



**First study on the feasibility of Stellar Flares detection  
with GPS**

**A Degree Thesis**

**Submitted to the Faculty of the  
Escola Tècnica d'Enginyeria de Telecomunicació de  
Barcelona**

**Universitat Politècnica de Catalunya**

**by**

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**In partial fulfilment  
of the requirements for the degree in  
TELECOMMUNICATIONS SYSTEMS ENGINEERING  
(SISTEL)**

**Advisors: Manuel Hernández-Pajares and Alberto Garcia  
Rigo**

**Barcelona, September 2016**

## **Abstract**

A new study of the capabilities of the so called GNSS Solar Flare Activity Indicator (GSFLAI) is presented. Instead of analysing Solar flares (for which GSFLAI provides a proxy of the solar EUV flux rate), this project is focused on far stellar flares, thus it may be said that GNSS Stellar Flare Activity Indicator (hereinafter G\*FLAI or equivalently GSFLAI) is born here. The results are supported by the comparison of GSFLAI with direct observations provided by GBM and BAT instruments on board Fermi<sup>[7]</sup> and Swift<sup>[18]</sup> satellites respectively. Moreover, the performance on stellar flares detection of an optimal detection algorithm called SISTED (Sunlit Ionosphere Sudden TEC Enhancement Detector<sup>[8]</sup>), which shares the same physical fundamentals as GSFLAI, is also presented. A total of four stellar flares coming from different sources have been studied, where GSFLAI and SISTED time evolution during the day when the event was detected are shown in graphics and three tables. Moreover, some parameters of interest are also shown for previous and later days of each of these flares. Finally it is reported at least two cases in which a peak in SISTED happens close to a reported stellar flare

## **Resum**

Es presenta un nou estudi del potencial de la coneguda GNSS Solar Flare Activity Indicator (GSFLAI). En comptes d'analitzar fulguracions solars, aquest projecte es centra en fulguracions provinents d'estrelles llunyanes, per tant es pot dir que el GNSS Stellar Flare Activity Indicator (d'aquí endavant G\*SFLAI o equivalentment GSFLAI) neix aquí. Els resultats estan recolzats per la comparació de GSFLAI amb observacions directes obtingudes pels instruments GBM i BAT a bord dels satèl·lits Fermi<sup>[7]</sup> i Swift<sup>[18]</sup> respectivament. A més a més, també es presenta el rendiment en la detecció d'estrelles llunyanes d'un algoritme òptim de detecció conegut com SISTED (Sunlit Ionosphere Sudden TEC Enhancement Detector<sup>[8]</sup>), el qual comparteix els mateixos fonaments físics que GSFLAI. S'han estudiat un total de quatre fulguracions estel·lars provinents de diferents fonts, de les quals es mostren gràfiques dels resultats obtinguts amb GSFLAI i SISTED pel dia en que es va detectar cada fulguració i també tres taules. A més a més, també es mostren alguns paràmetres d'interès pels dies previs i posteriors a cada fulguració. Finalment es reporten dos pics en SISTED compatibles amb una detecció de fulguració estel·lar.

## **Resumen**

Se presenta un nuevo estudio del potencial del conocido GNSS Solar Flare Activity Indicator (GSFLAI). En vez de analizar fulguraciones solares, este proyecto se centra en fulguraciones provenientes de estrellas lejanas, por lo tanto se puede decir que el GNSS Stellar Flare Activity Indicator (de aquí en adelante G\*SFLAI o equivalentemente GSFLAI) nace aquí. Los resultados están apoyados por la comparación de GSFLAI con observaciones obtenidas por los instrumentos GBM y BAT a bordo de los satélites Fermi<sup>[7]</sup> y Swift<sup>[18]</sup> respectivamente. Además, también se presenta el rendimiento en la detección de estrellas lejanas de un óptimo algoritmo de detección llamado SISTED (Sunlit Ionosphere Sudden TEC Enhancement Detector<sup>[8]</sup>), el cual comparte los mismos fundamentos físicos que GSFLAI. Se han estudiado un total de cuatro fulguraciones estelares provenientes de diferentes fuentes, de las cuales se muestran gráficas de los resultados obtenidos con GSFLAI y SISTED para el día en que se detectó cada fulguración y también tres tablas. Además, también se muestran algunos parámetros de interés para los días anteriores y posteriores a cada fulguración. Se concluye con dos de los casos, en el que un pico en SISTED es detectado muy próximo a la fulguración estelar.

## **Acknowledgements**

I would like to give a special note of thanks to my couple Laura Carbonell who had given support to me every single day during this project approving and reading this document.

I also would like to thank the members of my family who assisted me with this project, my parents, my sister and my brother in law who always had advised me when needed.

## Revision history and approval record

Revision	Date	Purpose
0	24/02/2016	Creation of the Work Plan
1	05/05/2016	Creation of the Critical Review
2	17/05/2016	Creation of the Memory
3	25/05/2016	Modification of the project title
4	17/09/2016	Delivery day

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Date	17/09/2016	Date	25/09/2016
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Position	Project Author	Position	Project Supervisor

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## 1. Introduction

A first introduction of the project is detailed below; the main objectives, the requirements and specifications, the methodology carried out during the work plan at the beginning of the project and finally, a list of deviations of the initial work plan.

### 1.1. Statement of purpose

The project is carried out at Mathematics Department in ETSETB, UPC – Campus Nord, Jordi Girona street, 1-3.

The purpose of this project is to develop a first study on the feasibility of stellar flares detection by means of the potentially associated overionization of the ionosphere detected with global GPS measurements.

The project main goals are:

- To understand how a near-far stellar burst detection space mission, such as NASA's Fermi and Swift satellites, works; its objective, relevant parameters (ephemerides ...), accessible data, software tools for these data, etc.
- To understand which impacts have a stellar flare on the Earth's ionosphere.
- To understand GNSS Stellar Flare Activity Indicator (GSFLAI) and Sunlit Ionosphere Sudden TEC Enhancement Detector (SISTED) measurements and techniques.

### 1.2. Requirements and specifications

- To provide the procedure of the study of a specific space mission; where to get the data collected from the satellite detectors involved in the mission and how to manage and process these data.
- In the best case, to provide a first conclusion on the goals of this project: the feasibility of detecting stellar flares. If this is not possible due to the challenging nature of the problem, and the limited time in the framework of this project, at least providing a first study of the stellar flares detection by means of the overionization of the Earth's ionosphere detected with global GPS measurements is foreseen.

### 1.3. **Methods and procedures**

This project arises from a previous research with positive results about detection of Solar flares by means of the overionization of the Earth's ionosphere detected with global GPS measurements<sup>1</sup>. One of the co-authors of this project which is actually my project supervisor, Manuel Hernández-Pajares, explained me the great results of the project and said me that it existed the possibility of starting a new project developing the same study with stellar –other distant stars apart from the Sun– flares. As I am also a passionate of astronomy and a telecommunication student, I thought this was the perfect project for me, even knowing its challenging purposes. So, it could be said that this project starts from the scratch, from the point of view of the stellar flares beyond the Sun.

In this project, the GSFLAI and SISTED softwares, which were developed previously, are used to analyze stellar flares.

This project is performed in the framework of the Mathematics Department of ETSETB, UPC, specifically in the framework of Ionosphere & Navigation based on Satellites & Terrestrial systems (IonSAT) where my project supervisors are involved in.

As described in the first paragraph, the initial ideas where provided by the supervisors.

## 1.4. Work plan

An initial work plan of the project is described below.

### 1.4.1. Work packages

- Work Package 1:
  - Start: 29/02/2016, End: 11/04/2016
  - Short description: Reading papers about near-far stellar burst detection space missions.
  - No Internal Tasks
    - No Deliverables
  
- Work Package 2:
  - Start: 04/04/2016, End: 11/04/2016
  - Short description: Look for the best ten stellar bursts registered where some characteristics may be satisfied by the star and the day of the burst
  - Internal Task 1: Excel table with best ten stellar flares to study.
    - Deliverables: Yes    Date: Week 04/04/2016 - 11/04/2016
  
- Work Package 3:
  - Start: 11/04/2016, End: -
  - Short description: Searching data collected from the satellites involved in the interested missions for each one of the top ten stellar bursts found.
  - No Internal Tasks
    - No Deliverables
  
- Work Package 4:
  - Start: 01/05/2016, End: -
  - Short description: Analyze the data got from the interested space missions involved in the field of the study for each one of the top ten stellar bursts found.
  - No Internal Tasks
    - No Deliverables

### 1.4.2. Milestones

WP#	Task#	Short title	Milestone / deliverable	Date (week)
2	1	Best ten stellar flares to study	Excel table	04/04/2016

### 1.4.3. Gantt diagram

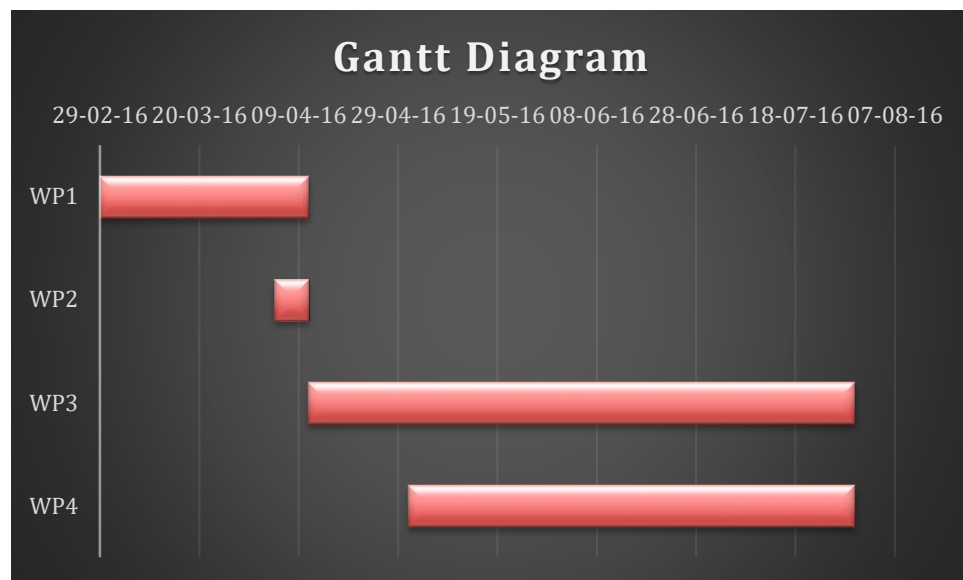


Fig. 1: Gantt diagram.

### 1.4.4. Meeting and communication plan

Meeting	Date
Project Proposal and WorkPlan approval	26/02/2016
Critical Review (midterm)	06/05/2016
Final Review	-
Project meetings (doubts, monitoring, next steps...)	Fortnightly

## 1.5. Work plan deviations

During the following months after the work plan creation, some deviations of the initial procedure and methodology have been appearing. These deviations are explained below.

### 1.5.1. Incidences

There was a main incidence that happened during the development of this project and others not such relevant related with that first one:

- The most relevant incidence happened when downloading data from any space mission, mainly Fermi and Swift satellites, and visualizing it. These data are almost all in FITS format files, which can be only opened with specific tools, so I had to spend some not planned time looking for a software which made me able to open and visualize these files correctly. Other problems appeared when I finally found a tool (see section 3.3) that made me able to open these type of files; the data of some events was so huge that when I wanted to sort some parameters the tool crashed every time and I had to install a Linux OS (Ubuntu) alongside Windows 10 that was already installed on my computer to be able to sort such data files.



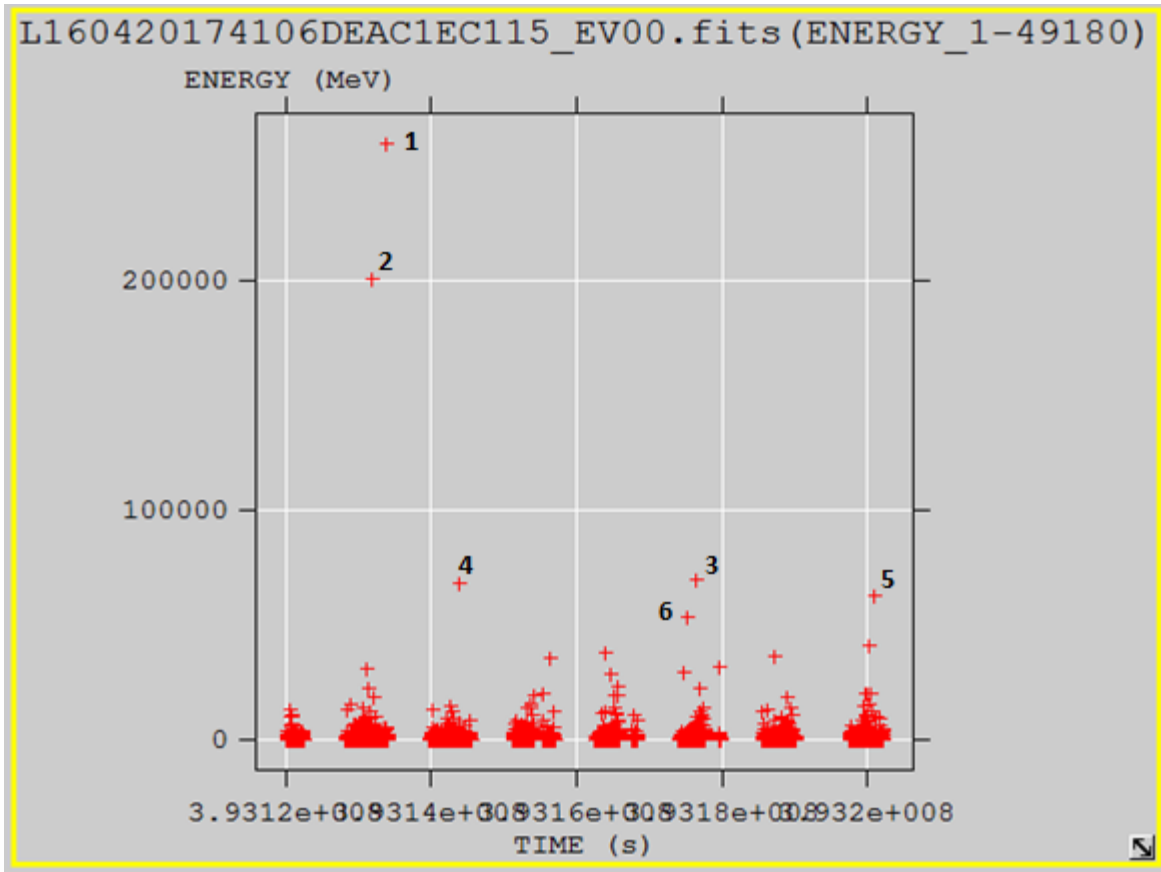


Fig. 2: FV plotting tool showing the energy of the Top2 event in MeV in function of the time of the day of interest (17th June 2013) in Fermi seconds (calculated as the seconds since 1st January 2001<sup>[1]</sup>) from the data collected by the Fermi GBM. The six most energetic peaks are marked during this day.

74 Fv: Binary Table of Top2\_160,2013\_EV00.fits[1] in C:/fv/sample\_data/

File Edit Tools Help

Select	TIME	ENERGY	RA	DEC	L	B	THETA	PHI	ZENITH_ANGLE	EARTH_AZIMUTH_ANGLE	EVENT_ID
All	D	E	E	E	E	E	E	E	E	E	J
Invert	s	MeV	deg	deg	deg	deg	deg	deg	deg	deg	
	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	3.931337926049E+00	2.597801E+005	2.298741E+002	-6.491109E+00	3.178171E+002	-6.409626E+00	3.042425E+001	1.327586E+002	6.373345E+001	1.562235E+002	11741369
2	3.931318120905E+00	2.006515E+005	2.401585E+002	-5.789931E+00	3.259724E+002	-3.757475E+00	6.354252E+001	2.167325E+002	1.122107E+002	1.900804E+002	6325060
3	3.931763911605E+00	6.983058E+004	2.313949E+002	-5.586787E+00	3.233950E+002	7.552961E-001	6.437634E+001	2.255414E+002	1.111972E+002	2.166171E+002	5351996
4	3.932439073008E+00	6.861964E+004	2.554048E+002	-4.556484E+00	3.413735E+002	-2.196421E+00	6.435818E+001	1.928339E+002	1.122333E+002	1.755409E+002	9391100
5	3.932009415611E+00	6.255335E+004	2.555130E+002	-4.793782E+00	3.395388E+002	-3.706217E+00	6.298912E+001	1.971339E+002	1.122787E+002	1.867991E+002	6442386
6	3.931751167823E+00	5.352986E+004	2.446594E+002	-4.847758E+00	3.343383E+002	1.344033E+00	2.207344E+001	3.564246E+002	6.621676E+001	1.789064E+002	3005133
7	3.932001302619E+00	4.114230E+004	2.515264E+002	-5.221580E+00	3.345929E+002	-4.405962E+00	6.219063E+001	2.126566E+002	1.118775E+002	2.119457E+002	4941508
8	3.931639493628E+00	3.799817E+004	2.478679E+002	-4.808500E+00	3.361125E+002	9.298007E-002	2.896830E+001	2.983624E+002	7.159284E+001	1.897169E+002	5613594
9	3.931871718975E+00	3.668528E+004	2.479860E+002	-4.156057E+00	3.409402E+002	4.488153E+00	3.564688E+001	2.218978E+002	7.442194E+001	2.065667E+002	3079480
10	3.931562275318E+00	3.564420E+004	2.410310E+002	-5.458405E+00	3.285258E+002	-1.584751E+00	3.425565E+001	1.833650E+002	7.711526E+001	1.441655E+002	3562407
11	3.931796595833E+00	3.231357E+004	2.522295E+002	-4.600650E+00	3.396390E+002	-7.503842E-00	4.875072E+001	1.595698E+002	7.232696E+001	1.349302E+002	361256
12	3.931311674384E+00	3.105921E+004	2.505183E+002	-5.286213E+00	3.337004E+002	-4.362333E+00	6.312162E+001	2.148362E+002	1.120636E+002	2.161372E+002	5216207
13	3.931747049066E+00	2.967269E+004	2.284855E+002	-5.635945E+00	3.217624E+002	1.211075E+00	2.194276E+001	4.378249E+002	6.494348E+001	1.738538E+002	2356280
14	3.931646895900E+00	2.886609E+004	2.179855E+002	-5.597174E+00	3.167536E+002	4.279367E+00	6.770913E+001	2.274244E+002	1.121891E+002	2.171658E+002	7320725
15	3.931657473222E+00	2.373359E+004	2.383542E+002	-6.287141E+00	3.220571E+002	-6.969911E+00	6.243116E+001	2.267122E+002	1.121463E+002	1.987429E+002	9952455
16	3.931768454227E+00	2.287577E+004	2.433433E+002	-5.664318E+00	3.280962E+002	-3.984720E+00	6.276789E+001	2.229776E+002	1.120861E+002	2.129257E+002	6234948
17	3.931312558011E+00	2.250938E+004	2.495884E+002	-5.770408E+00	3.296902E+002	-7.156433E+00	6.193275E+001	2.191607E+002	1.117583E+002	2.094897E+002	5372438
18	3.932005254262E+00	2.046052E+004	2.395769E+002	-6.361143E+00	3.219978E+002	-7.890321E+00	5.670474E+001	2.215002E+002	1.050005E+002	1.885021E+002	5611092
19	3.931998938693E+00	2.044351E+004	2.508125E+002	-4.317562E+00	3.411358E+002	1.855641E+00	6.521947E+001	2.061460E+002	1.120485E+002	2.259483E+002	4556110
20	3.931996435536E+00	2.004919E+004	2.413815E+002	-4.986109E+00	3.318277E+002	1.799442E+00	6.458739E+001	2.168143E+002	1.120457E+002	2.211691E+002	4155171
21	3.931554068727E+00	2.000014E+004	2.451409E+002	-5.075636E+00	3.329612E+002	-4.982766E+00	5.881183E+001	2.003856E+002	1.043726E+002	1.673691E+002	533502
22	3.931541068450E+00	1.978235E+004	2.531007E+002	-4.637586E+00	3.397401E+002	-1.450329E+00	6.415849E+001	2.076206E+002	1.118012E+002	2.227322E+002	6879929
23	3.931655981461E+00	1.955640E+004	2.498045E+002	-5.271481E+00	3.335255E+002	-3.940874E+00	6.296385E+001	2.148564E+002	1.122480E+002	2.147958E+002	9633471
24	3.931650779691E+00	1.924600E+004	2.358859E+002	-6.438731E+00	3.202390E+002	-7.465403E+00	6.229436E+001	2.335749E+002	1.117258E+002	2.070511E+002	8356587
25	3.931320880728E+00	1.890895E+004	2.363327E+002	-5.283823E+00	3.274994E+002	1.532957E+00	6.546090E+001	2.130395E+002	1.121060E+002	1.784453E+002	6862518
26	3.931890303412E+00	1.861110E+004	2.586781E+002	-4.969633E+00	3.393604E+002	-6.426895E+00	6.207984E+001	2.027305E+002	1.120116E+002	2.066918E+002	6355645
27	3.931536790451E+00	1.580223E+004	2.373820E+002	-4.352233E+00	3.338592E+002	8.400160E+00	6.841766E+001	2.108689E+002	1.121574E+002	2.293544E+002	5985844

Go to: Edit cell: 393133792.604923

Table 1: Fv tool showing a table with the data of different parameters that Fermi GBM collects from any detected burst. The first column shows the time in Fermi seconds and the second one shows the energy in MeV of the event. The rest of the parameters are irrelevant for our purposes.

As it will be explained on *chapter 3. Methodology and project development* this tool finally became useless due to the data shown from FV was not consistent with the information provided by papers and it could not be interpreted.

### 1.5.2. Updated work packages

Regarding the work packages proposed in the work plan there had been very few changes and unexpected time plans. In particular the WP2 it was expected to last one week and finally lasted almost three weeks. WP3 and WP4 consisted on searching and analyzing data from specific space missions for each one of the top ten stellar flares found, and I finally had to focus only in the top three stellar flares of the best ten. Few days from now, I started focusing on another stellar flares different from the top ten that had a strong impact in the Earth's ionosphere and could contribute on potential great results to this project.

The new work packages added and the initial work packages changes are described below:

- Work Package 1:
  - Start: 29/02/2016, End: 11/04/2016
  - Short description: Reading papers about near-far stellar burst detection space missions.
  - No Internal Tasks
    - No Deliverables
  
- Work Package 2:
  - Start: 04/04/2016, End: 24/04/2016
  - Short description: Look for the best ten stellar bursts registered where some characteristics may be satisfied by the star and the day of the burst
  - Internal Task 1: Excel table with best ten stellar flares to study.
    - Deliverables: Yes    Date: 24/04/2016

- Work Package 3:
  - Start: 11/04/2016, End: -
  - Short description: Searching data collected from the satellites involved in the interested missions for each one of the top ten stellar bursts found.
  - No Internal Tasks
    - No Deliverables
  
- Work Package 4:
  - Start: 13/04/2016, End: 14/04/2016
  - Short description: Looking for a software tool capable to correctly open and visualize FITS format files.
  - No Internal Tasks
    - No Deliverables
  
- Work Package 5:
  - Start: 18/04/2016, End: 28/04/2016
  - Short description: Installing OS Linux – Ubuntu alongside Windows 10 on my laptop.
  - No Internal Tasks
    - No Deliverables
  
- Work Package 6:
  - Start: 18/04/2016, End: -
  - Short description: Analyze the data got from the interested space missions involved in the field of the study for each one of the top ten stellar bursts found.
  - No Internal Tasks
    - No Deliverables

### 1.5.3. **Updated milestones**

There are the same milestones as defined in the work plan.

#### 1.5.4. Updated Gantt diagram

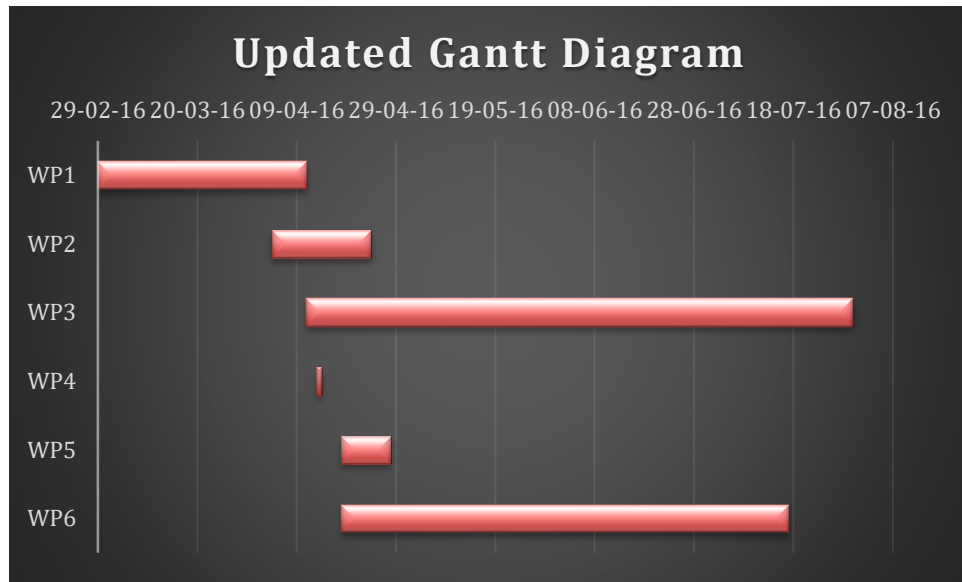


Fig. 3: Updated Gantt diagram.

#### 1.5.5. Updated meeting and communication plan

There is the same communication plan with the project advisors as defined in the work plan.

## **2. Review of literature**

In order to make the results and conclusions of this project more comprehensive, a couple of areas must be introduced before. These two topics, described below, are “GPS and ionospheric sounding” and “Solar and stellar flares impact on ionosphere”.

### **2.1. Introduction to GPS and ionospheric sounding**

The GPS constellation of 31 Medium Earth Orbiting (MEO) satellites, providing ranging signals at two L-band frequencies, has become one of the most successful tools to determine the distribution of free electrons in the ionosphere<sup>[12]</sup>. Indeed, GPS, and in general the multifrequency GNSS, provide an unprecedented high spatial and temporal resolution in the measurements of the number of free electrons per volume unit.

### **2.2. Introduction to Solar and faraway stellar flares impact on ionosphere**

Solar flares are sudden enhanced electromagnetic emissions, which are often associated with explosive events on the Sun’s surface releasing huge amounts of magnetic energy and charged energetic particles. In particular, they are characterized by the emission of radiation across the whole electromagnetic spectrum, especially in X-rays and Extreme Ultraviolet (EUV) band. The radiation in these bands is geo-effective in generating extra photoelectrons in Earth’s ionosphere, but affected differently by the locations of flares on the solar disk. X-rays are generally optically thin in the solar atmosphere, therefore are almost unaffected by flare locations. However, EUV bands are often optically thick in the solar atmosphere and the absorption of optically thick emissions is greater on the limb, due to the longer path lengths. Therefore, limb flares have less enhancement of EUV and thus are less geo-effective than centre flares.

The study which this project is based on presented a new GNSS Solar Flare Activity Indicator (GSFLAI), given by the gradient of the ionospheric Vertical Total Electron Content (VTEC) rate, in terms of the Solar-Zenithal Angle (SZA or  $\chi$ ), measured from a global network of dual-frequency GPS receivers pointing the detector to the Sun<sup>[11]</sup>. It is highly correlated with the EUV photons flux rate at the 26-34 nm spectral band, as it has been mentioned before, is geo-effective in the ionization of the mono-atomic oxygen in the Earth's atmosphere. The results obtained had been supported by the comparison of GSFLAI with direct EUV observations provided by SEM instrument of SOHO spacecraft.

The VTEC parameter (V) computed by the detector can be approximated by the Chapman model, predicting a dependence on the SZA<sup>[19]</sup> as follows:

$$\frac{\partial V}{\partial t} = a(t) \cos \chi$$

Where  $a(t)$  is the enhanced ionization gradient for time  $t$ .

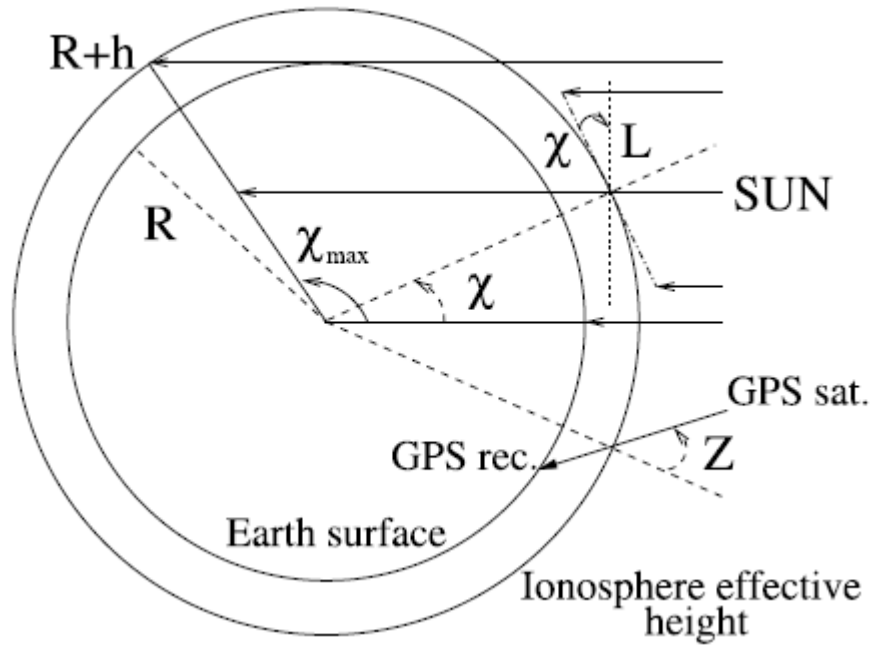


Fig. 4: Solar-Zenithal Angle illustration.

In summary, and due to the fact that X, Gamma and especially EUV radiation are responsible for the ionization process in the Earth's ionosphere, the study has shown how the proposed technique takes advantage of this, in order to complement the conventional measurements from space. In this way, solar flares can be indirectly, but precisely monitored by measuring the electron content enhancement through dual-frequency measurements from a global GPS network.

The fact that the VTEC dependence on the proportionality of the enhanced ionization of the Earth's ionosphere and the cosine of the SZA follows a physic first principle is the main reason that made possible this project could take place, because the procedure of that study and the present project is the same and the main differences are the following:

- I would be studying faraway stellar flares, such as Gamma-Ray Bursts (GRBs), Soft Gamma Repeaters (SGRs), Anomalous X-Ray Pulsars (AXPs) and so on, instead of Solar flares.
- Stellar bursts would be in higher spectrum bands such as X-rays and Gamma-rays because of the huge magnetic fields on these kind of stars. This means that the great majority of instruments on board the satellites destined to study this kind of bursts collect the information in X and Gamma bands instead of EUV bands. This would suppose a significant problem because the EUV band is the most geo-effective in the ionization of the mono-atomic oxygen present in the Earth's ionosphere and that is a parameter which the GSFLAI performance depends on.
- It would be a challenging study because of the lack of information on this kind of stars and their activity in relation with the information obtained from the Sun and its flares.
- The flares impact on the Earth's ionosphere would be much lower owing to the huge distances between these stars and the Earth's ionosphere and that, together with the high energetic band emissions (X-rays and Gamma rays), would impinge on the sensitivity of the detector.

Gamma Ray Bursts are flashes of gamma rays associated with extremely energetic explosions that have been observed in distant galaxies. They are the brightest electromagnetic events known to occur in the universe. Most observed GRBs are believed to consist of a narrow beam of intense radiation released during a supernova or hypernova as a rapidly rotating, high-mass star collapse to form a neutron star, quark star, or black hole<sup>[9]</sup>.

In this project, neutron stars were the most studied type of star, concretely magnetars, which are a kind of neutron star with an extremely powerful magnetic field, which its decay powers the emission of high-energy electromagnetic radiation, particularly X-rays and Gamma rays. The great majority of magnetars emit large bursts of Gamma rays and X-rays at irregular intervals, called Soft Gamma Repeaters (SGR), and these kind of stars have been our principal source of study.



### **3. Methodology and project development**

All the relevant learning methods and procedures are described in this chapter. Since the very beginning, it was well known that this project was much more challenging than common projects. It covers a very specific field of study with an important initial lack of information about it. Thus, a lot of time was spent in analysing by some ways which they finally had no relevant repercussion to the project. However, all the lanes that have been taken are explained below.

#### **3.1. Acquaint yourself with the environment of this project**

First, I had to read the paper published by my project supervisors about GSFLAI measurement of EUV photons flux rate during strong and mid solar flares to understand what I will be doing during the following months. After that, when I had an idea of what I would be working on, I started reading many papers about GRB detections with different satellites in order to know which was the methodology to study a GRB, which impacts had in the Earth's atmosphere, and in particular, the Earth's ionosphere, and finally the most relevant data to be analysed.

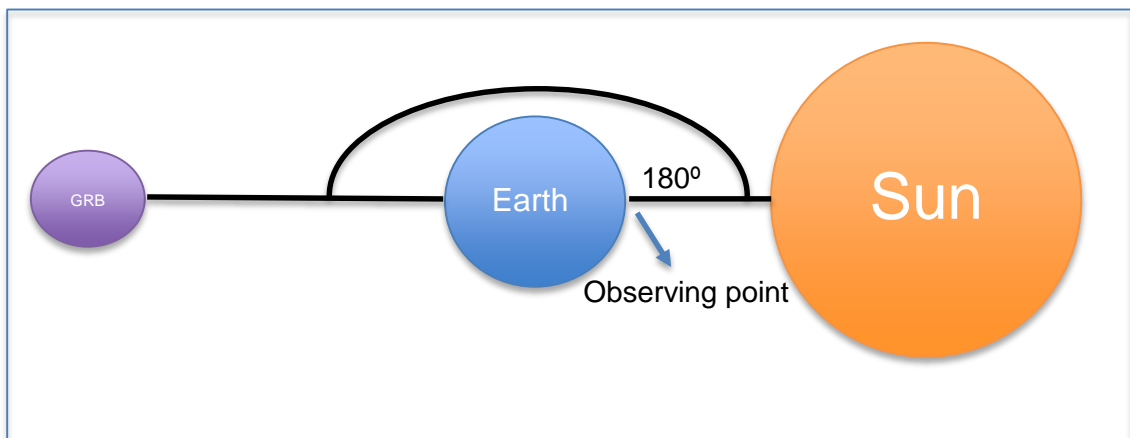
### 3.2. Selected GRBs and similar events

A top ten GRBs selection was made in order to focus on the most propitious events to be studied. This selection was made according to some different parameters described below:

- The **angular distance** between two objects, as observed from a location different from either of these objects, is the size of the angle between the two directions originating from the observer and pointing towards these two objects. In the context of this project, one point is the Sun and the second one is the star which emitted the selected GRB.

This value indicates how the GSFLAI results measured from this GRB will be affected by the solar radiation (noise), being this effect maximum when the angular distance is  $0^\circ$  (the Sun and the star are aligned), and this effect minimum when the angular distance is  $180^\circ$  (the Sun and the star radiation should not be detected simultaneously).

So I looked for GRBs with an angular distance greater than  $130^\circ$ , being this value enough to prevent a too high noise produced by the solar radiation.



*Fig. 5: A  $180^\circ$  angular distance between the Sun and the GRB star.*

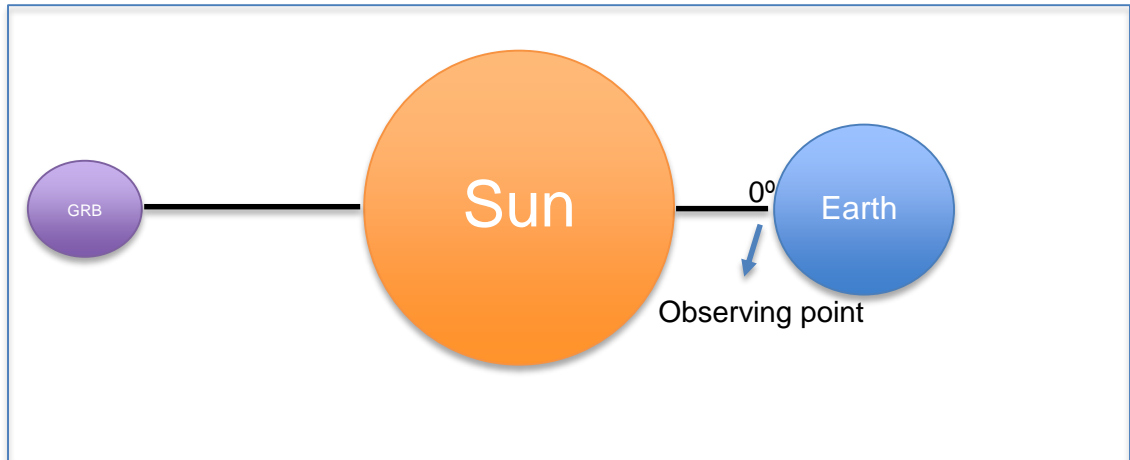


Fig. 6: A  $0^\circ$  angular distance between the Sun and the GRB star (one eclipses the other).

- The **geomagnetic activity index**, which is an excellent indicator of disturbances in the Earth's magnetic field, which might contribute on increasing the noise of the GSFLAI results. Thus, it is preferable to avoid high Kp indices if some stellar activity was detected, because it would be impossible to determine where it came from, or from the GRB star or from the Sun.
- The **event date**, which is crucial to ensure a good GSFLAI performance. The more recent the stellar flare is, the better GSFLAI performance will be due to the number of base stations deployed. A part from this, depending on the number of base stations, if there are enough, GSFLAI will be able to perform at a 1s rate sampling. On the contrary, only a 30s sampled data from GSFLAI will be possible, which is not a desired performance due to peaks masking caused by noise. This will also be the case for SISTED.

Top 10 (#)	Source Name	Angular Distance (°) <sup>[2]</sup>	Geomagnetic Activity Index, Kp <sup>[10]</sup>	Event Date	RA <sup>[4]</sup> (decimal)	Declination <sup>[4]</sup> (decimal)
1	SGR J1822.3-1606 <sup>[17]</sup>	163.8	2	14 July 2011	275.576	-16.074
2	SGR J1550-5418 <sup>[3]</sup>	143.8	1	17 June 2013	237.725	-54.307
3	PSR J1846-0258 <sup>[15]</sup>	150.9	1.5	27 July 2006	281.604	-2.975
4	SGR 1627-41 <sup>[5]</sup>	152.8	3	28 May 2008	248.97	-47.59
5	Swift J1834.9-0846 <sup>[6]</sup>	143.3	2	7 August 2011	280.46	-8.76
6	XTE J1810-197 <sup>[20]</sup>	146	2	19 May 2004	272.463	-19.731
7	PSR J1846-0258 <sup>[15]</sup>	141.3	1.5	31 May 2006	281.604	-2.975
8	SGR J1745-2900 <sup>[13]</sup>	126.4	2	25 April 2013	266.417	-29
9	AXP 1E 1841-045 <sup>[14]</sup>	121.9	2	6 May 2010	280.33	-4.936
10	XTE J1810-197 <sup>[20]</sup>	114	2	19 April 2004	272.463	-19.731

Table 2: List of the best ten GRBs to be studied depending on some different parameters.

### 3.3. Directly measured data analysis from satellites and GSFLAI launching with FV tool

Once the table of the best ten GRBs selected to be studied was made, we first focused on the best three ones (SGR J1822.3-1606, SGR J1550-5418, PSR J1846-0258) because we probably would obtain the best results from them. Later on, we only focused on SGR J1550-5418 as this event was the most recent one and it could be studied with better condition (1s sampling rate instead of 30s sampling rate).

Then the data searching and downloading was carried out from the different satellites (Fermi, Swift, XMM-Newton...) which observed these events, the great majority from NASA missions. I had to use a file viewer tool called FV (Fits Viewer) to be able to read and analyse these data.

In parallel, my supervisors MHP and AGR, who conceived and developed from scratch the GSFLAI and SISTED softwares respectively, had been launching these detection algorithms to the selected GRBs pointing the detector towards the source of each event (right ascension and declination coordinates) on the event's day in order to compare the results obtained with the directly measured data from the satellites of these GRBs.

### **3.4. GSFLAI and SISTED launching to GRBs with effects on the Earth's ionosphere.**

Once we have downloaded the data files from Fermi and Swift satellites and we could analyse them, we realized that this kind of study was not fruitful. The data of these files was supposed to show the measurements of the detected flares by the GBM and the BAT instruments on board Fermi and Swift satellites respectively, as it was mentioned on the different papers from where I found the SGR J1550-5418 event information. The point is that the registered time of the energy peaks shown in these files did not match to the time mentioned in the paper<sup>[3]</sup> (03:49:49.605 Coordinated Universal Time -UTC- versus 09:52:30.276 UTC; times extracted from the downloaded file from NASA Fermi satellite and directly extracted from the paper of the event, respectively) and that not only occurred with SGR J1550-5418, but with SGR J1822.3-1606 and PSR J1846-0258 too.

This unclear point bring us to mostly rely on the information included in published papers to carry on the study. Finally we started selecting GRBs which had some kind of effect on the Earth's ionosphere at EUV band and launching GSFLAI and SISTED detection algorithms, pointing to their coordinates, in order to see any evidence of detection in their results.

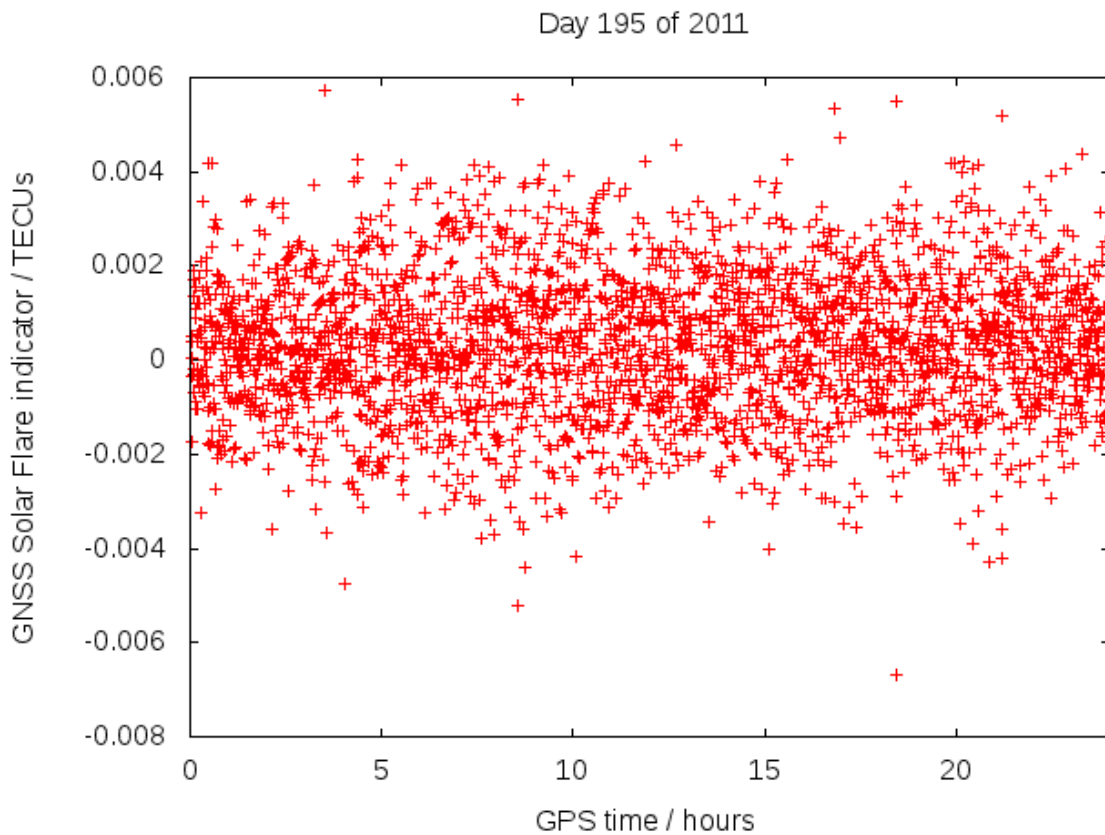
Finally, three tables of each stellar flare were made, showing some relevant parameters of the GSFLAI results from the three days before the event, the day of the event and the three days after. Plots zoomed to the surroundings of the exact hour of the event's day are also shown in order to look for some important peaks that could evidence a possible detection.

#### 4. First results applying GSFLAI and SISTED detection algorithms

The first stellar flares studied were the best three candidates of the *Table 2*; SGR J1822.3-1606, SGR J1550-5418 and PSR J1846-0258. Thus, we first launched GSFLAI at a 30s sampling rate to these three sources pointing the detector towards their respective coordinates, not only for the day when the events occurred, but three days before and three days after of each one of them.

##### **SGR J1822.3-1606**

The results of GSFLAI from the first source we selected to be studied, SGR J1822.3-1606, are presented below.



*Fig. 7: GSFLAI in TECUs in function of the GPS time in hours of the day of SGR J1822.3-1606 burst (14<sup>th</sup> July 2011) at 30s sampling rate.*

The event was triggered by the Gamma-Ray Burst Monitor (GBM) on board Fermi satellite at 12:47:54.38 UTC<sup>[17]</sup> on 14<sup>th</sup> July 2011. In the image above there is no a significant peak at this time, and there are more relevant peaks at other times during the whole day.

The three previous and the three following days of the day when the flare was detected were also analysed with no positive result.

Analysed day (yyymmdd)	Source (star name)	Right Ascension (decimal)	Declination (decimal)	Time of the event (UTC)	Sampling rate (Hz)	Differences (Simple/Double)	Software (GSFLAI/SISTED)
20110711	SGR J1822.3-1606	275.576	-16.074	-	30	Simple	GSFLAI
20110712	SGR J1822.3-1606	275.576	-16.074	-	30	Simple	GSFLAI
20110713	SGR J1822.3-1606	275.576	-16.074	-	30	Simple	GSFLAI
20110714	SGR J1822.3-1606	275.576	-16.074	12:47:54.38	30	Simple	GSFLAI
20110715	SGR J1822.3-1606	275.576	-16.074	-	30	Simple	GSFLAI
20110716	SGR J1822.3-1606	275.576	-16.074	-	30	Simple	GSFLAI
20110717	SGR J1822.3-1606	275.576	-16.074	-	30	Simple	GSFLAI

*Table 3: Previous and subsequent days analysed for SGR J1822.3-1606 stellar flare on 14<sup>th</sup> July 2011.*

Apart from the high level of noise, there were also significant peaks during the whole day with similar intensity than those obtained the day of the SGR J1822.3-1606 flare. Such a result did not prove any possible detection because the origin of those peaks were unknown. It could be originated by cosmic noise, or even by solar activity, it could also really be a real detection of the SGR J1822.3-1606 flare, but there is no evidence of its origins, so we rejected a possible detection of this flare.

### SGR J1550-5418

After analysing the SGR 1822.3-606 flare, GSFLAI was launched for the second source selected to be studied, SGR J1550-5418. Next, the results are shown.

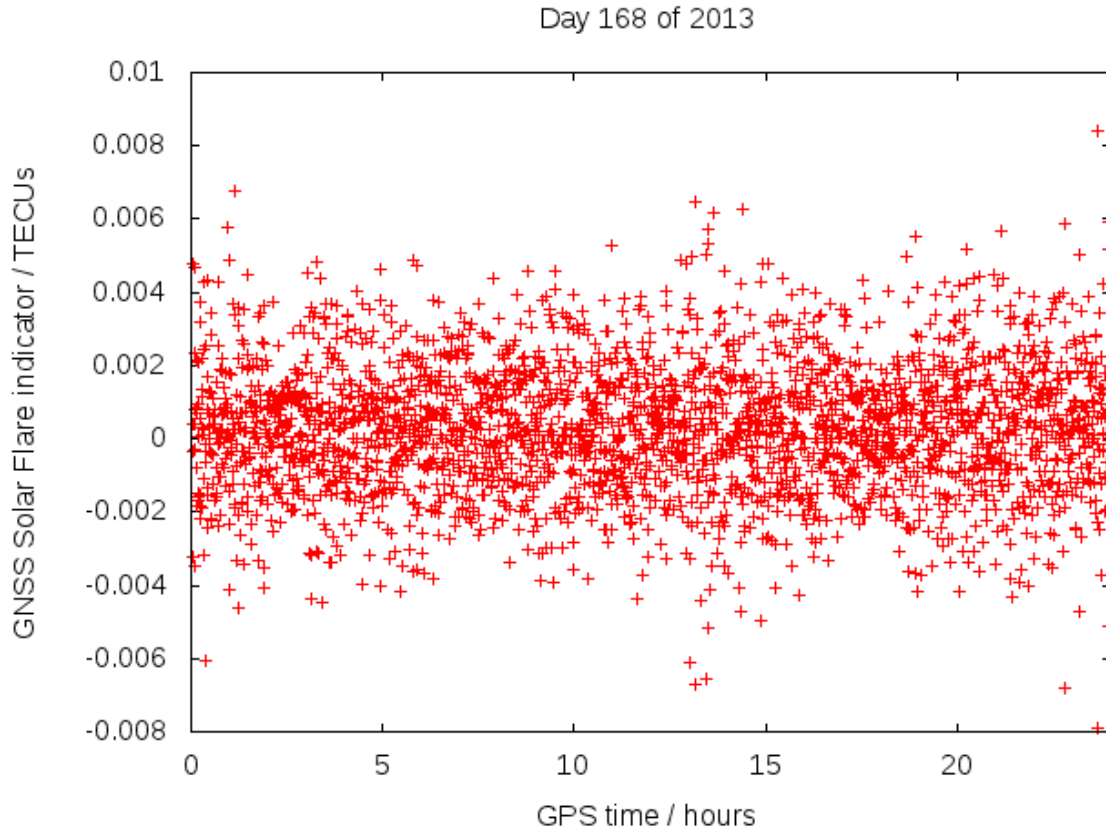


Fig. 8: GSFLAI in TECUs in function of the GPS time in hours of the day of SGR J1550-5418 burst (17<sup>th</sup> June 2013) at 30s sampling rate.

The event was observed by the Gamma-Ray Burst Monitor (GBM) on board Fermi satellite at 09:52:30.48 UTC<sup>[3]</sup> on 17<sup>th</sup> June 2013, which was also detected by the Swift satellite. As it is shown before, in the image above there is no a significant peak at this time, and there are more relevant peaks at other times during the whole day.



As in the previous source analysis, the three previous and the three days after of SGR J1550-5418 flare were also analysed, but with the same negative results.

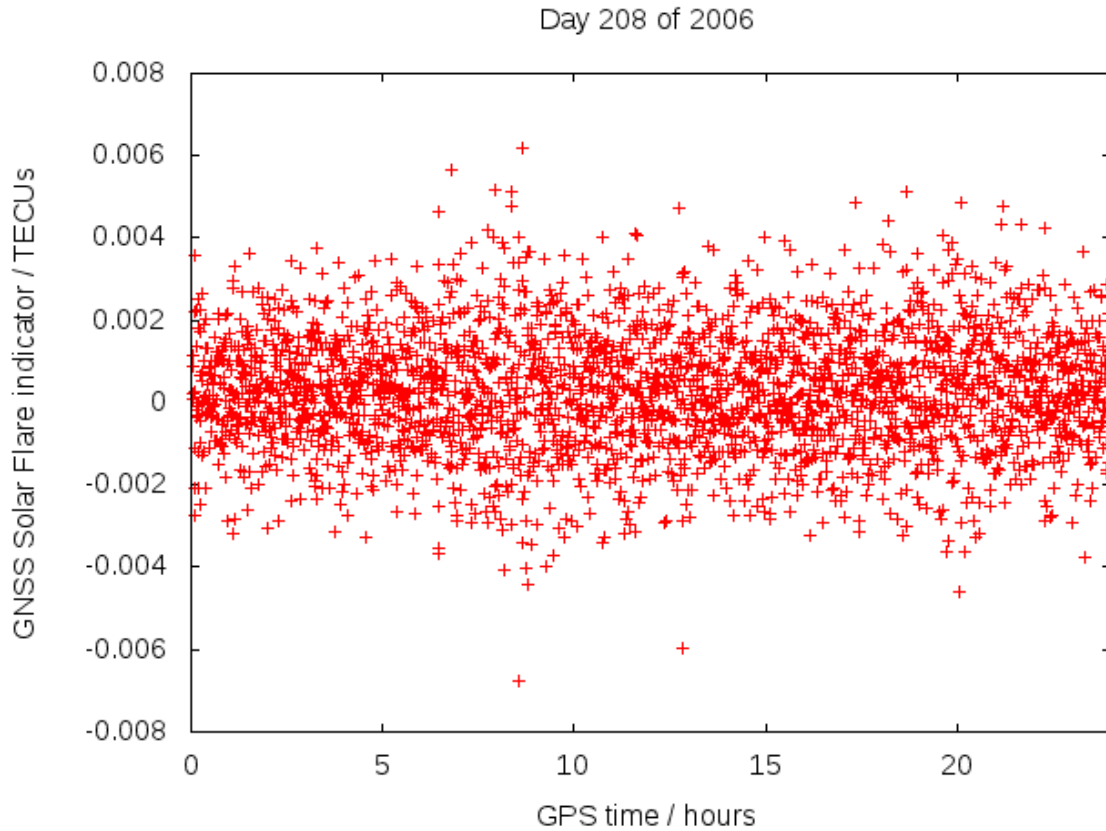
Analysed day (yymmdd)	Source (star name)	Right Ascension (decimal)	Declination (decimal)	Time of the event (UTC)	Sampling rate (Hz)	Differences (Simple/Double)	Software (GSFLAI/SISTED)
20130614	SGR J1550-5418	237.725	-54.307	-	30	Simple	GSFLAI
20130615	SGR J1550-5418	237.725	-54.307	-	30	Simple	GSFLAI
20130616	SGR J1550-5418	237.725	-54.307	-	30	Simple	GSFLAI
20130617	SGR J1550-5418	237.725	-54.307	09:52:30.48	30	Simple	GSFLAI
20130617	SGR J1550-5418	237.725	-54.307	09:52:30.48	1	Double	GSFLAI
20130617	SGR J1550-5418	237.725	-54.307	09:52:30.48	1	Double	SISTED
20130618	SGR J1550-5418	237.725	-54.307	-	30	Simple	GSFLAI
20130619	SGR J1550-5418	237.725	-54.307	-	30	Simple	GSFLAI
20130620	SGR J1550-5418	237.725	-54.307	-	30	Simple	GSFLAI

Table 4: Previous and subsequent days analysed for SGR J1550-5418 stellar flare on 17<sup>th</sup> June 2013.

The days around 17<sup>th</sup> June 2013 did not provide us any evidence of a successful detection because there was also a lot of peaks as in the event's day, thus it is not possible to confirm a detection of this flare due to the unclear origin of all these peaks.

### PSR J1846-0258

The third stellar flare analysed was that coming from PSR J1846-0258 on 27<sup>th</sup> July 2006. The results of GSFLAI are shown below.



*Fig. 9: GSFLAI in TECUs in function of the GPS time in hours of the day of PSR J1846-0258 burst (27<sup>th</sup> July 2006) at 30s sampling rate.*

The exact GRB time was not informed anywhere and we could not make a comparison with the GSFLAI results, however we insist on looking for any peak during the whole day and comparing this result with the previous and later three days of the event's day. The results obtained, as expected, were quite identical than last two stellar bursts and we could not confirm any detection again.

Analysed day (yyymmdd)	Source (star name)	Right Ascension (decimal)	Declination (decimal)	Time of the event (UTC)	Sampling rate (Hz)	Differences (Simple/Double)	Software (GSFLAI/SISTED)
20060724	PSR J1846-0258	281.604	-2.975	-	30	Simple	GSFLAI
20060725	PSR J1846-0258	281.604	-2.975	-	30	Simple	GSFLAI
20060726	PSR J1846-0258	281.604	-2.975	-	30	Simple	GSFLAI
20060727	PSR J1846-0258	281.604	-2.975	Not specified	30	Simple	GSFLAI
20060728	PSR J1846-0258	281.604	-2.975	-	30	Simple	GSFLAI
20060729	PSR J1846-0258	281.604	-2.975	-	30	Simple	GSFLAI
20060730	PSR J1846-0258	281.604	-2.975	-	30	Simple	GSFLAI

*Table 5: Previous and subsequent days analysed for PSR J1846-0258 stellar flare on 27<sup>th</sup> July 2006.*

Observing the results above, we noticed the resolution was not enough at a 30s sampling rate because of the important presence of noise, so this made it very low reliable to analyse and to compare with direct measurements from Fermi and Swift satellites. This drawback, together with the fact that there were a lot of similar peaks both in the day of the stellar flare than in those days before and after not knowing the origin of all of them, made us to look for another way to carry on studying stellar flares, so we finally decided not spending more time studying through this type of analysis. However, later on we realized that the second best candidate (SGR J1550-5418) could be sampled at 1s sampling rate, improving the performance of GSFLAI and avoiding excessive noise, because it was the most recent event (June 2013), and this means that more base stations were deployed at this time and high accuracy data could be obtained. We spent an important part of the time on studying this event.

## SGR J1550-5418

Results from GSFLAI pointing again to SGR J1550-5418 on 17<sup>th</sup> June 2013 are shown below, but this time launching GSFLAI at a 1s sampling rate instead of at a 30s sampling rate.

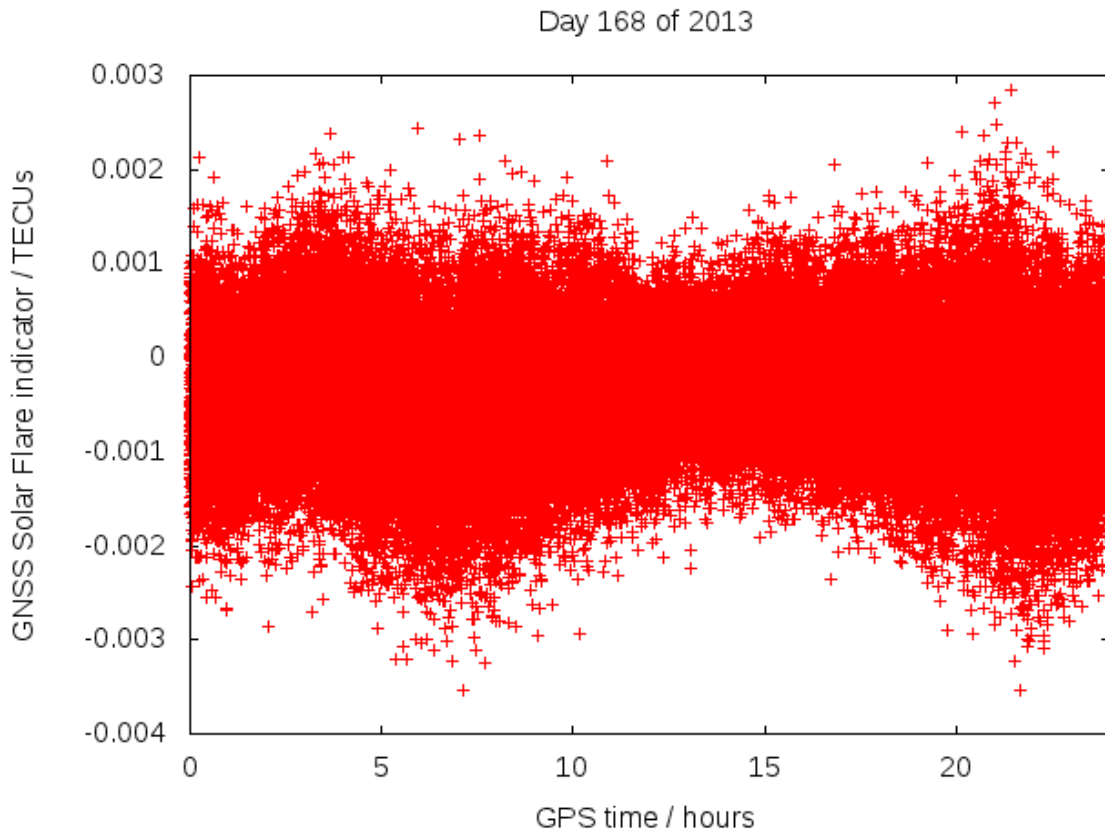


Fig. 10: GSFLAI in TECUs in function of the GPS time in hours of the day of SGR J1550-5418 burst (17<sup>th</sup> June 2013) at 1s sampling rate.

As expected, the results from GSFLAI were more accurate thanks to the high resolution sampling at 1s instead of 30s, as the three results before, avoiding an important noise level and being able to detect peaks close together (thirty times more samples than before).

We first thought about contrasting GSFLAI results with the data obtained by the Fermi GBM and the Swift BAT instruments<sup>[7]</sup> using FV tool, but as explained in chapter 3.3 *Directly measured data analysis from satellites and GSFLAI launching*, the data provided by these files was not consistent with the paper<sup>[3]</sup>. Thus, we decided to directly compare the results obtained from GSFLAI with the exact hour of detection provided by the paper to ensure if there was an evidence of detection.

Table 10. Locations, durations, peak fluxes, and fluences for bursts of known sources

Trigger (yyymmddff)	Source	Location <sup>a</sup>		$T_{90}$ Start (UT)	$T_{90}$ (ms)	$T_{50}$ Start (UT)	$T_{50}$ (ms)	4ms Peak Flux <sup>b c</sup> (erg/cm <sup>2</sup> )	Fluence <sup>b c</sup> (erg/cm <sup>2</sup> )
		RA	Dec.						
090605862a	SGR J0418+5729	04h 18m 33.867s	+57° 32' 22.91"	20:30:48.875	40 ± 7	20:30:48.881	10 ± 4	1.00E-05 ± 5.80E-07	9.80E-08 ± 3.92E-09
090605876a	SGR J0418+5729	04h 18m 33.867s	+57° 32' 22.91"	21:01:35.011	80 ± 6	21:01:35.019	34 ± 4	1.71E-06 ± 1.50E-07	2.94E-08 ± 1.72E-09
100326867a	SGR 1806-20	18h 08m 39.337s	-20° 24' 39.85"	20:48:59.836	64 ± 9	20:48:59.848	32 ± 6	1.99E-06 ± 3.59E-07	8.44E-08 ± 5.46E-09
110714533a	SGR J1822.3-1606	18h 22m 18.00s	-16° 04' 26.8"	12:47:54.368	40 ± 18	12:47:54.368	8 ± 11	8.66E-06 ± 6.42E-07	5.81E-08 ± 4.52E-09
110729737a	AXP 4U 0142+61	01h 46m 22.407s	+61° 45' 03.19"	17:40:37.110	20 ± 6	17:40:37.114	12 ± 6	6.50E-06 ± 1.08E-06	1.33E-07 ± 9.72E-09
120421346a	AXP 1E 2259+586	23h 01m 08.295s	+58° 52' 44.45"	08:17:43.694	40 ± 33	08:17:43.694	8 ± 11	6.71E-06 ± 7.91E-07	5.73E-08 ± 5.40E-09
130617411a	SGR J1550-5418	15h 50m 54.12386s	-54° 18' 24.1141"	09:52:30.276	156 ± 16	09:52:30.300	88 ± 11	1.72E-06 ± 3.76E-07	1.27E-07 ± 6.66E-09

<sup>a</sup>Source: [Olausen & Kaspi \[2013\]](#)

<sup>b</sup>by COMP model

<sup>c</sup>8-200 keV energy range

Table 6: List of detected stellar flares from known sources showing some parameters of interest<sup>[3]</sup>. SGR J1550-5418 burst marked in red.

Observing the table above, the last row shows the detection of SGR J1550-5418 flare of 17<sup>th</sup> June 2013. The fifth column of the respective row shows the start time,  $T_{90}$  Start (UT), of that flare in Universal Time (UT), which started at 09:52:30.276 UT.

At this moment, it was the time to take a look at the GSFLAI results to search for coincidences. A great result would have been a single noted peak around 09:52:30.276 UT and no one else to evidence a very possible detection, but lots of distinguished peaks all along that day where showed in the GSFLAI results, and there was not a single noted one around this time.

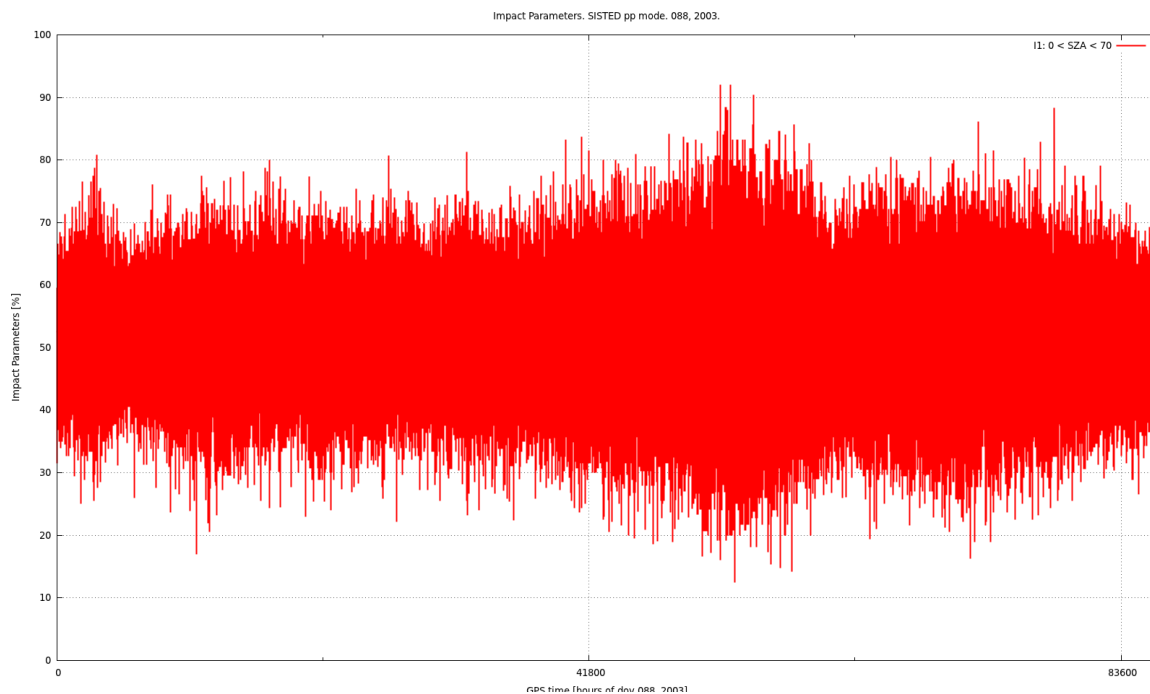
This result confirmed the very challenging nature of the problem and we had to reconsider how to carry on analysing stellar flares.

After puzzling over how to proceed on next steps to study GSFLAI detections we decided to continue, instead of with the best ten flares table, with reported burst detections with a relevant effect on the Earth's ionosphere and then check if around the exact time of the event said in the respective paper appeared a peak on the GSFLAI and now also SISTED results.

## GRB030329

On 29<sup>th</sup> March 2003 at 11:37:14.67 UTC, GRB030329 triggered all three instruments on board the High Energy Transient Explorer (HETE-II) and lasted for more than 25 seconds causing an important impact to the Earth's ionosphere<sup>[16]</sup>.

For the first time, we thought about launching SISTED pointing towards this source at a 1s sampling rate and the results obtained were quite curious. The following graphic shows the SISTED results.



*Fig. 11: SISTED results for GRB030329 burst (29<sup>th</sup> Mars 2003) at 1s sampling rate. Plotting impact parameters in % in function of the GPS time in hours.*

At first sight there is not an evidence of detection with SISTED to this event around the 41200 seconds marker in the figure (which corresponds to approximately 11:37:14.67 UTC, the hour of the burst).

Nevertheless, we zoomed this plot narrowing the time span around the exact time when the flare was detected.

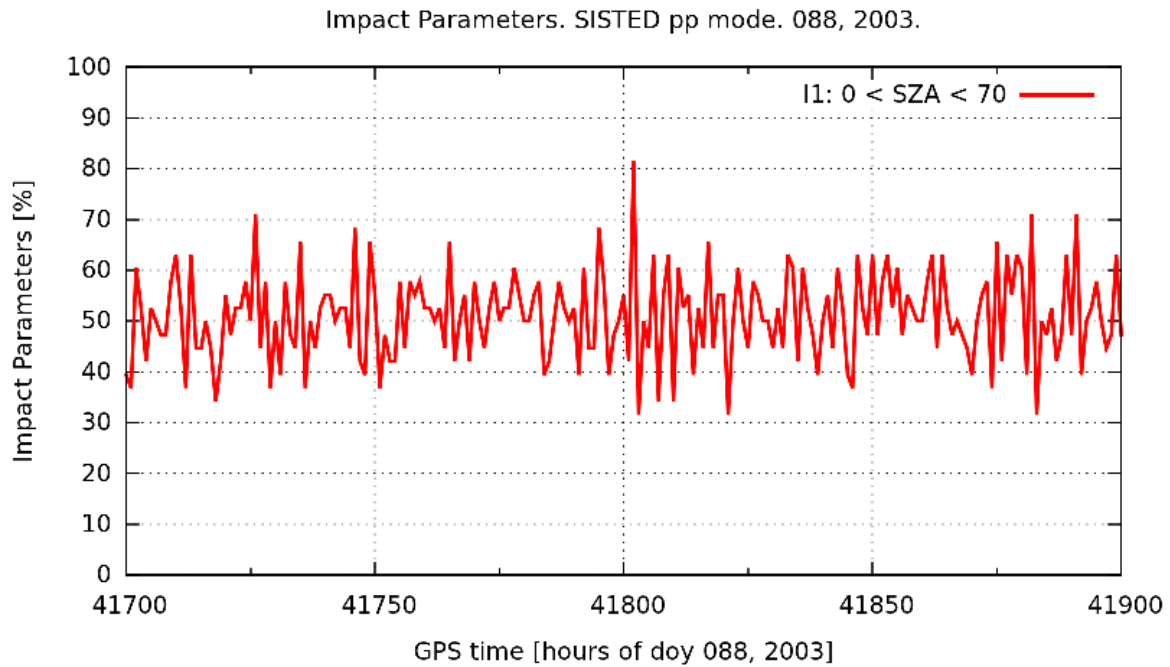


Fig. 12: SISTED results zoomed to the seconds around the GRB030329 burst.

If we observe the figure above we rapidly notice there is a peak approximately in 41805 seconds which correspond to 11:36:45 UTC and the burst was triggered at 11:37:14.67 UTC (41834.67 seconds).

Since there is no clarification to this time, if it was the start time, the maximum activity moment or the end time of the burst, and taking into account it lasted more than 25 seconds and the time lapse between the peak detected from SISTED (11:36:45 UTC) and the reported burst time from HETE-II (11:37:14.67 UTC) was almost 30s, we could not obviate this result. Thus, it could be a successful detection by SISTED, so we analysed it deeper.

This result is important, but it does not evidence a detection because this peak could be produced by other causes than GRB030329 flare, such as solar activity or cosmic rays. It is logical to think about this because many more peaks can be observed in the SISTED results along the whole day, even greater than that one at 41834.67 seconds, as it occurred with the first three stellar flares studied.

Thus, we first ensured that the results from SISTED were reliable by looking the ionospheric Pierce Point (IPPs) distribution at the time of the burst to ascertain if there was a considerable number of base stations collecting data from the event with no presence of noise from Sun activity. The substellar point at the time of the burst was at the Pacific Ocean and the IPPs in the sunlit region were at West North America to East Asia.

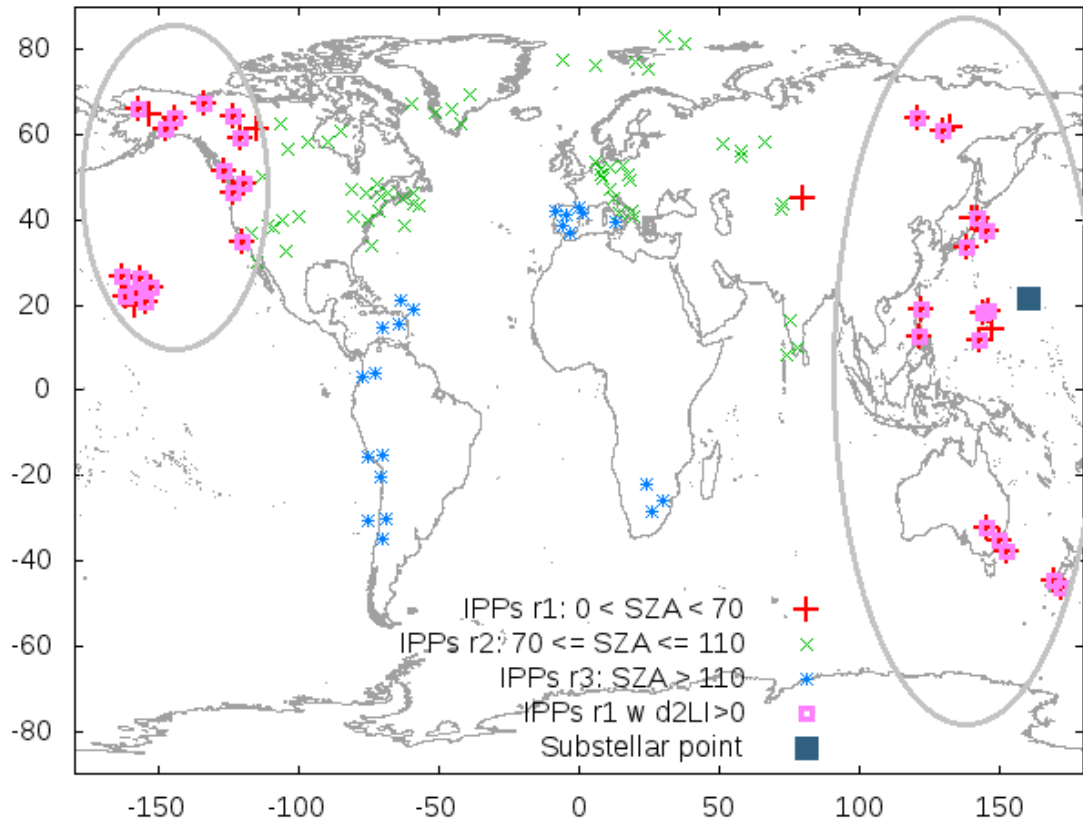


Fig. 13: IPPs distribution at the time of the GRB030329 burst.

There were a total of 31 illuminated IPPs out of 38 (81.5%) during the burst in the range of  $0^\circ < \text{SZA} < 70^\circ$ , that were detecting overionization potentially caused by GRB030329 flare. Regarding the explanation before, now it is more probable that this peak could be related to the GRB030329 flare, it is not decisive, but it is a good beginning.



### SGR J1550-5418

We had already ran GSFLAI for this flare at 09:52:30.276 UT on 17<sup>th</sup> June 2013, but later on, because of the possible detection obtained by SISTED for GRB030329 stellar flare, we thought about running SISTED for it too and zooming the results to the exact hour of detection, like we did in GRB030329 flare, looking for a nearby peak.

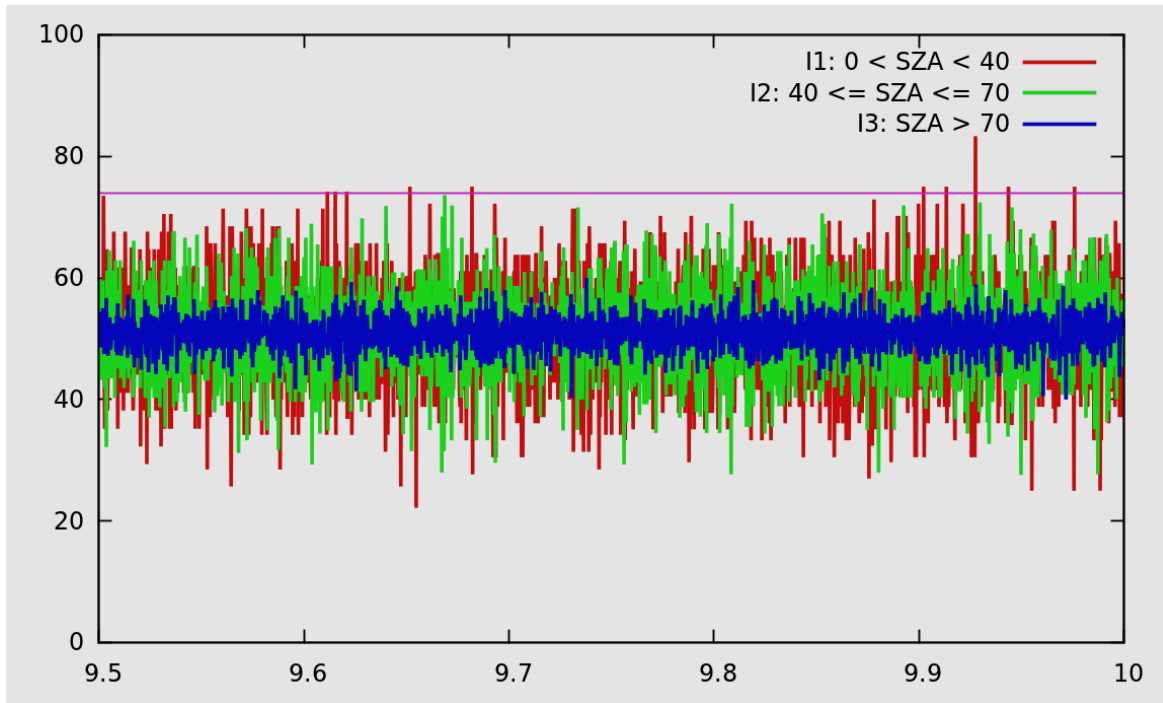


Fig. 14: SISTED results for SGR J1550-5418 zoomed around the exact flare detection time 09:52:30.276 UT (17<sup>th</sup> June 2013).

As shown in the plot above there is a significant peak around 9.93 hours (09:55:48 UT), where 30 out of 36 IPPs (83.3%) were detecting overionization in the zenith closest zone ( $0^\circ < \text{SZA} < 40^\circ$ ). Thus, SISTED detected a peak 3 minutes after the exact detection time of the flare.

In conclusion, at first sight from the results obtained by GSFLAI and SISTED we do not see any peak which can be considered as a possible detection of a stellar flare for any of the four analysed ones, because there are lots of peaks during the whole day when each stellar flare occurred and there are more peaks even greater on the days before and after. Then, that is why graphics were zoomed around the hour when the stellar flare was detected.

Thus, it was when we realized that in two out of the four studied stellar flares there was a peak very close to the exact hour of detection, that it could mean a successful detection, but as it was mentioned above in this project, it is difficult to assure the origin of this peak. That is why in the future many stellar flares should be studied looking for more peaks around the exact time of detection in order to make an average probability of successful detection.

## 5. Budget

This is not a project where a prototype is designed, thus it can only be included an estimation of the hours that have been dedicated to this thesis and a cost evaluation considering as a junior engineer.

Weekly hours:	15 hours
Weeks:	25 weeks
Total hours:	375 hours
Junior engineer cost per hour:	9 €/hour
<b>Project estimation cost</b>	<b>3375 €</b>

GSFLAI and SISTED software have been used in this project, run by the advisor and co-advisor (with a similar budget cost than the one estimated by the candidate), but since UPC is the owner, it has not supposed any license cost.

## 6. Conclusions and future development

After some months working on the stellar flare analysis there is no clear evidence to prove that GSFLAI or SISTED software detection are able to successfully detect any stellar flare coming from the most energetic stars known in the universe, called magnetars. However, in two cases a significant time co-location between stellar flares and SISTED peak is remarkable, suggesting studying more cases in future.

Four stellar flares has been studied in this project, those from SGR 1822.3-1606, SGR J1550-5418, PSR J1846-0258 and GRB030329 on 14<sup>th</sup> July 2011, 17<sup>th</sup> June 2013, 27<sup>th</sup> July 2006 and 29<sup>th</sup> March 2003 respectively, and only in two out of these four stellar flares there could be a possible detection since a peak, close to the exact hour of detection, appears on the GSFLAI and SISTED results.

These two peaks do not demonstrate a detection by GSFLAI or SISTED algorithms, but do not discard it neither. The fact that there are lots of peaks during the whole day of the event and not only this one close to the exact hour, and there are also many peaks the days before and after the event, even greater than that one detected close to the hour of the stellar flare, does not prove that these two peaks correspond to a stellar flare detection (on the other hand we are not sure of the comprehensive character of the available spacecraft-based measurements). Even there were only these two peaks and not one else, the origin of these peaks is unknown; they could be cosmic rays, solar activity or they even could be really a stellar flare.

Thus, as the first of many next steps on this project are left, many more stellar flares should be studied in order to provide a kind of a probability of detection, based on the number of the stellar flares studied and the number of peaks found around the exact hour of the stellar flare detection. If this probability was close to one, what it means that in almost all the studied stellar flares a peak around the exact hour of detection appears in the GSFLAI or SISTED results, it could be considered that both detection algorithms based on GPS are able to detect stellar flares. And in the other way around, if this probability was close to zero, it could not be affirmed that these two detection algorithms are able to detect stellar flares, at least by the moment.

## 7. Bibliography

Reference list:

- [1] A service of the Astrophysics Science Division at NASA/GSFC and the High Energy Astrophysics Division of the Smithsonian Astrophysical Observatory (SAO). [Online] Available: <https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/xTime/xTime.pl>.
- [2] "Angular distance calculation guide". [Online] Available: [http://www.gyes.eu/calculator/calculator\\_page1.htm](http://www.gyes.eu/calculator/calculator_page1.htm).
- [3] Collazzi, A. C. "The five year Fermi/GBM magnetar burst catalog". *The Astrophysical Journal Supplement Series*, vol. 218, no. 1, p. 11, May 2015. DOI: 10.1088/0067-0049/218/1/11.
- [4] "Coordinates searcher". [Online] Available: <http://simbad.u-strasbg.fr/simbad/>
- [5] Esposito, P. "The 2008 May burst activation of SGR 1627-41". *Monthly Notices of the Royal Astronomical Society*, vol. 390, no. 1, p. L34-L38., October 2008. DOI: 10.1111/j.1745-3933.2008.00530.x.
- [6] Esposito, P. "X-ray and radio observations of the magnetar Swift J1834.9-0846 and its dust-scattering halo". *Monthly Notices of the Royal Astronomical Society*, p. st569, January 2013. DOI: 10.1093/mnras/sts569.
- [7] Fermi Science Support Centre, NASA. [Online] Available: <http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi>.
- [8] García-Rigo, A. Contributions to ionospheric determination with global positioning system: solar flare detection and prediction of global maps of total electron content. Ph.D. dissertation. Barcelona, 2012.
- [9] "Gamma Ray Bursts, Soft Gamma Repeaters and Magnetars". [Online] Available: [https://en.wikipedia.org/wiki/Gamma-ray\\_burst](https://en.wikipedia.org/wiki/Gamma-ray_burst)
- [10] Geomagnetic Activity Index, old indices. [Online] Available: [ftp://ftp.swpc.noaa.gov/pub/indices/old\\_indices/](ftp://ftp.swpc.noaa.gov/pub/indices/old_indices/).
- [11] Hernández - Pajares, M. "GNSS measurement of EUV photons flux rate during strong and mid solar flares". *Space Weather*, vol. 10, no. 12, December 2012. DOI: 10.1029/2012SW000826.
- [12] Hernández - Pajares, M. "The ionosphere: effects, GPS modeling and the benefits for space geodetic techniques". *Journal of Geodesy*, vol. 85, no. 12, p. 887-907, September 2011 .DOI: 10.1007/s00190-011-0508-5.
- [13] Kennea, J. A. "Swift Discovery of a new soft gamma repeater, SGR J1745-29, near Sagittarius A". *The Astrophysical Journal Letters*, vol. 770, no. 2, p. L24, May 2013. DOI: 10.1088/2041-8205/770/2/L23.
- [14] Lin, L. "Burst and Persistent Emission Properties during the Recent Active Episode of the Anomalous X-Ray Pulsar 1E 1841-045". *The Astrophysical Journal Letters*, vol. 740, no. 1, p. L16, September 2011. DOI: 10.1088/2041-8205/740/1/L16.
- [15] Livingstone, Margaret A. "Post-outburst Observations of the Magnetically Active Pulsar J1846-0258. A New Braking Index, Increased Timing Noise, and Radiative Recovery". *The Astrophysical Journal*, vol. 730, no. 2, p. 66, March 2011. DOI: 10.1088/0004-637X/730/2/66.
- [16] Maeda, K. "Ionospheric effects of the cosmic gamma ray burst of 29 March 2003". *Geophysical research letters*, vol. 32, no. 18, September 2005. DOI: 10.1029/2005GL023525.
- [17] Rea, N. "A new low magnetic field magnetar: the 2011 outburst of Swift J1822.3-1606". *The Astrophysical Journal*, vol. 754, no. 1, p. 27, July 2012. DOI: 10.1088/0004-637X/754/1/27.
- [18] "Swift: Catching Gamma-Ray Bursts on the Fly" mission, HEASARC Archive Search, NASA. [Online] Available: <http://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/swift.pl>.
- [19] Wan, W. "The GPS measured SITEC caused by the very intense solar flare on July 14, 2000". *Advances in Space Research*, vol. 36, no. 12, p. 2465-2469, January 2004. DOI: 10.1016/j.asr.2004.01.027.
- [20] Woods, Peter M. "X-Ray Bursts from the Transient Magnetar Candidate XTE J1810-197". *The Astrophysical Journal*, vol. 629, no. 2, p. 985, May 2005. DOI: 10.1086/431476.

## 8. Glossary

<b>BAT</b>	Burst Alert Telescope
<b>EUV</b>	Extreme Ultraviolet
<b>FV</b>	Fits Viewer
<b>GBM</b>	Gamma-Ray Burst Monitor
<b>GNSS</b>	Global Navigation Satellite System
<b>GPS</b>	Global Positioning System
<b>GRB</b>	Gamma Ray Burst
<b>GSFLAI</b>	GNSS Stellar Flare Activity Indicator
<b>HETE</b>	High Energy Transient Explorer
<b>IPP</b>	Ionospheric Pierce Point
<b>MEO</b>	Medium Earth Orbit
<b>NASA</b>	National Aeronautics and Space Administration
<b>SGR</b>	Soft Gamma Repeater
<b>SZA</b>	Solar-Zenithal Angle
<b>UT</b>	Universal Time
<b>UTC</b>	Coordinated Universal Time
<b>VTEC</b>	Vertical Total Electron Content