Real-time 24/7 Global Navigation Satellite Systems based EUV solar astronomy and beyond

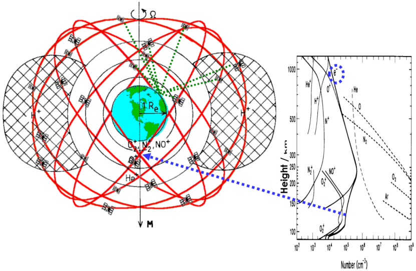
M. Hernández-Pajares[1,2], D. Moreno-Borràs[1], O. Fors[3], J. Poyatos[3], Q. Liu[1], H. Lyu[4,1], V. Graffigna[1,2], G. Olivares-Pulido[1,2], D. Roma-Dollase[2], A. García-Rigo[2], E. Monte-Moreno[5], H. Yang[6,5,1], J.M. Gómez-Cama[7], J. Ventura-Traveset[8], and R. Orús-Pérez[9]

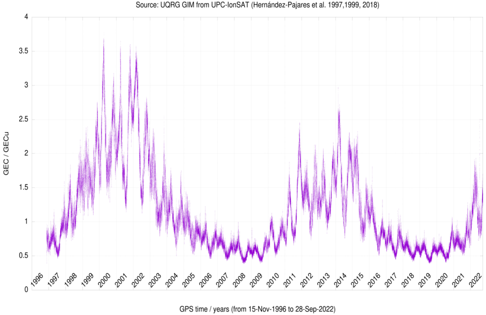
(1) UPC-IonSAT, Barcelona, Spain; (2) IEEC, Barcelona; (3) ICCUB, IEEC-UB, Barcelona, Spain; (4) GNSS Research Center, WHU, Wuhan, China; (5) UPC-TALP, Barcelona, Spain; (6) Yangtze Normal Univ., Chongqing, China; (7) UB, Barcelona, Spain; (8) Centre Spatial de Toulouse, ESA, Toulouse, France; (9) ESTEC, ESA, Noordwijk, The Netherlands. Contact email: manuel.hernandez@upc.edu

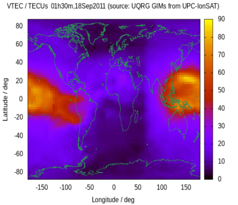
NUVA eMeeting 2024 "The impact of UV surveys in astronomy", 15-16-17 October 2024

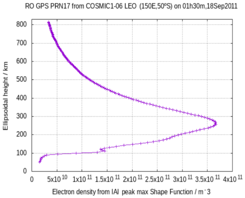
GNSS Ionosphere

GNSS Ionosphere[2] studies the effects and computation of the distribution of free electrons, located at the partially ionized part of the atmosphere above 50 km height, from the Global Navigation Satellite Systems (GNSS) multi-frequency measurements crossing it; and its applications...









[2] Manuel Hernández-Pajares. “GNSS Ionosphere”. In: Encyclopedia of Geodesy, Sideris, Michael G. (ed)., Springer International Publishing, New York City, 2022, pp. 1–7. ISBN: 978-3-319-02370-0. DOI: 10.1007/978-3-319-02370-0_172-1. URL: https://doi.org/10.1007/978-3-319-02370-0_172-1.

GNSS Astronomy

What? **The EUV flux from solar flares generates a sudden overionization in the illuminated ionosphere** (at main layer F2).

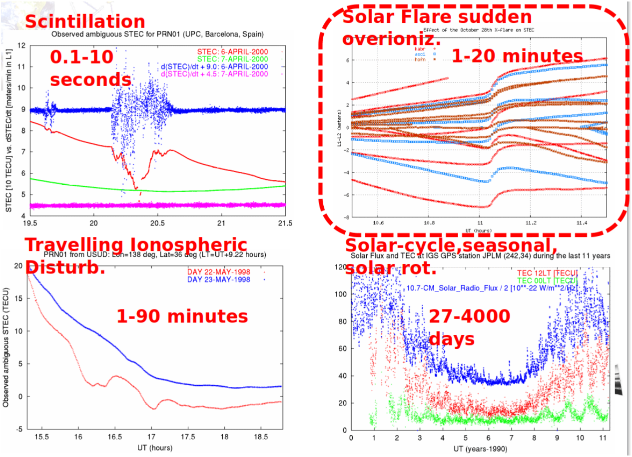
How? GNSS Ionosphere, with **global and continuous coverage.**

Why? *Original idea: (conceived & implemented as UPC-IonSAT RT products for ESA I-ESC)* **to transform the Earth ionosphere crossed by GNSS multi-frequency signals in a giant RT 24/7 solar EUV flux rate sensor & flare warning** system.

Application? **24/7 RT monitoring and warning of solar flares** since 2011.

Extension? This technique has been adapted to potentially detect and validate the Earth ionospheric footprint of **super flares of nearby stars** and **extremely energetic events of distant astronomical sources**, with recent improvement conceived and implemented in ***GNSS Astronomy*** **ESA-funded project.**

Solar flare footprint on GNSS obs.



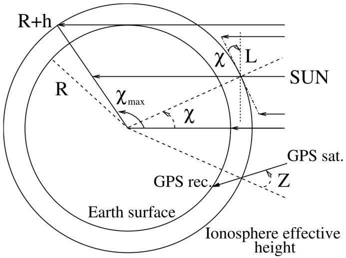
More details can be found, e.g., in[5]

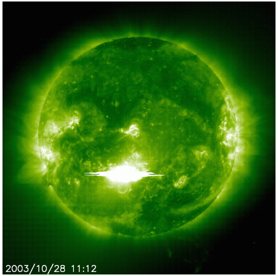
[5] Manuel Hernández-Pajares et al. "The ionosphere: effects, GPS modeling and the benefits for space geodetic techniques". In: *Journal of Geodesy* 85.12 (2011), pp. 887–907. DOI: 10.1007/s00190-011-0508-5. URL: https://doi.org/10.1007/s00190-011-0508-5.

How? First Principles

The VTEC rate associated to the sudden overionization of the Earth ionosphere due to a solar flare, $\dot{V}$, for a given Solar zenith angle χ, can be related with the source solar EUV flux rate, $\dot{I}$, by means of the geo-effectiveness, η', which depends on physical constants (see[7] &[8]):

$$\dot{V} = \eta' \cdot C(\chi) \cdot \dot{I} \implies \frac{\partial V}{\partial t} = a(t) \cos\chi + b(t) \quad (1)$$



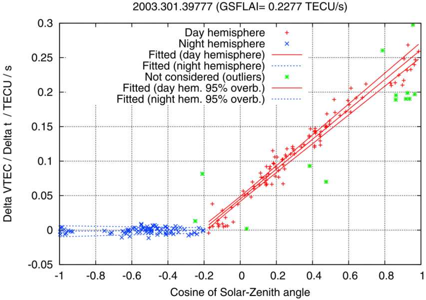


[7] Weixing Wan et al. "The sudden increase in ionospheric total electron content caused by the very intense solar flare on July 14, 2000". In: *Science in China Series A: Mathematics* 45.1 (2002), p. 142. DOI: 10.1007/BF02889695. URL: https://doi.org/10.1007/BF02889695.

[8] Manuel Hernández-Pajares et al. "GNSS measurement of EUV photons flux rate during strong and mid solar flares". In: *Space Weather* 10.12 (2012), pp. 1–16. DOI: 10.1029/2012SW000826. URL: https://doi.org/10.1029/2012SW000826.

How? The overionization model behaves well

How well does the model fit? Example: major (X17.2) solar flare preceding the Halloween ionospheric storm, day 301 of year 2003, 39777s.



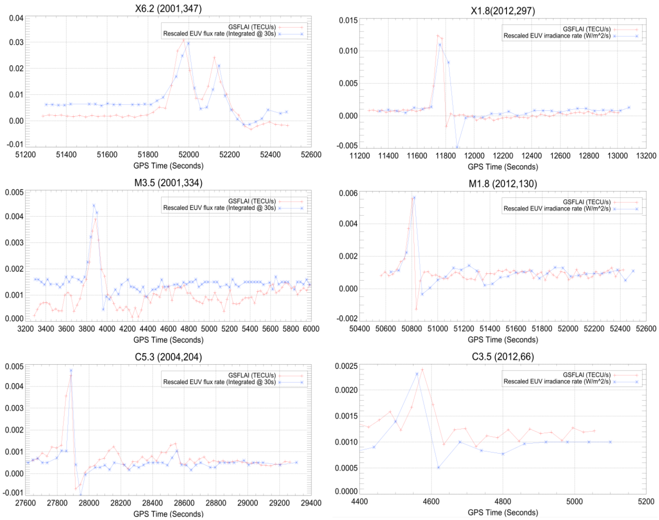
$$\dot{V} = a(t)\cos\chi + b(t)$$

The GNSS solar EUV flux rate proxy $a(t)$ (GSFLAI, AKA SOLERA) was presented in Hernández-Pajares et al. (2012)[10], besides the solar flare detector SISTED (evolved from García-Rigo et al. (2007)[11]).

[10] Manuel Hernández-Pajares et al. “GNSS measurement of EUV photons flux rate during strong and mid solar flares”. In: *Space Weather* 10.12 (2012), pp. 1–16. DOI: 10.1029/2012SW000826. URL: https://doi.org/10.1029/2012SW000826.

[11] A. García-Rigo et al. “Solar flare detection system based on global positioning system data: First results”. In: *Advances in Space Research* 39.5 (2007), pp. 889–895. DOI: 10.1016/j.asr.2006.09.031. URL: https://doi.org/10.1016/j.asr.2006.09.031.

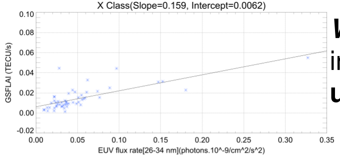
What? Overionization validation

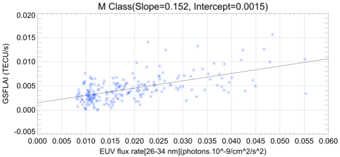


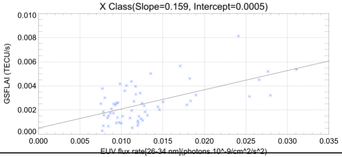
Examples of time series of GS-FLAI vs time series of EUV flux rate from SOHO-SEM space borned photometer, from top to bottom & left to right:

1. X6.2 flare, day 347, 2001
2. M3.5 flare, day 334, 2001
3. C5.3 flare, day 204, 2004
4. X1.8 flare, day 297, 2012
5. M1.8 flare, day 130, 2012
6. C3.5 flare, day 66, 2012

Why? GNSS Ionosphere works very well





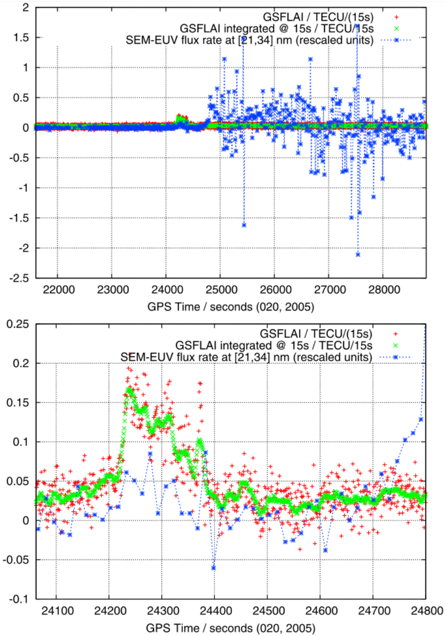


Why should this indirect way (GSFLAI/SOLERA) of measuring the EUV flux rate be considered? **It works very well, using existing (GNSS) infrastructures**:

- GSFLAI versus EUV flux rate data provided by SOHO/SEM in the 26-34 nm range for peak values: X, M, and C class flares respectively (2001-2015).
- **The X-, M- & C- class flares regression lines slopes agrees +95%, confirming the consistency of the first-principles model**, Singh et al. (2015)[14].
- We have **applied SOLERA to confirm solar flare time series have a long tail distribution** in amplitude and time corr. (Monte-Moreno et al. 2014)[15].

[14] Talwinder Singh et al. "GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares". In: *Journal of Geophysical Research: Space Physics* 120.12 (2015), pp. 1–11. DOI: 10.1002/2015JA021824. URL: https://doi.org/10.1002/2015JA021824.

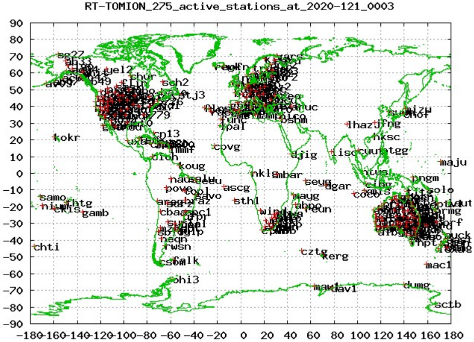
[15] Enrique Monte-Moreno and Manuel Hernández-Pajares. "Occurrence of solar flares viewed with GPS: Statistics and fractal nature". In: *Journal of Geophysical Research: Space Physics* 119.11 (2014), pp. 9216–9227. DOI: 10.1002/2014JA020206. URL:

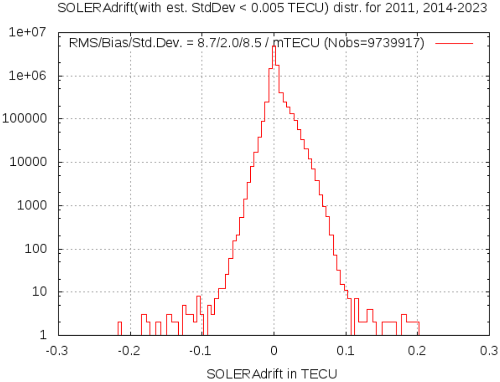


Why? Relativistic e^--free

And the indirect ionosphere-GNSS solar EUV sensor can work better than the direct conventional spacecraft-based measurements: The X7.1 solar flare, reported by GOES on January 20th, 2005, is of special interest because of the **relativistic electrons that reached the Earth less than 10 min later**, produced a contamination of the SOHO/SEM detector with wrong readings of EUV starting from t = 24750s of GPS time. However GSFLAI remains unaffected due to its definition as solar-zenith angle gradient of VTEC rate (see above) generated by the photons enhancement, since it filters out any influence of relativistic electrons.

Application?RT GNSS Solar Astronomy 24/7 by UPC-IonSAT since 2011





More details in:

ELSEVIER

Check for updates

Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 74 (2024) 2593–2598

ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

GNSS Solar Astronomy in real-time during more than one solar cycle

Manuel Hernández-Pajares [a,b,*], Alberto García-Rigo [b,a], Enric Monte-Moreno [c], Qi Liu [d,a], David Roma-Dollase [b,a], Heng Yang [e,a], Yannick Béniguel [f], David Moreno-Borràs [a], Octavi Fors [g], Haixia Lyu [h,a], Raul Orus-Perez [i], Javier Ventura-Traveset [j]

[a] *UPC-IonSAT, Mod. C3 Campus Nord UPC, Barcelona 08034, Spain*
[b] *IEEC, Ed.Nexus Campus Nord UPC, Barcelona 08034, Spain*
[c] *UPC-TALP, Mod. D5 Campus Nord UPC, Barcelona 08034, Spain*
[d] *College of Geography and Environmental Science, Henan University, Kaifeng 475004, China*
[e] *School of Electronic Information and Engineering, Yangtze Normal University, Chongqing 408100, China*
[f] *Informatique, Electromagnétisme, Electronique, Analyse numérique, IEEA, Courbevoie 92400, France*
[g] *Dept. Física Quàntica i Astrofísica, Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona, IEEC-UB, Martí i Franquès 1, Barcelona 08028, Spain*
[h] *GNSS Research Center, Wuhan University, Wuhan 430079, China*
[i] *ESA, ESTEC, Noordwijk, 2201 AZ, The Netherlands*
[j] *ESA, Centre Spatial de Toulouse, Toulouse 31000, France*

Received 29 June 2023; received in revised form 4 December 2023; accepted 6 December 2023
Available online 9 December 2023

Extension? To extrasolar superflares

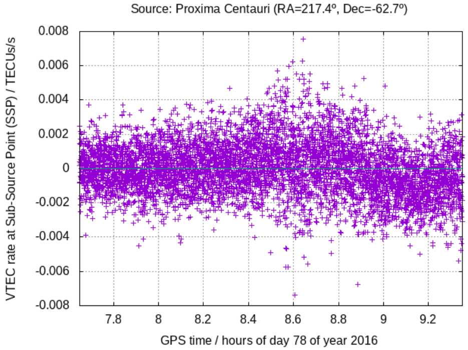
- **Can GNSS Astronomy be extended** from solar flares **to superflares of extrasolar stars?** Our first answer, in 2020, was "Likely yes": see the **first Proxima Cen superflare (08h32m, day 78, 2016) that was detected by naked-eye** studied in Hernández-Pajares & Moreno-Borràs (2020)[20], among NGTS J121939.5-355557 (1 February 2016, 04h00m UT).
- Indeed, we introduced the ***Blind GNSS search of Extraterrestrial EUV Sources*** **(BGEES) model**, to **simultaneously solve the flare intensity and the source position**:

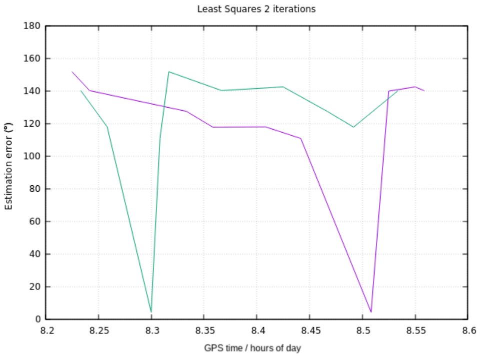
$$\dot{V} = a\cos\chi + b = a(XX' + YY' + ZZ') = \alpha X' + \beta Y' + \gamma Z' + b$$

where (X', Y', Z') and (X, Y, Z) are the IPP's and source unit vectors. Taking $\alpha = aX, \beta = aY$ and $\gamma = aZ$, the equations (one per IPP) becomes linear vs. the unknowns $(\alpha, \beta, \gamma, b)$, and can be solved by LMS.

[20] Manuel Hernández-Pajares and David Moreno-Borràs. “Real-Time Detection, Location, and Measurement of Geoeffective Stellar Flares From Global Navigation Satellite System Data: New Technique and Case Studies”. In: *Space Weather* 18.3 (2020), e2020SW002441.

Extension? Proxima Cen superflare 18/03/16





Left: Mean VTEC rate at sub-stellar point of Proxima Centauri flare during more than 1 hr around its March 2016 superflare peak (0832UT, day 78).
Right: BGEES results (source location error) for the Proxima Centauri superflare of March 2016, with two iterations using 20 epochs.

More details in:

AGU100 ADVANCING EARTH AND SPACE SCIENCE

Space Weather

RESEARCH ARTICLE
10.1029/2020SW002441

Key Points:
- The simultaneous determination of stellar EUV flares in time and location with the existing GNSS infrastructure is presented
- It is based on the modeling of the Earth ionosphere electron content increase, from dual-frequency GNSS data, due to the stellar flare
- The new technique is assessed versus several solar flares of different intensities and two stellar superflares previously studied in detail

Correspondence to:
M. Hernández-Pajares,
manuel.hernandez@upc.edu

Citation:
Hernández-Pajares, M., & Moreno-Borràs, D. (2020). Real-time detection, location, and measurement of geoeffective stellar flares from Global Navigation Satellite System data: New technique and case studies. *Space Weather*, *18*, e2020SW002441. https://doi.org/10.1029/2020SW002441

Received 5 JAN 2020
Accepted 21 FEB 2020
Accepted article online 22 FEB 2020

Real-Time Detection, Location, and Measurement of Geoeffective Stellar Flares From Global Navigation Satellite System Data: New Technique and Case Studies

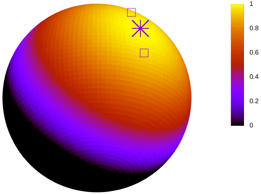
Manuel Hernández-Pajares[1] and David Moreno-Borràs[1]

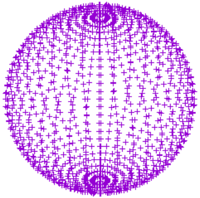
[1]Department of Mathematics, Universitat Politècnica de Catalunya, UPC-IonSAT and IEEC-UPC res. groups, Barcelona, Spain

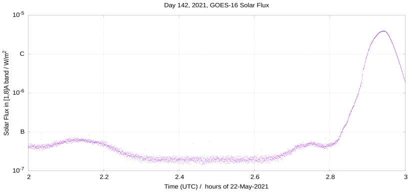
Abstract An alternative approach to detect solar flares and quantify the associated extreme ultraviolet (EUV) solar flux rate was introduced in this journal by the authors: Global Navigation Satellite Systems Solar FLAre Indicator (GSFLAI) was founded on the dependence of the sudden electron content increase of the Earth ionosphere versus the angle regarding the flare source, the Sun, given by a simple but accurate first-principles-based model. Such overionization is directly measured from the dual-frequency phase measurements gathered from hundreds of worldwide permanent receivers of the Global Navigation Satellite Systems, GNSS (like the Global Positioning System GPS), working many of them in real time. In this work we generalize GSFLAI for the very challenging scenario of stellar superflares, with a much weaker expected geoeffectiveness on the Earth ionosphere, making it difficult to distinguish its potential footprint regarding conventional ionospheric variability sources. Indeed, we will show that, unlike GSFLAI for solar flares, the new algorithm presented here (Blind GNSS search of Extraterrestrial EUV Sources [BGEES]) is able to detect EUV flares without the previous knowledge of the position of the source, which is also simultaneously estimated, providing an additional quality check of the detection. It will be first assessed with several case studies of solar flares of different intensities analyzed previously with GSFLAI. Finally, by focusing on the night hemisphere to avoid the Sun's larger effect on the ionosphere, the detection and location with BGEES of two recent stellar superflares, Proxima Centauri (18 March 2016, 08:32UT) and NGTS J121939.5-355557 (1 February 2016, 04:00UT), are presented, strongly suggesting the extension and applicability of the new technique, also in real time.

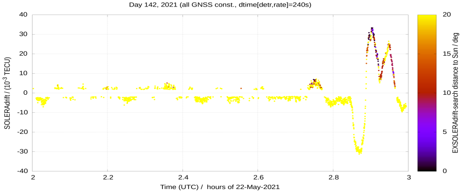
Extension? Higher sensitivity: ESds model

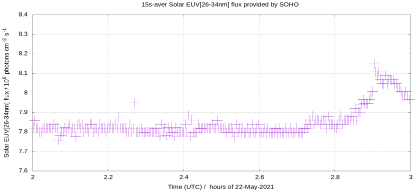
- (EX)SOLERAdrift-search model (**ESds**) estimates every obs. time the likely position and flare intensity of a potential winner source, differently than BGEES model: **Eq. 3 is iteratively solved on a global grid of potential source positions** (e.g. $\Delta\alpha = 10^\circ$ and $\Delta\delta = 5^\circ$ in right ascension, α, and declination, δ, see right plot).
- **The run providing at the given time the highest significant Pearson correlation coefficient, fulfilling the null hypothesis probability (p-value) $\leq$ 5%, is selected** . It will indicate the likely existence of mainly an external EUV flare (and/or X-ray) overionization pattern (left figure) approximately centered at the given grid point (cross in same figure).











ESds validation

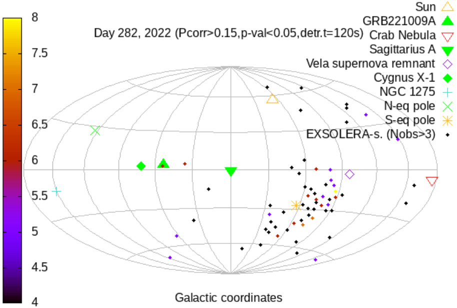
This is a **typical solar flare (C-class) and sub-flare (B-class) detection with ESds** (02h-03h UTC of May 22, 2021, see top plot).

The intensity of the p-value validated ESds (points in central plot) and the **lower angular distance to the Sun of the ESds winner grid** centre (colour of points) **agree well** between them. And they **agree as well vs the peaks in direct X-ray (top) and EUV** (see double peak at bottom plot) band solar flux measurements by GOES and SOHO-SEM photometers.

This **clear ESds tracking of solar weak flare, subflares and smaller** variations is continuous, and happens under **both relatively high and very low ESds model Pearson correlation values**: in this example **above 0.4 and 0.5 at the double peak** during the C-class flare, and **slightly below 0.1 for the B-class** subflare.

Five recent potential ESDs detections[26]

Proxima Cen superflare happened during 1 May 2019.
Giant star superflare (TIC332487879), on 14 September 2018.
Gamma Ray Burst GRB221009A on 9 October 2022.
Transient superflare AT2022tsd during 19 December 2022.
TIC251845156 star superflare during 01-Sep-2018.



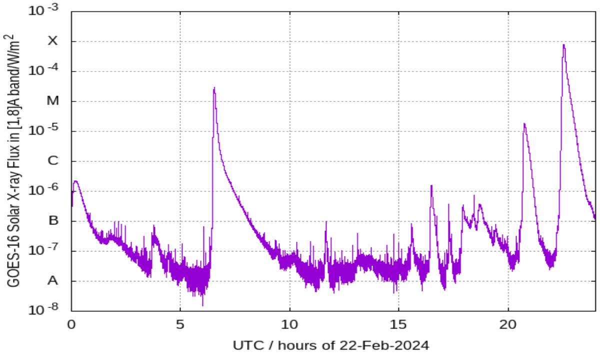
Next?: The **continuous RT operation** and **detrend of GIM - calibrated TEC**, **can consolidate** the omnidirectional, continuous & high cadence way of measuring astrophysical events, slightly / very sensitivity to X-ray / EUV (almost unexplored), estimating the confussion matrix. **THANK YOU!**

[26] Manuel Hernández-Pajares et al. "GNSS Astronomy: Detection and measurement of solar sub-flares, Gamma-ray burst, stellar and transient superflares from their impact on the ionosphere". In: *In preparation* (2025), pp. –.

BACKUP SLIDES

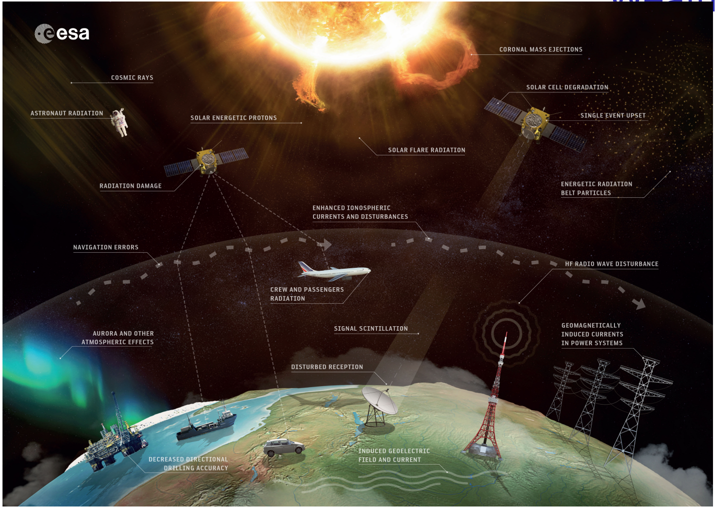
Solar flare

- A solar flare is a burst of electromagnetic radiation on the Sun (from radio waves to EUV-, x- and gamma-rays) that happens when energy stored in twisted magnetic fields (usually above sunspots) is suddenly released.
- The solar flares are classified by their x-ray brightness in [1,8]Å comprising the five categories: X -major-,M -mid-,C -small-, B, and A (see example from GOES spacecraft during solar flares on February 22, 2024):



Flare type	PeakFlux([1,8]Å) / W/m^2
A	$< 10^{-7}$
B	$10^{-7} - 10^{-6}$
C	$10^{-6} - 10^{-5}$
M	$10^{-5} - 10^{-4}$
X	$> 10^{-4}$

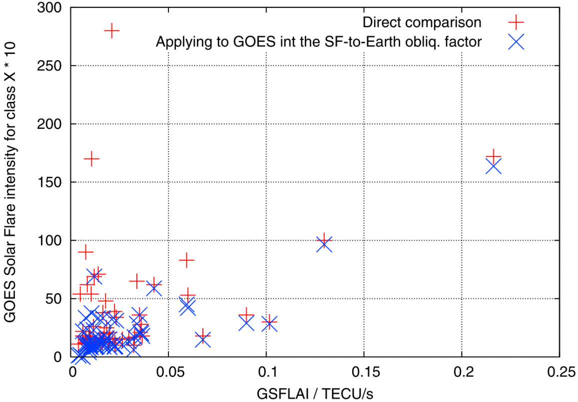
Five recent potential ESds detections[30] Space Weather



(Reproduced from ESA Science Office, 2018)

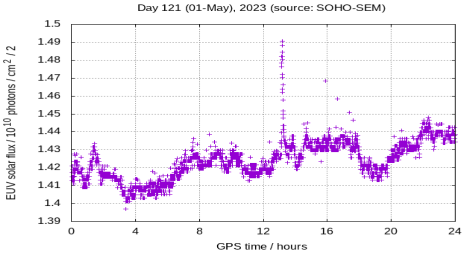
30 Manuel Hernández-Pajares et al. "GNSS Astronomy: Detection and measurement of solar sub-flares, Gamma-ray burst, stellar and

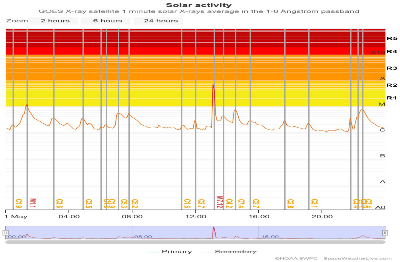
GSFLAI vs direct X-ray solar flux

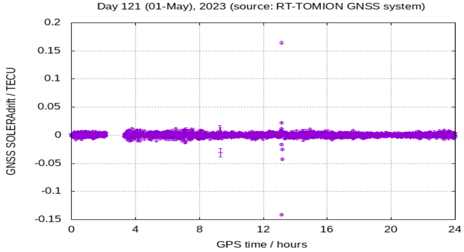


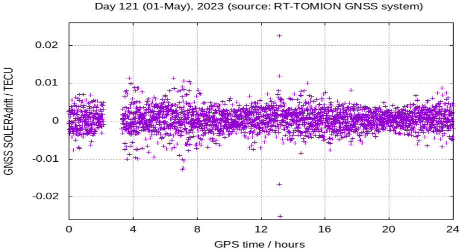
X-ray band solar flare intensity, corresponding to the GOES index for all the X-class flares between 2001 and 2011, versus the GSFLAI value at each given peak: (1) Direct comparison (red points), (2) Comparison after applying a solar-earth deprojecting factor, in terms of the flare location on the surface of the Sun (blue points).

RT GNSS Solar Astronomy 24/7 since 2011









Statistical distribution of solar flares from GNSS Astronomy

We have already applied this technique in Monte-Moreno et al. (2014)[34]:

1. To confirm that solar flare time series have extreme properties regarding amplitude and time correlation.
2. To build a model to account for the probability of the observed extremely high values of the time series, and also with the fact that the flares appear in bursts.
3. To estimate the probability of a given GSFLAI value and also the length of a given burst of flares.
4. In particular, the probability of observing a GSFLAI value 2 times greater than the maximum observed one in the last solar cycle (X28 intensity, happened on 4 November 2003) is once every 44 years approximately.

[34] Enrique Monte-Moreno and Manuel Hernández-Pajares. "Occurrence of solar flares viewed with GPS: Statistics and fractal nature". In: *Journal of Geophysical Research: Space Physics* 119.11 (2014), pp. 9216–9227. DOI: 10.1002/2014JA020206. URL: https://doi.org/10.1002/2014JA020206.

Five recent potential ESds detections[37]

Table: Slope, intercept and correlation of linear fitting of GSFLAI vs SOHO/SEM Solar EUV flux rate when only GSFLAI peaks are taken$_{(a)}$, for X, M and C class flares, which are fully consistent with the assumed physical model (see the number of them in second column).

Flares		No. Points	Slope	Intercept	Corr. Factor	p values
C.	#	Peaks	Peaks	Peaks	Peaks	
X	59	53	159 ± 06	6.2 ± 1.5	0.73	0
M	323	219	152 ± 12	1.5 ± 0.3	0.64	0
C	390	58	159 ± 29	0.5 ± 0.4	0.59	$1.9 * 10^{-6}$

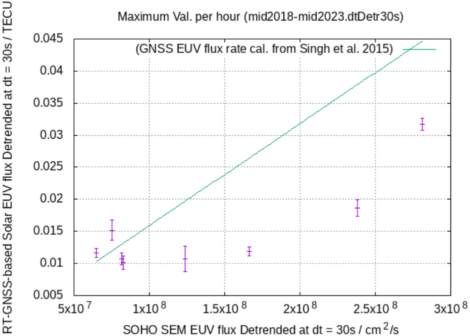
(a) The units are $TECU/s$ for GSFLAI and $photons.10^{-}9/cm^2/s^2$ for EUV flux rate.

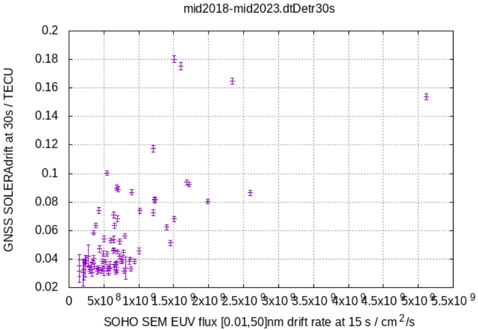
More details can be found in Singh et al. (2015)[36].

[36] Talwinder Singh et al. "GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares". In: *Journal of Geophysical Research: Space Physics* 120.12 (2015), pp. 1–11. DOI: 10.1002/2015JA021824. URL: https://doi.org/10.1002/2015JA021824.

[37] Manuel Hernández-Pajares et al. "GNSS Astronomy: Detection and measurement of solar sub-flares, Gamma-ray burst, stellar and transient superflares from their impact on the ionosphere". In: *In preparation* (2025), pp. –.

Five recent potential ESds detections[39] RT SOLERAdrift vs detr. SOHO-SEM EUV





In both plots we represent the most significant relationshipts of the SOLERAdrift index, computed in real-time and with a detrending time interval of 30 seconds, in TECUs, vs the detrended EUV SOHO-SEM observations (in photons per squared cm and second) within the spectral range of [26,34]nm detrended at a time interval of 30 seconds (left plot), and vs the detrended EUV SOHO-SEM observations in the same units within the spectral range of [0.01,50]nm and detrended at a time interval of 15 seconds (right plot).

[39] Manuel Hernández-Pajares et al. "GNSS Astronomy: Detection and measurement of solar sub-flares, Gamma-ray burst, stellar and

To facilitate the detection of significant EUV flux increase from superflaring sources, but very far from the Earth, **we analyze the detrended VTEC $\tilde{V}$ at different time scales** δt, from the iono. comb. of GNSS carrier phases for each pair GNSS transmitter-receiver $L_I = L_1 - L_2$, approx. with the central mapping function M (see[41]):

$$\tilde{V}(t) = V(t) - \frac{V(t-\delta t) + V(t+\delta t)}{2} \simeq \frac{1}{M(t)} \left(L_I(t) - \frac{L_I(t-\delta t) + L_I(t+\delta t)}{2} \right) \quad (2)$$

(formally related with the drift rate, $\ddot{V} = -2\tilde{V}/\delta t$) by applying correspondingly the (EX)SOLERA-search (hereinafter **ESds**) model:

$$\tilde{V} = \eta' \cdot C(\chi) \cdot \tilde{I} \implies \tilde{V} = \tilde{a}(t) \cos\chi + \tilde{b}(t) \quad (3)$$

This further **facilitates the detection** of the acumulated overionization **when** δt **is a significant part of the flare duration.**

[41] Manuel Hernández-Pajares et al. "The ionosphere: effects, GPS modeling and the benefits for space geodetic techniques". In: *Journal of Geodesy* 85.12 (2011), pp. 887–907. DOI: 10.1007/s00190-011-0508-5. URL: https://doi.org/10.1007/s00190-011-0508-5.

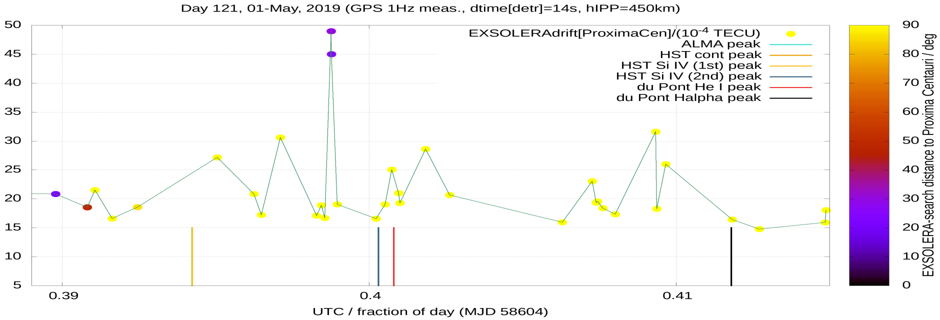
Extension? Higher sensitivity & diff. targets

Can the GNSS Ionosphere technique summarized above, evolve **to detect and validate extremely weak subflare solar EUV flux variations**, in order to extend the first potential detection of extrasolar superflares reported in[43] **to other extremely energetic astronomical targets?** The successful answer has been possible thanks to the ESA-funded GNSS-Astronomy (GA) project:

1. We have extended a **new low-cost, all-time, all-weather, multi-directional, high-cadence** way of detecting and measuring extremely energetic Astrophysics phenomena in **Extreme Ultraviolet (EUV) and X-ray** spectral ranges, **estimating event time, source position, intensity, intensity error and reliability** (new (EX)SOLERAdrift-search technique).
2. *GNSS Astronomy* has the potential to contribute to **some major questions like the better determination of the Habitable Zone (HZ) for exoplanets orbiting around nearby and active M-type dwarf stars.**

[43] Manuel Hernández-Pajares and David Moreno-Borràs. "Real-Time Detection, Location, and Measurement of Geoeffective Stellar Flares From Global Navigation Satellite System Data: New Technique and Case Studies". In: *Space Weather* 18.3 (2020), e2020SW002441.

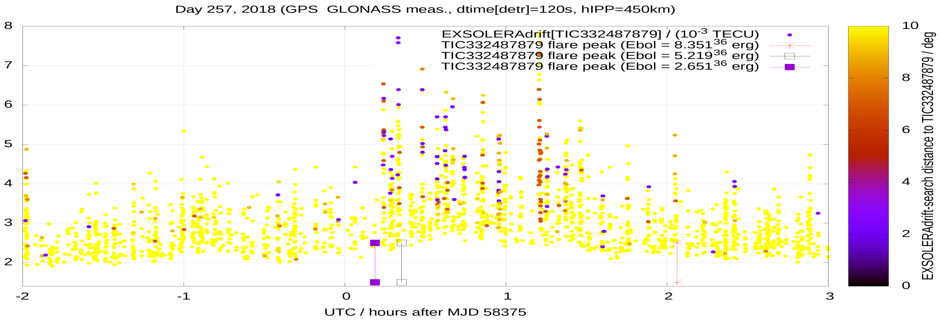
New case #1: Proxima Cen superflare



The **ESds result at 1 Hz, the most part of one hour** around the Proxima Cen superflare happened during 1 May 2019, including the occurrence of the supeflare peak(s) measured with **conventional techniques** (ALMA, HST cont. and HST Si IV coincident and overlapping ALMA peak, HST Si IV -2nd peak-, du Pont He I and du Pont Hα, see Fig. 1 in[45]). The distance in deg. of ESds source position is shown by the points colour palette.

[45] Meredith A MacGregor et al. "Discovery of an Extremely Short Duration Flare from Proxima Centauri Using Millimeter through Far-ultraviolet Observations". In: *The Astrophysical Journal Letters* 911.2 (2021), p. L25.

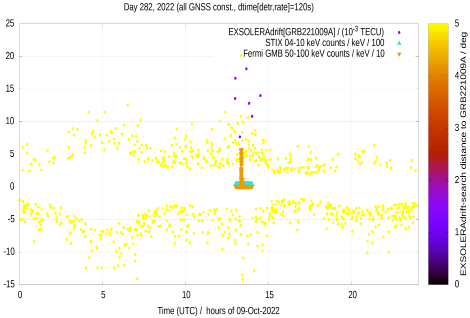
New case #2: Giant star superflare

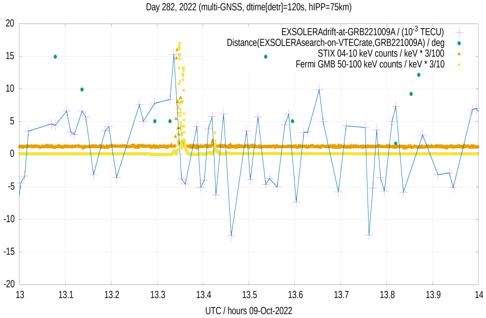


The **ESds result at 1 Hz**, five hours around the beginning of 14 September 2018, including the occurrence of **three stellar superflares of the source TIC332487879**, is summarised vs time: the dots colour palette represents the distance to TIC332487879 (in deg., saturating at 10°) of the direction with the highest significant overionisation pattern, with intensity (in mTECU) represented by the points. The supeflare peak times are represented with **conventional techniques**, and the measured bolometric energies are also given (from ref.[47]).

[47] Anna YQ Ho et al. "Minutes-duration optical flares with supernova luminosities". In: *Nature* 623.7989 (2023), pp. 927–931.

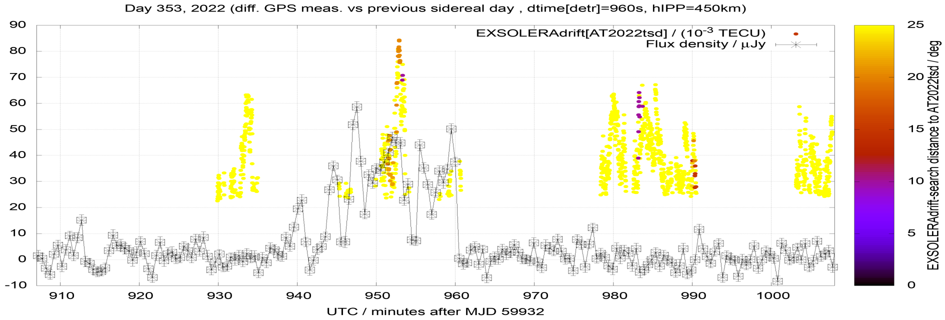
New case #3: Gamma Ray Burst





The ESds vs time on 9 October 2022 with 120 s detr. time is compared with direct measurements in X-ray (STIC) and γ-ray (Fermi): **(Left) at 30-sec rate**, the dots colour palette represents the distance to **GRB221009A** of the direction with the highest significant overionisation pattern (in deg., saturating at 5°), with intensity (in mTECU) represented by the points. **(Right) at 1 Hz**, from 13h to 14h UTC, by **assuming an ionospheric effective height of 75 km** (assuming a important influence of **X-ray driven D ionospheric layer**).

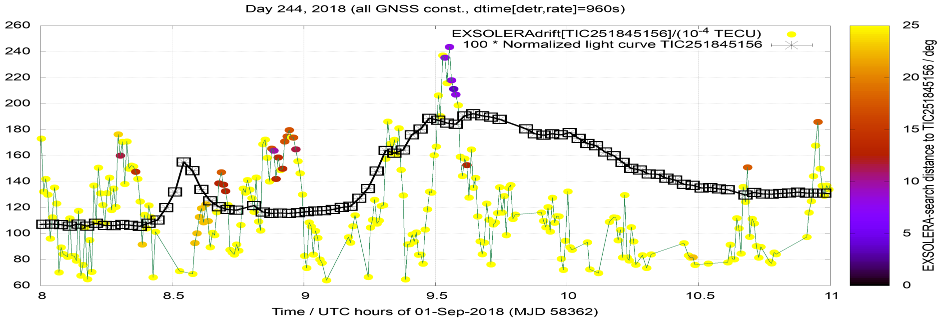
New case #4: Transient superflare



The ESds result, applied from the **sidereal-day differenced GPS measurements** (30s rate with detr. time of 960s), during 19 December 2022, 15h08m-16h48m approximately, is summarised vs time: the dots colour palette represents the distance to AT2022tsd (in deg., up to 25°) of the winner direction, with intensity (in mTECU) represented by the points. **Direct measurements of AT2022tsd in red optical band**, are reproduced in black lined-squares (from ref.[50])

[50] Anna YQ Ho et al. "Minutes-duration optical flares with supernova luminosities". In: *Nature* 623.7989 (2023), pp. 927–931.

New case #5: TIC251845156 star superflare



Finally we report the ESds(*) consistent blind location, time detection and intensity of the **TIC251845156 superflare during 01-Sep-2018 08h-11h, compared with the optical light curve**, obtained by conventional means[52] .

(*) run with multiGNSS multifrequency signals at 30s rate and 960s detrending time

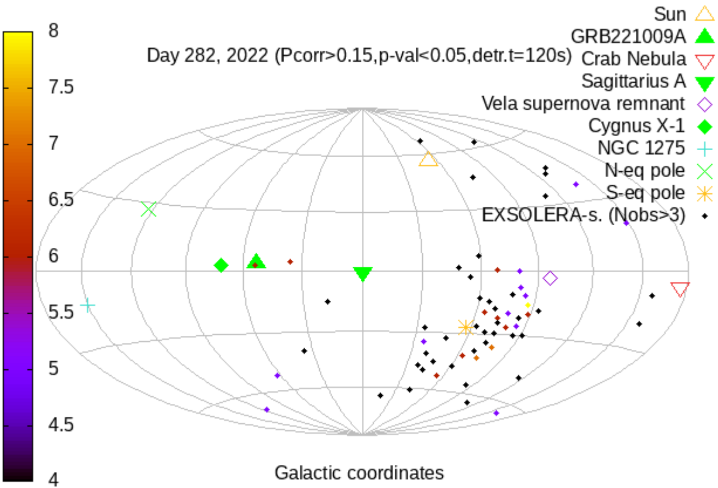
[52] Małgorzata Pietras et al. "Statistical Analysis of Stellar Flares from the First Three Years of TESS Observations". In: *The Astrophysical Journal* 935.2 (2022), p. 143.

Conclusions

- The new **GNSS Ionosphere-based** technique, **EXSOLERAdrift-search (ESds)**, assesses the overionisation pattern, **detecting, measuring and locating** the potential astronomical EUV (or X-ray) **flaring source.**
- Importantly, this technique achieves **significantly higher sensitivity than previous methods** (more details in preparation[54]).
- The new validated and compared ESds detections are :
  1. **Solar subflares**
  2. Extremely distant energetic events like **Gamma-Ray Burst** GRB22109A,
  3. Short- (ten of seconds or minutes) or larger-duration (1 hour) **stellar or giant stellar superflares**, like Proxima Cen, TIC251845156 or TIC332487879.
  4. and AT2022tsd **transient superflare** with **luminosity sim. to supernovae**.
- **Next?**: The **continuous RT operation** and **detrend of GIM - calibrated TEC**, **can consolidate** the omnidirectional, continuous & high cadence way of measuring astrophysical events, slightly / very sensitivity to X-ray / EUV (almost unexplored), **estimating the confussion matrix.**

[54] Manuel Hernández-Pajares et al. "GNSS Astronomy: Detection and measurement of solar sub-flares, Gamma-ray burst, stellar and transient superflares from their impact on the ionosphere". In: *In preparation* (2025), pp. –.

Five recent potential ESds detections[56] # daily pot. detections & sources



We are starting to perform **blind daily ESds runs**, taking advantage of the processing chain of rapid VTEC GIMs at UPC-IonSAT, looking for geoeffective flaring events from external sources, similarly as it is shown here for the **whole day of GRB221009A event**, than can help to get a first confusion matrix estimation of the potential detections.

And the comprehensive Tsunami Early-Warning Cubesat mission looking for international support

NTRS - NASA Technical Reports Server

Search all fields

Back to Results

Tsunami Early-Warning CubeSat Design Reference Mission (DRM)

Global constellation for near real-time detection, characterization, and warning of dangerous tsunami; detection and evaluation of large earthquakes and volcanic eruptions; and study and continuous monitoring of the ionosphere and climate change.

https://ntrs.nasa.gov/api/citations/20230003987/downloads/NASA%20TM%2020230003987.pdf

Document ID	20230003987
Acquisition Source	Goddard Space Flight Center
Document Type	Technical Memorandum (TM)
Authors	Oscar L. Colombo *(Science Systems and Applications (United States) Lanham, Maryland, United States)* Michael J. Croteau *(Goddard Space Flight Center Greenbelt, Maryland, United States)*
Date Acquired	March 24, 2023
Publication Date	March 1, 2023

THANK YOU Prof. Oscar Lucas Colombo (July 16, 1942 — June 1, 2024). Rest in peace