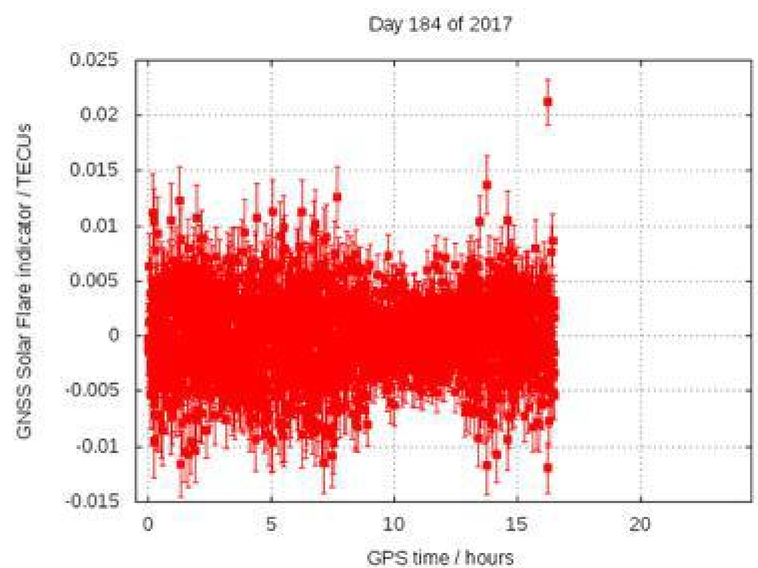
GSFLAI@184, 2017 M1.3 flare

Federated products from the Finnish Meteorological Institute (FMI)

FMI | Introduction | SISTED | GSFLAI | Additional Information | Acknowledgements

In addition to the text file, GSFLAI generates a plot (below) showing the time evolution of the daylight correlation solar flare coefficient. The plot is generated in UPC once per 15 min after which it is updated to this page. Values of the daylight correlation solar flare coefficient exceeding 0.025 TECU can be associated with flare activity. STD values exceeding one third of the daylight correlation solar flare coefficient values are a signal of increased uncertainty in the estimated flux rate. The time axis in these plots is given as GPS time, which is 17 s ahead of UTC (year 2016).



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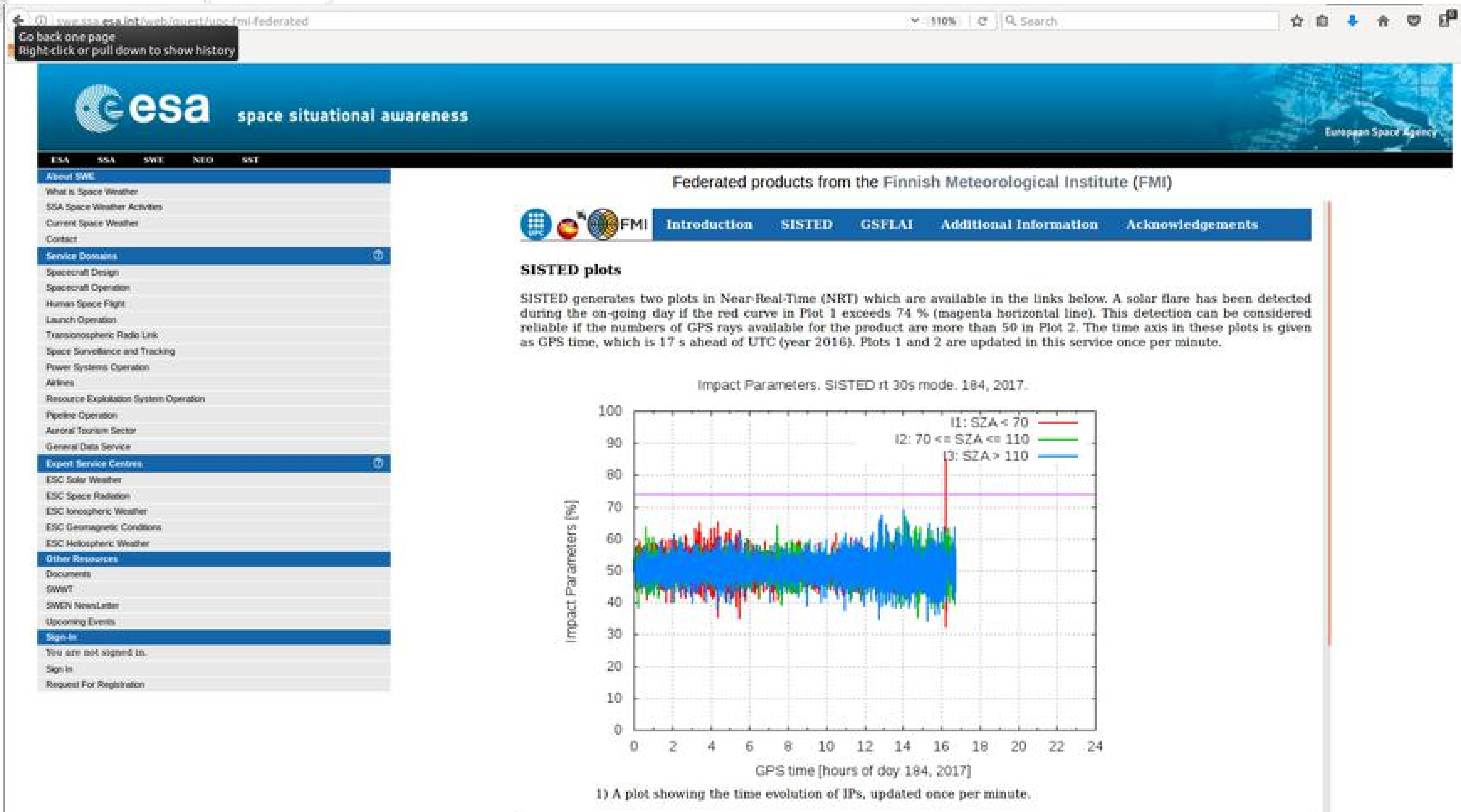
SISTED@184, 2017 M1.3 flare



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Warning e-mails

[ips-flare-alert] IPS FLARE INFORMATION - END OF EVENT issued 1619 UT on 03 Jul 2017 [SEC=UNCLASSI...	Regional Warning Centre	18:19
[ips-flare-alert] IPS FLARE INFORMATION - START OF EVENT GT C8 issued 1616 UT on 03 Jul 2017 [SEC=...	Regional Warning Centre	18:16
SISTED: Solar Flare WARNING (day 184, 2017; hour: 16.2333333333)	ionex4@chapman.upc.edu	18:14

SISTED and BOM's Regional Warning Centre, M1.3@184, 2017

From ionex4@chapman.upc.edu
Subject SISTED: Solar Flare WARNING (day 184, 2017; hour: 16.2333333333)
To kirsti.kauristie@fmi.fi, manuel.hernandez@upc.edu, Me

```
SISTED Solar Flare Detection
(Sunlit Ionosphere Sudden TEC Enhancement Detection by means of GPS real-time datastreams)

I1 = 84.8% of receiver-satellite rays with a simultaneous TEC enhancement in the Sunlit regi

          YY DOY THours               I1              I2              I3
  SF_WARN 17 184 16.2333333333  500  424 0.848  115   71 0.617  121   65 0.537 161400

I1: Impact Parameter in the Sunlit region ( SZA < 70 deg)
I2: Impact Parameter in the Dawn/Dusk region ( 70 <= SZA <= 110 deg)
I3: Impact Parameter in the Night region ( SZA > 110 deg)

SISTED real-time outputs are available at ftp://chapman.upc.es/SISTED/
(and ftp://newg1.upc.es/SISTED/)

SISTED @ UPC-IonSAT
```

From Regional Warning Centre <rwc@ips.gov.au>
Subject [ips-flare-alert] IPS FLARE INFORMATION - END OF EVENT issued 1619 UT on 03 Jul 2017 [SEC=UNCLASSIFIED]
Reply to asfc@ips.gov.au
To ips-flare-alert@ips.gov.au

```
IPS FLARE ALERT - PART C
PRELIMINARY FLARE DETAILS AT END OF FLARE
ISSUE TIME: Mon Jul  3 16:19:07 UTC 2017
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Approximate Flare Start   :  03-07-2017 1613 UT
Approximate Flare Maximum:  03-07-2017 1615 UT  at Flux M 1.3
Approximate Flare End     :  03-07-2017 1617 UT
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Follow the progress of flares on the IPS Web site
http://www.ips.gov.au Click "Space Weather" Click "X-Ray Flux"
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
Australian Space Forecast Centre
IPS Radio and Space Services
(61)(2)9213 8010 (phone)
(61)(2)9213 8061 (fax)
asfc@bom.gov.au
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

Space Weather Services                email: asfc@bom.gov.au
Bureau of Meteorology
PO Box 1386                           WWW: http://www.sws.bom.gov.au
Haymarket NSW 1240  AUSTRALIA         FTP: ftp://ftp-out.sws.bom.gov.au
tel: +61 2 9213 8010                  fax: +61 2 9213 8060
```

Statistical fractal behaviour of solar flare occurrence

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

- A **fractional Brownian model** has been proposed accounting 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 GSFLAI value 2 times greater than the maximum observed one in last solar cycle (by Halloween storm), is once every 44 years approximately.

(Monte-Moreno & Hernández-Pajares, 2014)

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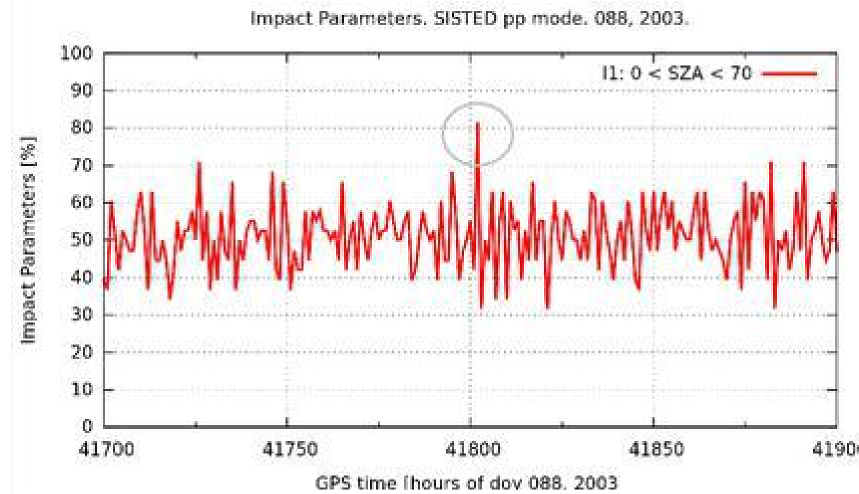
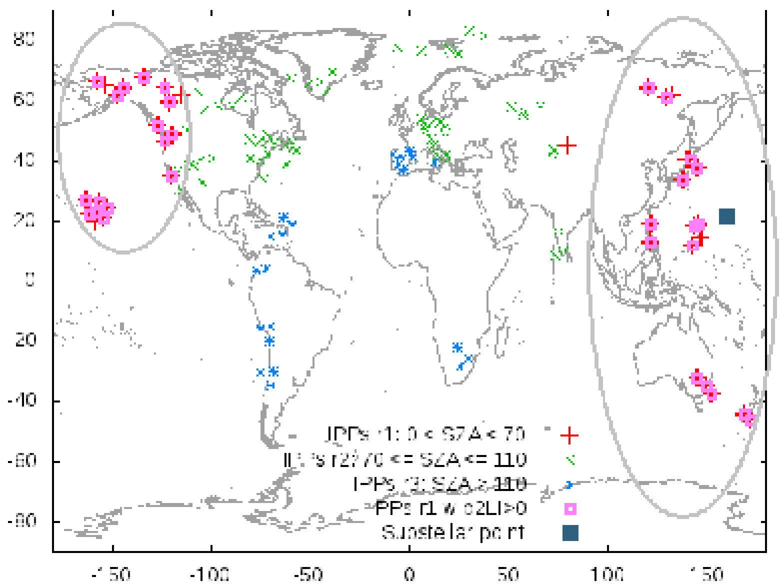
First GPS signatures of stellar bursts?

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.**

Conclusions

- **ESA SSA's I-ESC and ESA's MONITOR server** provide **two real-time products on solar flares nowcasting based on ionospheric monitorization** by Global Navigation Satellite Systems (**GNSS**) and the use of a world-wide network of GNSS receivers from the International GNSS Service (**IGS**):
  - o The GNSS Solar Flare Indicator (**GSFLAI**) and its rate (GSFLAI-rate)
  - o The Sunlit Ionosphere Sudden TEC Enhancement Detector (**SISTED**)
- GNSS proves its versatility and potential to become not only an extremely sensitive and accurate global ionospheric sounder but a reliable **Solar Flare Detector (SISTED)** as well as a calibrated solar observational instrument, able to provide reliable estimates of the **Solar EUV flux rate during Solar Flares (GSFLAI)**.
- **Warnings** on the occurrence of mid- and strong- **geoeffective solar flares** are being **triggered automatically in real time**.

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References

Béniguel, Y., I. Cherniak, A. Garcia-Rigo, P. Hamel, M. Hernández-Pajares, et al. (2017), MONITOR Ionospheric Network: two case studies on scintillation and electron content variability Ann. Geophys., 35, 377–391, 2017, doi:10.5194/angeo-35-377-2017.

Garcia-Rigo, A., Contributions to ionospheric determination with Global Positioning System: solar flare detection and prediction of global maps of Total Electron Content, PhD Thesis, Universitat Politècnica de Catalunya, Spain, 2012.

Garcia-Rigo, A., Hernández-Pajares, M., Juan, J. M., & Sanz, J. (2007), Solar flare detection system based on global positioning system data: First results. Advances in Space Research, 39(5), 889-895, 2007.

Hernandez-Pajares, M., A. Garcia-Rigo, J.M. Juan, J. Sanz, E. Monte, and A. Aragon-Angel, GNSS measurement of EUV photons flux rate during strong and mid solar flares, Space Weather, vol 10, S12001, doi:10.1029/2012SW000826, 2012.

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

Singh, T., Hernandez-Pajares, M., Monte, E., Garcia-Rigo, A., & Olivares-Pulido, G., GPS as a solar observational instrument: Real-Time estimation of EUV photons flux rate during strong, medium, and weak solar flares, Journal of Geophysical Research: Space Physics, 120(12), 2015.

Acknowledgements

European Space Agency

ESA's Space Situational Awareness (SSA) Programme (contract no. 4000113184/15/D/MRP) http://swe.ssa.esa.int/

MONITOR - ESA/ESTEC and ESA/EGNOS Project Office (contract no. 4000100988) http://monitor.estec.esa.int

International GNSS Service

EUREF

BKG/CNES

UNAVCO

Bureau of Meteorology

Thank you very much!

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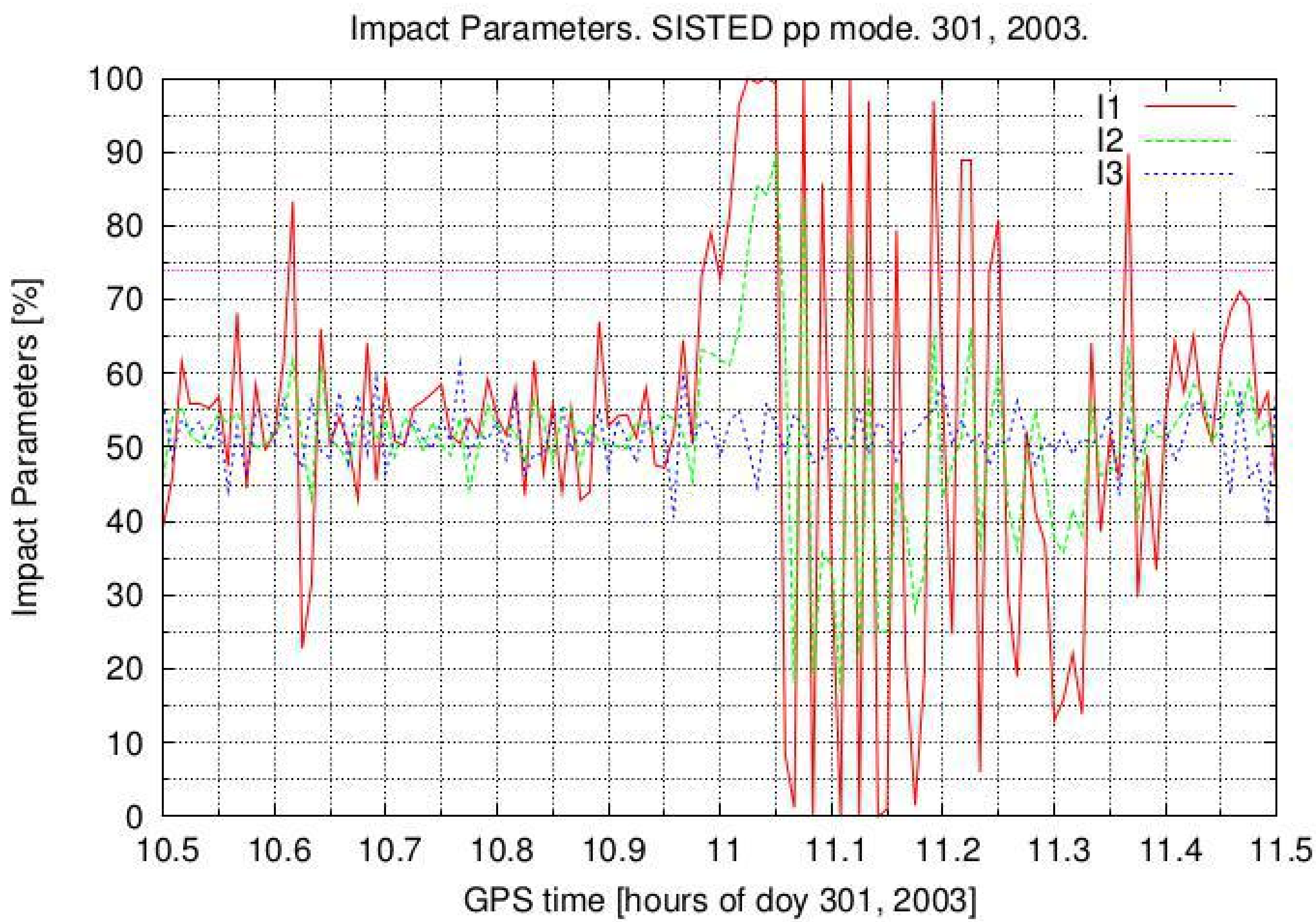
Back-up slides

SISTED



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Waiting times between flares: scale invariant

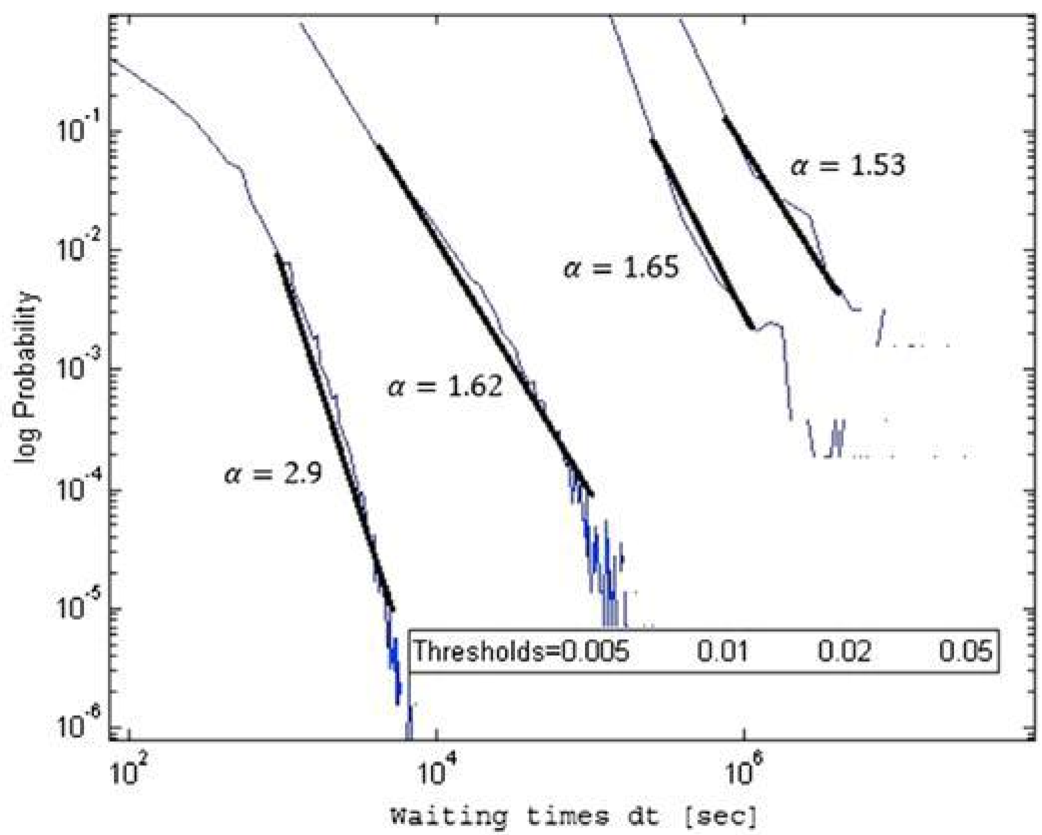

Figure 4. Normalized histograms of the gaps (elapsed or waiting times) between peaks for different decision thresholds (expressed as a function of standard deviations σ) in a double logarithmic scale. The thresholds from left to right are 0.005 TECU ($\mu + 1 \times \sigma$), 0.01 TECU ($\mu + 2\sigma$), 0.02 TECU ($\mu + 4\sigma$), and 0.05 TECU ($\mu + 10\sigma$).

- The meaning is that the behavior of the waiting times between flares with a level higher than 0.01 TECU is scale invariant.

- The statistical behavior of the interpeaks waiting time barely changes for a range of thresholds that spans from $\mu + 2\sigma$ to $\mu + 10\sigma$.

-This property allow us to compute the likelihood of having clusters of peaks of intense activity, or the likelihood of the duration of gaps of low activity.

More details on GSFLAI for strong and mid solar flares & SISTED:

SPACE WEATHER, VOL. 10, S12001, doi:10.1029/2012SW000826, 2012

GNSS measurement of EUV photons flux rate during strong and mid solar flares

M. Hernández-Pajares,[1] A. García-Rigo,[2] J. M. Juan,[1] J. Sanz,[1] E. Monte,[3] and A. Aragón-Àngel[1,2]

Received 6 June 2012; revised 14 October 2012; accepted 18 October 2012; published 12 December 2012.

[1] A new GNSS Solar Flare Activity Indicator (GSFLAI) is presented, given by the gradient of the ionospheric Vertical Total Electron Content (VTEC) rate, in terms of the solar-zenithal angle, measured from a global network of dual-frequency GPS receivers. It is highly correlated with the Extreme Ultraviolet (EUV) photons flux rate at the 26–34 nm spectral band, which is geo-effective in the ionization of the mono-atomic oxygen in the Earth's atmosphere. The results are supported by the comparison of GSFLAI with direct EUV observations provided by SEM instrument of SOHO spacecraft, for all the X-class solar flares occurring between 2001 and 2011 (more than 1000 direct comparisons at the 15 s SEM EUV sampling rate). The GSFLAI sensitivity enables detection of not only extreme X-class flares, but also of variations of one order of magnitude or even smaller (such as for M-class flares). Moreover, an optimal detection algorithm (SISTED), sharing the same physical fundamentals as GSFLAI, is also presented, providing 100% successful detection for all the X-class solar flares during 2000–2006 with registered location outside of the solar limb (i.e., detection of 94% of all of X-class solar-flares) and about 65% for M-class ones. As a final conclusion, GSFLAI is proposed as a new potential proxy of solar EUV photons flux rate for strong and mid solar flares, presenting high sensitivity with high temporal resolution (1 Hz, greater than previous solar EUV irradiance instruments), using existing ground GNSS facilities, and with the potential use as a solar flare detection parameter.

Citation: 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.

More details on GSFLAI, including weak solar flares:

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2015JA021824

Key Points:
- It is shown how GPS can be efficiently used as an accurate solar observational tool
- A constant linear EUV photon flux-GSFLAI dependence is found for all kind of solar flares
- GSFLAI present advantages regarding to direct EUV photons flux measurements taken from solar probes

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Citation:
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.

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GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares

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Abstract In this manuscript, the authors show how the Global Navigation Satellite Systems, GNSS (exemplified in the Global Positioning System, GPS), can be efficiently used for a very different purpose from that for which it was designed as an accurate Solar observational tool, already operational from the open global GPS measurements available in real-time, and with some advantages regarding dedicated instruments onboard spacecraft. The very high correlation of the solar extreme ultraviolet (EUV) photon flux rate in the 26–34 mm spectral band, obtained from the solar EUV monitor instrument onboard the SOHO spacecraft during Solar flares, is shown with the GNSS solar flare activity indicator (GSFLAI). The GSFLAI is defined as the gradient of the ionospheric vertical total electron content rate versus the cosine of the Solar zenith angle in the day hemisphere (which filters out nonsolar over ionization), and it is measured from data collected by a global network of dual frequency GPS receivers (giving in this way continuous coverage). GSFLAI for 60 X class flares, 320 M class flares, and 300 C class flares, occurred since 2001, were directly compared with the EUV solar flux rate data to show existing correlations. It was found that the GSFLAI and EUV flux rate present the same linear relationship for all classes of flares, not only the strong and medium intensity ones, X and M class, as in previous works, but also for the weakest C class solar flares, which is a remarkable result.

UPC

onSAT

More details on Solar Flares "fractality" from GSFLAI:

AGU PUBLICATIONS

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Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE
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Occurrence of solar flares viewed with GPS: Statistics and fractal nature

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Key Points:
- Statistical properties of the EUV solar flux sudden variation as a time series
- Sudden overionization studied during one solar cycle from GNSS signals
- The solar flux rate follows the Levy-Mandelbrot and fractional Brownian models

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Abstract In this paper we describe the statistical properties of the EUV solar flux sudden variation. The solar flux variation is modeled as a time series characterized by the subsolar Vertical Total Electron Content double difference in time, computed with dual-frequency GNSS (Global Navigation Satellite Systems) measurements in the daylight hemisphere (GNSS solar flare indicator rate parameter). We propose a model that explains its characteristics and the forecasting limitations. The sudden overionization pattern is assumed to be of solar origin, and the data used in this study was collected during the last solar cycle. The two defining characteristics of this time series are an extreme variability (i.e., in a solar cycle one can find events at 400σ from the mean value) and a temporal correlation that is independent of the timescale. We give a characterization of a model that explains the empirical results and properties such as (a) the persistence and presence of bursts of solar flares and (b) their long tail peak values of the solar flux variation. We show that the solar flux variation time series can be characterized by a fractional Brownian model for the long-term dependence, and a power law distribution for the extreme values that appear in the time series.

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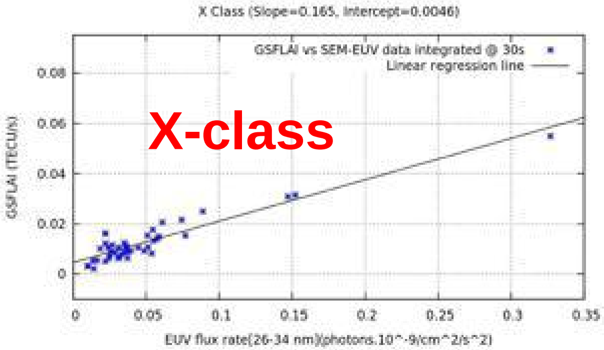

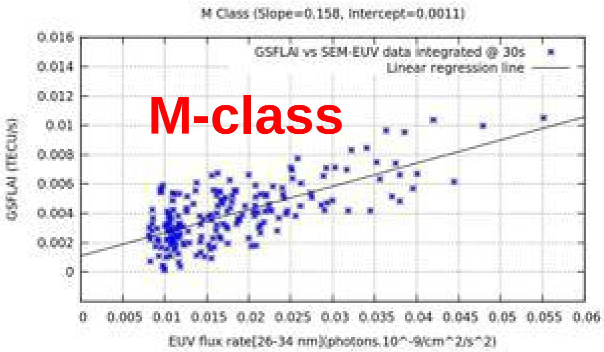

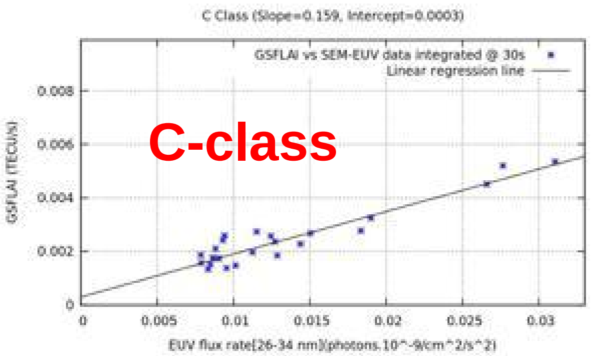

The GSFLAI, a proxy of EUV flux rate for X, M & C-class S. Flares

- 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.

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.

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