The IGS network as a real-time solar and multipurpose scientific instrument

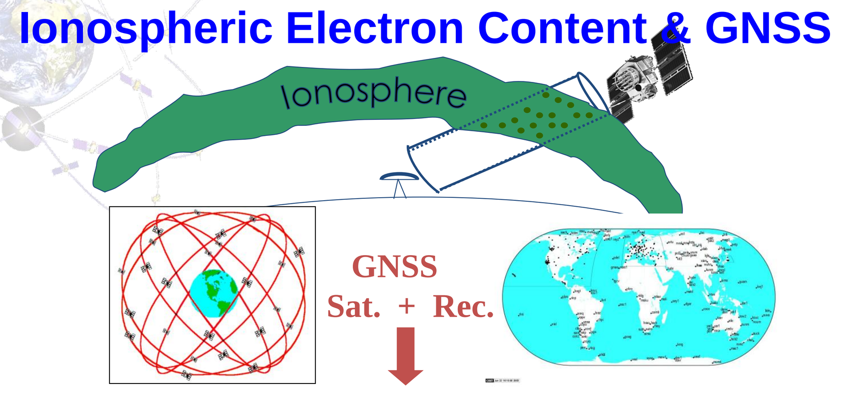
M. Hernández-Pajares[1], T. Singh[2], E. Monte-Moreno[1], A. García-Rigo[1]
[1] UPC-IonSAT/TALP Res. groups, Barcelona, Spain,
[2] Indian Institute of Technology (BHU) ,Varanasi, India.
[contact e-mail: manuel@ma4.upc.edu]

IGS Workshop 2016, February 8-12, Sydney, Australia

Summary: In this work we focus on the last results (Singh et al. 2015) obtained in the development of a new application using IGS global network of permanent GNSS receivers as solar photometer, providing accurate and continuous measurements of solar EUV rate, in particular during solar flares, by properly measuring the sudden associated increase of electron content in the Earth's ionosphere. Other GNSS-Science activities are also mentioned.

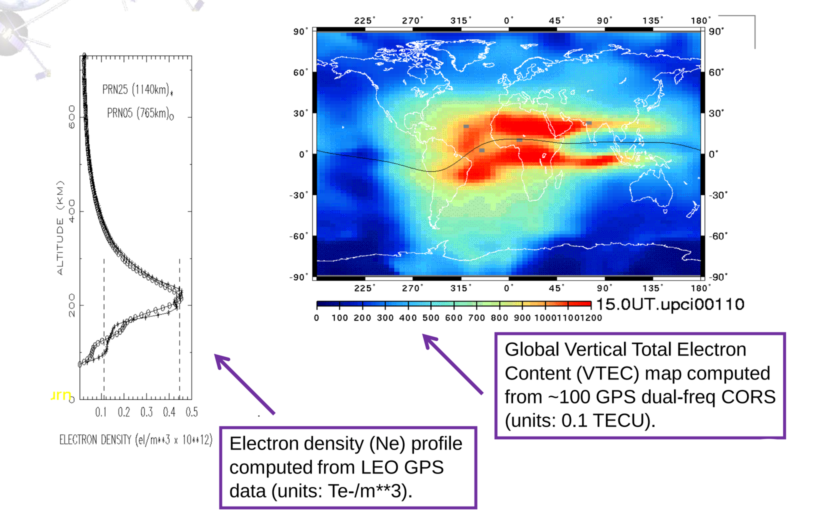
1. Ionospheric electron content and GNSS

Ionospheric Electron Content & GNSS

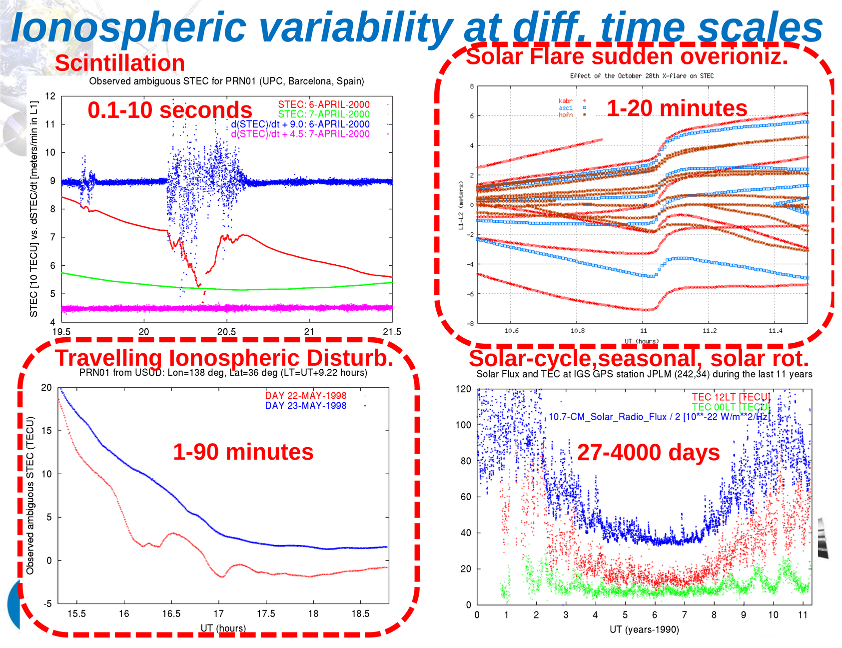


- GNSS iono delay is prop. to Slant Total Electron Content (STEC) & inversely proportional to the squared frequency.
- Dual-freq users can cancel out 99.9% of iono delay.
- Dual-freq permanent GNSS nets.: VTEC & Ne for improving single and multi-frequency GNSS precise navigation, Space Weather monitoring, Seismic-related signatures...

Ionospheric variability at large horizontal and vertical scales



Ionospheric variability at diff. time scales



Main ongoing UPC-IonSAT research on Ionosphere & GNSS

- **Monitoring Ionospheric variability phenomena**: real-time (RT) detection of Solar Flares, global ROTI, etc. (**MONITOR2**, ESA funded project).
- **Earthquake-related ionospheric signals** (**INSPIRE** –new research, funded by ESA- & IPRESES –implementation of existing techniques, funded by an USA SME-).
- **Prediction of Solar Energetic Particle events** (**SEPFLAREs**, funded by ESA).
- **Climatology of predominant ionospheric waves** (MSTIDs) and improvement of its RT modelling and application to precise GNSS (PIOM-FIPP, ESA funded project).
- **Realistic modelling of ionospheric effects in GNSS radio-occultations for improving weather forecast** (**ROPE**, funded by EUMETSAT).
- **Global VTEC Ionospheric Maps** with final, rapid, RT and 2-days-forward latencies (IGS cooperative project, since 1998).
- **New extrapolation techniques in real-time regional modelling** (project funded by a research agency from Asia).
- **Application of comprehensive higher order ionospheric correction models** for precise positioning (HORION, ESA funded project).
- **Application of Wide Area RTK technique & Software GNSS Receivers t Precise Farming in South-Europe** (AUDITOR, H2020-EC funded project).

2. Some examples of IGS usage in Science

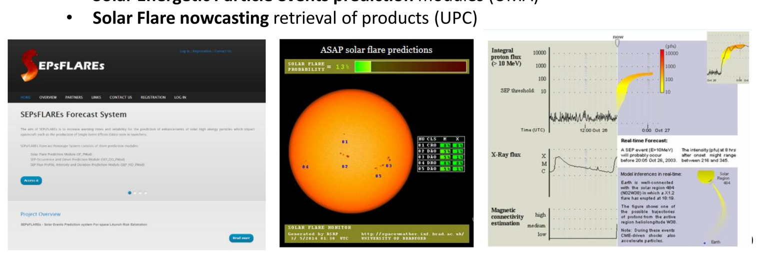
SEPsFLAREs

Solar Events Prediction system For space Launch Risk Estimation

- UPC (coordinator), University of Bradford (UoB) and University of Malaga (UMA)
- Funded by **European Space Agency** - ESA Space Environments & Effects section
- Contact person: Alberto García-Rigo (agarcia@ma4.upc.edu)
- Related subject: 230680 - GPS and Galileo Data Processing: From Fundamentals to High Accuracy Navigation

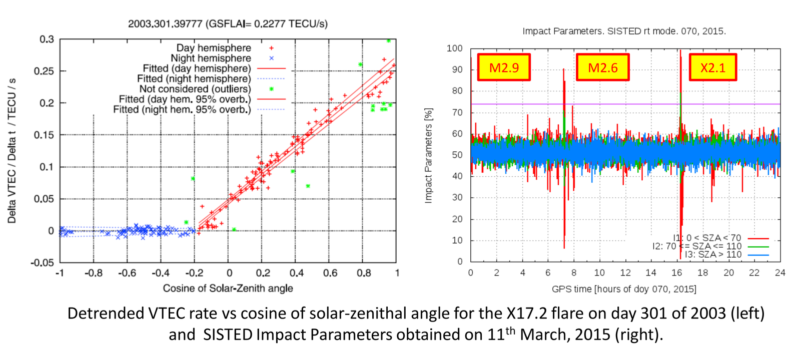
A web-based prototype system has been implemented comprising the following modules:

- **Solar Flare prediction** module (ASAP; UOB)
- **Solar Energetic Particle events prediction** modules (UMA)
- **Solar Flare nowcasting** retrieval of products (UPC)



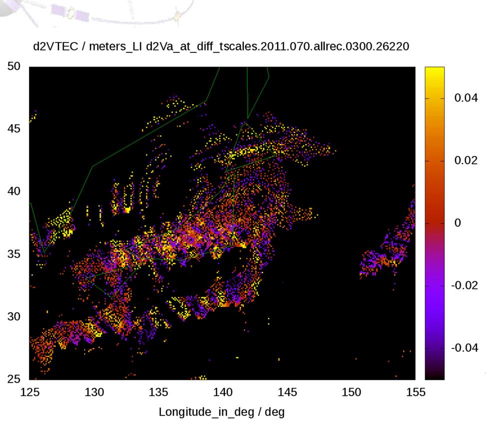
Solar Flare nowcasting

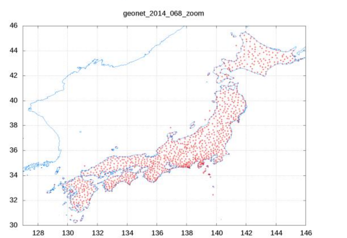
- SEPsFLAREs system provides as well, from **ESA's MONITOR server**, **two real-time products on solar flares nowcasting based on ionospheric monitorization** by Global Navigation Satellite Systems (**GNSS**) and the use of a world-wide network of GNSS receivers from the Int. GNSS Service (**IGS**):
  - The GNSS Solar Flare Detector (**GSFLAD**)
  - The Sunlit Ionosphere Sudden TEC Enhancement Detector (**SISTED**)



Detrended VTEC rate vs cosine of solar-zenithal angle for the X17.2 flare on day 301 of 2003 (left) and SISTED Impact Parameters obtained on 11th March, 2015 (right).

Co-seismic and EQ-centered ionospheric circular waves from large dense network, like GEONET: Tohoku EQ and Tsunami, Japan, day 70, 2011



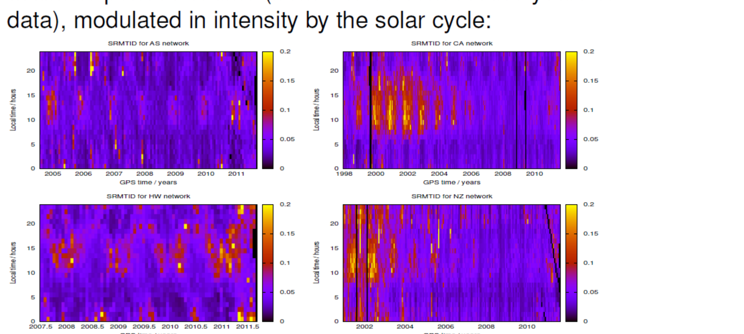


Result obtained after applying the **GNSS Massive Ionospheric Detrending (GMID)** technique to +1200 GPS receivers in GEONET dense network.

The propagation of the MSTIDs can be directly seen from the detrended VTEC, because: (a) the rec. separations < half wavelength; and (b) there are such receivers over regions of hundreds of km to properly identify the wave-fronts

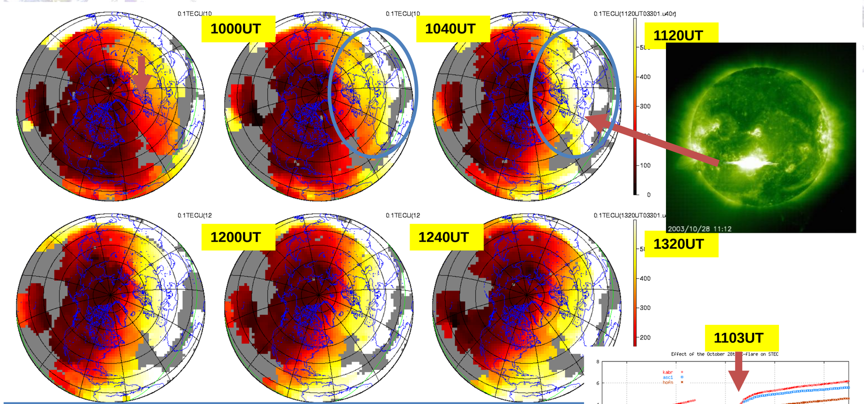
Occurrence (1)

The majority of the most intense MSTID activity occurs at daytime during in fall/winter and nighttime during spring/summer, not only at mid latitudes (as it was shown in previous works), but also at low and high latitudes for all the available periods of time (from 4 to 13 consecutive years of data), modulated in intensity by the solar cycle:



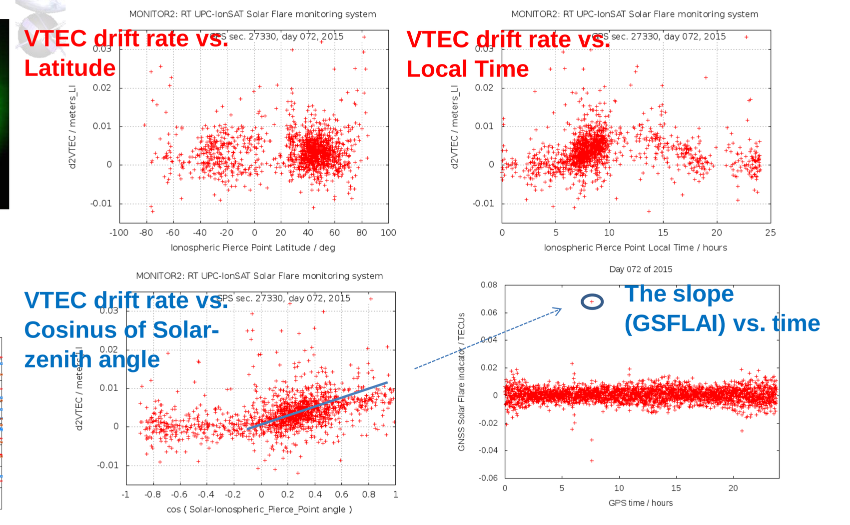
3. Focusing on Solar Flares and GNSS

Global and sudden STEC increase in the day hemisphere due to Solar X-flares

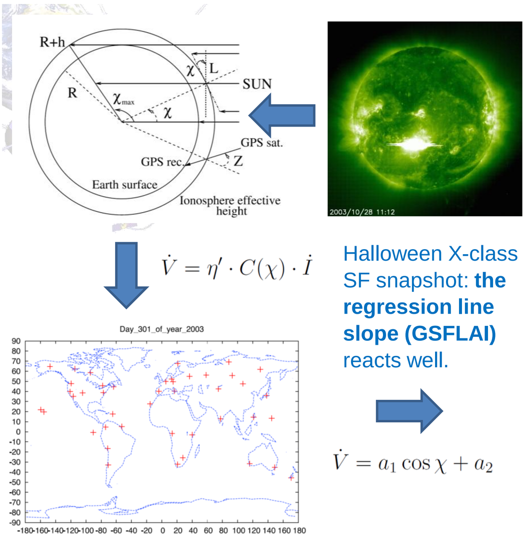


High and sudden STEC variations are experienced in the day hemisphere GPS receivers due to the arrival of the X-rays extra radiation due to Solar X-flares (example: event during 28 Oct. 2003, 11UT approx, preceding the previous mentioned superstorm).

Recent example: M-class Solar Flare during day 072, 2015 (preceeding St. Patrick's geom. storm)



Overionization model: First principles, GPS... and GSFLAI

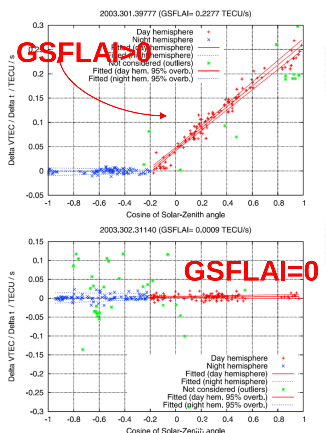


$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I}$$

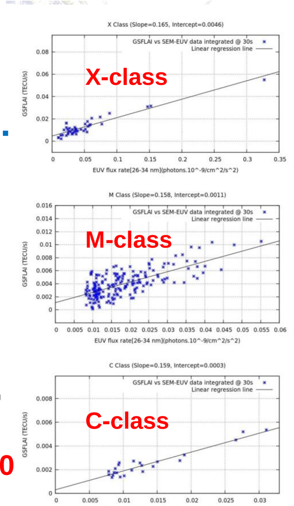
$$\dot{V} = a_1 \cos\chi + a_2$$

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

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



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.

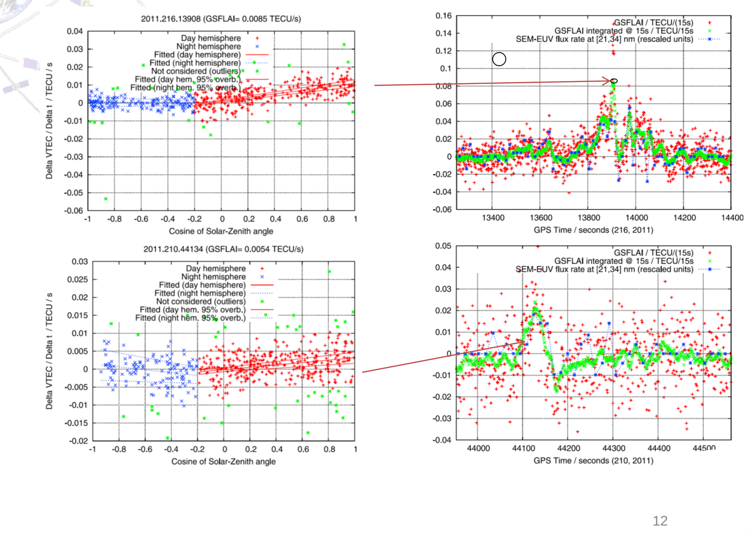
- Regression lines, with **slopes 0.165, 0.157 and 0.159 for X, M & C-class** => high consistency of the simple physical model & technique.

Singh et al. (2015), Estimation of Solar EUV ux rate during Strong, Mid and Weak Solar flares using GPS satellite data, in submission to JGR-Space Physics.

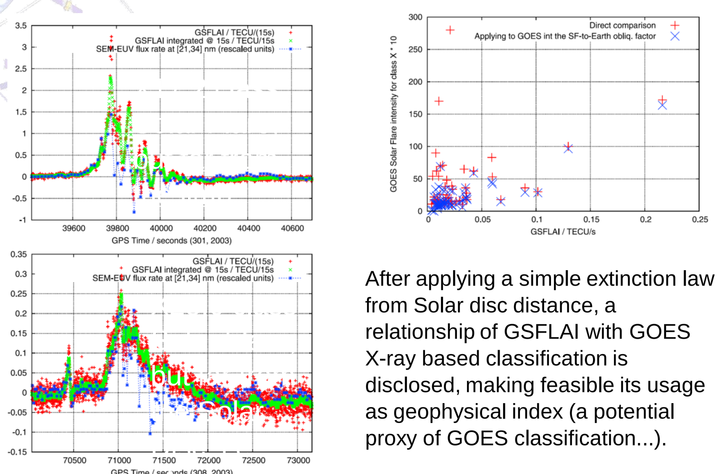
Flares		Slope		Intercept		Corr. Factor	
Class	Number	All	Peaks	All	Peaks	All	Peaks
X	60	0.184	0.165	0.0022	0.0046	0.83	0.94
M	320	0.127	0.157	0.0012	0.0012	0.63	0.70
C	300	0.111	0.159	0.0008	0.0003	0.46	0.94

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

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



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



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...).

Conclusions

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.

Conclusions

- Recent findings on the study of Solar Flares and MSTIDs with GNSS have been summarized as far as its applications
- GNSS proves again its versatility and strength in order to become not only an extremely sensitive and accurate global ionospheric sounder but a calibrated solar observational instrument as well.
- This is a recent example of usage of GNSS as new scientific instrument, among others cases briefly mentioned (potential earthquake monitoring with ionospheric signals, contribution to prediction of SEPs, climatology of MSTIDs)

More details can be found in:

Hernández-Pajares, M., Juan, J. M., Sanz, J., Aragón-Àngel, À., García-Rigo, A., Salazar, D., & Escudero, M. (2011). The ionosphere: effects, GPS modeling and the benefits for space geodetic techniques. Journal of Geodesy, 85(12), 887-907.

Hernández-Pajares, M., García-Rigo, A., Juan, J. M., Sanz, J., Monte, E., & Aragón-Àngel, A. (2012). GNSS measurement of EUV photons flux rate during strong and mid solar flares. Space Weather, 10(12).

Hernández-Pajares, M., Juan, J. M., Sanz, J., & Aragón-Àngel, A. (2012). Propagation of medium scale traveling ionospheric disturbances at different latitudes and solar cycle conditions. Radio Science, 47(6).

Hernández-Pajares, M., R. Prieto-Cerdeira, Y. Béniguel, A. Garcia-Rigo, J. Kinrade, K. Kauristie, R. Orus-Perez, S. Schlueter, D. Serant, B. Nava, A. Krankowski, H. Secretan, R. Sampedro, X. Prats, MONITOR ionospheric monitoring system: analysis of perturbed days affecting SBAS Performance, Proceedings of the ION-Pacific meeting, 2015.

Monte-Moreno, 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.

Singh, T., Hernandez-Pajares, M., Monte, E., Garcia-Rigo, A., & Olivares-Pulido, G. (2015). 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), Dec. 2015, pp. 10,840-10,850.

Acknowledgements

The authors appreciate the direct or indirect support of different organization, funding agencies and companies, like the International GNSS Service and the European Space Agency, support which has made possible the most part of our contributions in the last 20 years.