

hola

New real-time GNSS algorithms for detection and measurement of
potential geoeffective stellar flares

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Abstract

Solar flares are sudden electromagnetic emissions on the Sun's surface that release large amounts of magnetic energy. These flares emit radiation that has an effect on Earth's ionosphere electron content and are detected by telescopes such as Swift or Fermi by performing gamma-ray observations from low Earth orbit. (Swift y fermi no son para solar flares son para GRB en general!!, quizas aqui deberia ir alguno que se centre en el sol especificamente)

Another approach for detecting these events is possible: the ionosphere electron content variation can be studied using data from the Global Navigation Satellite System (GNSS) (such as GPS)

Algorithms for detecting solar flares without knowing the location of the source, that is, the position of the Sun relative to Earth, as well as a study on the feasibility of the detection of such events for the challenging scenario of far-away stars, are presented, aiming to find an alternative detection method to that of the telescopes and using free, open-source data.

Keywords: Solar flares, Stellar flares, GNSS, GPS, IGS, GRB

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Chapter 1

GEP

merda del gep

Chapter 2

Background

As the project has a large background in physics and astronomy, some of the relevant topics that are going to be studied are introduced: Global Navigation Satellite Systems, the Ionosphere, Stellar Flares and Gamma-Ray Bursts.

2.1 Global Navigation Satellite Systems

GNSS and GPS

These two terms may lead to confusion as Global Navigation Satellite Systems (GNSS) is the generic term for all satellite navigation systems. The Global Positioning System (GPS), in particular, is the United States' GNSS system, the world's most used one. Other systems, for example, are the European Galileo or Russian GLONASS [7].

Global Navigation Satellite Systems use satellites to determine the position of a given object or device in terms of latitude, longitude and height.

Positioning

In short, GNSS works as follows: out of all the GNSS satellites orbiting Earth, at least four of them are constantly visible from a specific point and transmitting information at a certain frequency. When a device receives a signal from one of them, the distance to the satellite can be calculated by means of the time required to reach it and the speed of light. As many variables might affect the speed of light such as the medium through which it is propagating, this estimation of the distance is called **pseudo-range**.

Thus, the location of the receiver can be estimated using a technique called **trilateration**. Having three spheres around each of the satellites with the pseudo-range as their radius, the intersection of these spheres yields the location of the receiver [11].

Ionospheric Pierce Points

Ionospheric Pierce Points (IPP) are going to be very relevant throughout the development of the project. These will be the locations that we are going to use for our measurements, not those of satellites or receivers. A Ionospheric Pierce Point is the point where the line between the satellite and a receiver intersect with the ionosphere, where the Total Electron Content can be estimated. [4]

The International GNSS Service

In 1998 the International GNSS Service (IGS) was created as a collaboration of several members of the scientific community: Center for Orbit Determination in Europe (CODE), (European Space Agency) ESA, Jet Propulsion Laboratory (JPL) and Polytechnic University of Catalonia (UPC). This voluntary federation has made available open access GNSS data since its creation [2] [3].

Its data is provided by more than 300 GPS receivers around the globe and is processed by the previous institutions which compute the global distribution of the Total Electron Content (TEC) [9].

GNSS is a key component to this project because, as mentioned before, many variables can affect the speed of light and therefore the time it takes for the transmitter's signal to be intercepted by the receiver. One of these variables is the electron content of the layer of the atmosphere where GNSS satellites operate: the ionosphere.

2.2 Ionosphere

The ionosphere is a layer of the Earth's atmosphere that lies 75-1000km above the surface of the planet [18].

High energy from Extreme UltraViolet (EUV) and X-ray radiation can cause its atoms to be ionized and create a layer of electrons [15]. Due to these free electrons and ionized molecules, it is capable of affecting radio wave propagation, thus having an effect on Global Navigation Satellite Systems (GNSS) technology, this phenomena allows these satellites to be used as a global scanner for the ionosphere [10].

The main physical quantity used for describing the electron content of the ionosphere is the **Total Electron Content (TEC)**, the TEC is the total number of electrons between two points ($r1, r2$) along a cylinder of base $1m^2$. Slant TEC (STEC), in particular, can be defined as the TEC in which $r1$ and $r2$ are a satellite and a receiver's positions [17].

The unique properties the ionosphere has enable us to use the data provided by the GNSS technology to study a powerful phenomena that occurs in many stars across the universe: stellar flares.

2.3 Stellar flares

Flares from stars, in particular those that have the Sun as a source, more noticeable due to its proximity, are sudden flashes of brightness in the surface of stars which release large amounts of energy across the whole electromagnetic spectrum¹. Flares that have the Sun as a source can increase the electron content of the ionosphere and have an effect on waves passing through it, affecting satellite communications and causing a delay. This phenomena is the key element of the project, as it enables us to study these events.

Satellites can also be harmed by this effects: the flares heat up the outer atmosphere, which in turn increases the drag on these satellites reducing their lifetime in orbit. GPS as a solar observational instrument: Real-time estimation of EUV photons flux rate during strong, medium, and weak solar flares se explica el efecto del sol sobre ionosfera

The previous phenomena applies to flares originating in the Sun, whether a flare that has a star from outside the Solar System as a source has an effect on the Earth's atmosphere or not is one of the topic that is going to be studied in this project.

SOHO and GOES are space probes used for obtaining solar flare information [8]

2.4 Gamma-Ray Bursts

Throughout the project, in particular when studying the feasibility of stellar flares detection, another type of event will be mentioned and studied as well: Gamma-Ray Bursts (GRBs):

GRBs are highly energetic explosions that occur in distant galaxies, releasing large amounts of radiation, in particular Gamma rays, hence the name of the event. These bursts, despite being millions of light years away from Earth are so powerful they might still have an impact on the ionosphere, like the aforementioned stellar flares. The main difference with flares originating from stars is that GRBs are thought to be originated from the death of massive stars, that is, supernovas.

This event, despite not being a stellar flare, the phenomena we aim to detect, is going to be studied in the following sections to test the currently working algorithms mainly for two reasons: it has been studied and cataloged by telescopes such as the Fermi Observatory and there's is available information that we can use for our study, and the large amounts of energy they emit it make GRBs a more feasible target to detect.

Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C

Although a study on GRBs is presented in the next chapter, other cosmic events that may be detected using our proposed methods can be studied as well later on.

¹X-rays and Extreme Ultraviolet (EUV) radiation

Chapter 3

Study on the feasibility of stellar flare detection

Flares from far-away stars and Gamma-ray Bursts, albeit more powerful than flares that have the Sun as their source, may not be possible to detect due to the large distances that separate them from our measurement tool: the ionosphere.

Before starting to adapt the algorithm for detecting solar flares to this scenario, a study was conducted parallel to its development, to see if the energy from flares originating in far-away stars could be detected using the already existing method, namely the GNSS Solar Flare Activity Indicator (GSFLAI) algorithms [8].

To study if this was feasible, the algorithms were run on certain candidates of flares and GRBs to see if they could be detected.

The project supervisor, Manuel Hernández-Pajares, who as mentioned before has previously performed several studies on the subject, provided the GSFLAI algorithm to test the candidates. The GSFLAI algorithm takes into consideration the location of the source (the Sun) to see if there's a relation between an increase in the VTEC of the ionosphere and the solar-zenith angle to determine if this increase is caused by a solar flare. [GNSS measurement of EUV photons flux rate during strong and mid solar flares]

However, its execution may take up to 2 hours, because of this the aim was to:

- Find a database for possible candidates, several online archives with information about previously recorded Gamma Ray Bursts were considered.
- Select an appropriate source of this pool of candidates by writing a quick script that yielded an ordered list of the best candidates based on certain factors, instead of selecting a random source.

3.1 Sources of data and possible candidates

The three main databases we considered for the study were:

- The GRB collection website of Jochen Greiner, scientist at the Max-Planck-Institute for extraterrestrial Physics (MPE) [13], which offers a collection of detected GRBs by different telescopes and observatories.
- The Magnetar Outburst Online Catalog (MOOC), developed by the Institute of Space Sciences (CSIC-IEEC, Barcelona) [12]. We also had the pleasure to meet one of the leaders of this project, Nanda Rea, and discuss
- The Neil Gehrels Swift Observatory website and archive by the National Aeronautics and Space Administration (NASA), Goddard Space Flight Center [6] which contains an archive of detected GRBs by the Swift observatory and is constantly updated.

Because of the layout of the website and how the data could be accessed, the option with which we started was the Swift Database, as the data could be visualized in an HTML table and was easily accessible.

3.2 The Neil Gehrels Swift Observatory and its data

The Swift Observatory is a NASA mission with international participation, designed to observe GRBs and their afterglows to study topics such as the origins of GRBs or what they can reveal about the early stages of the universe [16]. The observatory is equipped with three main instruments that work with each other to study GRBs [5] [6]:

- The **Burst Alert Telescope (BAT)**, tasked with detecting the GRBs and computing their positions. This triggers the spacecraft to point the other telescopes to the burst so it can be studied in more detail.
- The **X-ray Telescope (XRT)**, used for studying the X-ray radiation and taking images of the bursts which in turn help increase the accuracy of the location estimation.
- The **UV/Optical Telescope (UVOT)**, which serves a similar purpose to the XRT, but studies the ultraviolet band of the spectrum.

For each detected GRB, the data obtained by the different telescopes is given. The parameters that are relevant to our study and determine the fitness of each of the candidates are:

- The **name of the burst**, given by the date it was detected. For example, the GRB named 190220A was detected the 20th of February of 2019.
- The **Universal Time (UT)** of the detection, that is, hh:mm:ss of the day given by the name.
- The fluence detected by the BAT component, in units of keV. that is.
- The **UVOT magnitude**, measured by the UV Telescope.
- The location that triggered the detection, given as **Right Ascension (Ra)** and **Declination (Dec)**.

Right Ascension and Declination are two concepts similar to longitude and latitude, respectively, used to describe the location of objects in the sky, in particular in a sphere of infinite radius that with the Earth as its center called the **celestial sphere**.

Taking this into account, Right Ascension is the equivalent of longitude, expressed in degrees (or more commonly in hours, minutes and seconds) and Declination, the equivalent of latitude, is expressed in degrees between the two poles: $+90^\circ$ and -90° . [19]

This reference system is used to describe the position of objects in the sky, and it is the one used by the Swift telescope to specify the location of the sources. Afterwards these concepts will play an important role when computing the angle formed between the source and the Sun.

3.3 Objective function

Our main goal in this section was to obtain a list of GRB candidates ordered from more to less probable to be detected by the algorithm, that is, their fitness. To obtain this score we had to define an objective function, taking into consideration two factors:

- The **strength** of the burst, given by the UVOT magnitude. If this value was not available (as it was the case with many of the candidates) the BAT fluence was considered as its strength. This values were already given by the archive and no additional computations were required.
- The **angle between the burst and the Sun**, this was an important factor because bursts having an effect on the night hemisphere should be more noticeable than those hitting the day one, where the Sun has a bigger influence.

Computing the angle

As mentioned before, the Swift archive gives us the Right Ascension (Ra) and Declination (Dec) where the source is thought to be located.

The location of the Sun, on the other hand, is unknown. But we do know the time when the burst was detected.

The supervisor, Manuel Hernández-Pajares, provided me an algorithm which takes date (year, month, day and UT) and a planet of the Solar System (or the Sun, our case) as the input and returns its location in the celestial sphere, that is, its Ra and Dec.

This algorithm belongs to the **Starlink Project** (Rutherford Appleton Laboratory), which provided open-source software like the one at hand to astronomical institutions. Although it was shut down in 2005, the code still remains and we could use it for our study [1].

Knowing the location of the GRB: (δ_g, α_g) , declination and right ascension, respectively. And that of the Sun: (δ_s, α_s) , the cosine of the angle between both can be computed and used as a parameter for the objective function.

This computation is done by performing the dot product of the two unit vectors that can be obtained from the Ra and Dec of the objects given by the following formulas: [?] TODO: arreglar esta cita

$$unitVectorGRB = \begin{bmatrix} \cos \delta_g * \cos \alpha_g \\ \cos \delta_g * \sin \alpha_g \\ \sin \delta_g \end{bmatrix} \quad (3.1)$$

$$unitVectorSun = \begin{bmatrix} \cos \delta_s * \cos \alpha_s \\ \cos \delta_s * \sin \alpha_s \\ \sin \delta_s \end{bmatrix} \quad (3.2)$$

$$\cos angleSunGRB = unitVectorGRB \cdot unitVectorSun \quad (3.3)$$

The code for the previous computation is shown here:

```

1 def scorePosition(sunRa, sunDec, ra, dec):
2     # If Ra and/or Dec are n/a, return 0, else, compute the dotProduct
3     if ra == 0 or dec == 0:
4         return 0
5
6     coordSun = [math.cos(sunDec)*math.cos(sunRa),
7                 math.cos(sunDec)*math.sin(sunRa),
8                 math.sin(sunDec)]
9
10    coordGRB = [math.cos(dec)*math.cos(ra),
```



```
11     math.cos(dec)*math.sin(ra),
12     math.sin(dec)]
13
14     angle = math.acos(coordSun[0]*coordGRB[0] +
15 coordSun[1]*coordGRB[1] +
16 coordSun[2]*coordGRB[2])
17
18     angle = angle*180/math.pi
19
20     return angle
```

Listing 3.1: Python function for computing the angle

3.4 Obtaining the data

Regarding the scrapping of the website to parse the data and obtain this ordered list, **Python** was chosen because the problem required a quick implementation, and Python's libraries offered a great tool to develop a simple solution as quick as possible.

In the script, the website with the table of bursts (see figure x) is scrapped using Python's **BeautifulSoup** library, which has an HTML and XML parser that allows us to easily select and obtain data from a given website.

Insertion sort was used so we could insert every considered GRB into a list of sorted candidates as we were traversing the table.

Regarding the distribution of weight between both factors, strength and angle, we

The best 10 candidates of the resulting sorted table (pie de pagina: bursts registered up to the 26th of February of 2019), is shown here:

We proceeded to study these bursts

3.5 Results

Chapter 4

Solar flare detection

Before developing the main solar flare detection algorithm a first program was developed that would target a powerful solar flare for which we knew the time of the event and therefore, the location of the Sun.

Although the aim of the main algorithm is detecting the solar flare without taking into consideration the position of the Sun, this first approach was done to understand how the inner part of the algorithm works: studying the correlation between the cosine of the solar-zenith angle and the VTEC content.

This sections also provides an introduction to the formatting and use of the Global Navigation Satellite Systems data (GPS in this case) and how the main parameters necessary for the algorithms are computed.

4.1 Data

4.1.1 GPS Data

As we have seen in previous sections, the International GNSS Service (IGS) has made available open access GNSS data since its creation. The Crustal Dynamics Data Information System (CDDIS) is a central data archive for the NASA's Crustal Dynamics Project (CDP), dedicated to archiving space geodesy data for research. This archive has been storing and providing access to the GNSS data generated by the IGS since 1992.

Figure 4.1 shows how data is stored in de CDDIS server (<ftp://cddis.nasa.gov/gps/data/hourly/>).

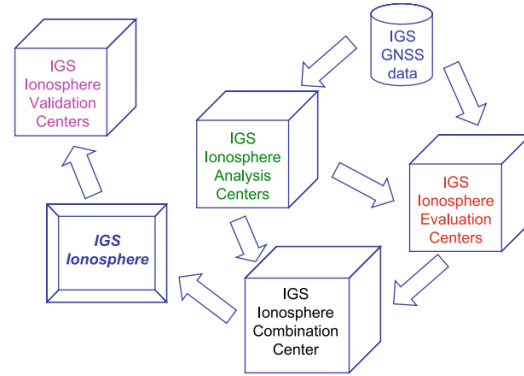
The files in this server contain raw GPS data that is then pre-processed to obtain VTEC maps in the form of **ti** files. An example diagram of this complex, several step procedure is shown in figure ??, extracted from the paper "The IGS VTEC maps: a reliable source of ionospheric information since 1998" [9] by Manuel Hernández-Pajares, which offers a detailed explanation of this process.

Index of /gps/data/hourly/

[parent directory]

Name	Size	Date Modified
1999/		4/1/19, 6:30:00 AM
2005/		11/15/17, 1:00:00 AM
2006/		11/15/17, 1:00:00 AM
2007/		11/16/17, 1:00:00 AM
2008/		11/15/18, 12:23:00 PM
2009/		1/30/18, 1:00:00 AM
2010/		1/30/18, 1:00:00 AM
2011/		1/29/18, 1:00:00 AM
2012/		1/29/18, 1:00:00 AM
2013/		1/26/18, 1:00:00 AM
2014/		1/26/18, 1:00:00 AM
2015/		1/25/18, 1:00:00 AM
2016/		1/24/18, 1:00:00 AM
2017/		1/23/18, 1:00:00 AM
2018/		12/13/18, 1:31:00 AM
2019/		4/10/19, 2:31:00 AM
reports	0 B	8/9/17, 2:00:00 AM

(a) Files



(b) Data flow

Figure 4.1: VTEC distribution throughout the day for all IPPS (a) and for IPPs that have Vill as the receiver (b)

However, for this and the following section, only the pre-processed ti files of past dates were needed, as detecting the flares in real time is a task that will be discussed later in the project, in which this pre-processing will have to be taken into consideration. The project supervisor, Manuel Hernández-Pajares, provided me with some of data sets to use as input for the algorithms, along with information about the formatting of this files.

4.1.2 Formatting

The ti files contain several rows of pre-processed GPS data. Each row has a Receiver Id. and a Transmitter Id., therefore, for each row we have the Ionospheric Pierce Point between the Receiver and Transmitter. Each IPP has several parameters that are relevant for our computations:

- The **GPS time**
- The **Receiver Id.**
- The **Transmitter Id.**
- The **double derivate of Li**
- The **xmappingion**
- The **right ascension** and **declination** of the IPP

```

1 Field number | Example value | Description
2 [...]
3 3            0.008333333333333333 GPS time/hours (tsecdayobs/3600.d0)
4 4            cand                      Receiver Id.
5 5            3                        Transmitter Id.
6 [...]
7 21           -0.5131586E-02          d2li
8 [...]
9 43           0.1565765332E+01        xmapping_ion
10 44           334.449                 xraion
11 45           33.092                  xlation
12 [...]

```

Listing 4.1: Format of the ti file

4.1.3 The Halloween Solar Storm: X17.2 flare

The data set we used was that of the so-called Halloween Storm, a powerful solar storm that took place from October to early November in the year 2003. In particular, we will try to replicate the results shown in figure 4.2, shown in the paper "GNSS measurement of EUV photons flux rate during strong and mid solar flares" for a powerful flare that took place in October 28th, 2003 [8].

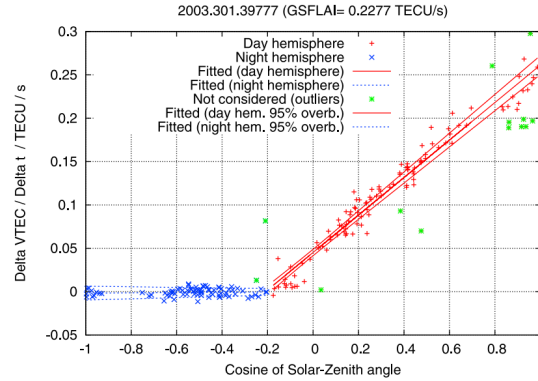


Figure 4.2: VTEC distribution throughout the day for all IPPS (a) and for IPPs that have Vill as the receiver (b)

As we can see the plot of the flare called X17.2 took place exactly at 2003.301.39777 (year.day.seconds of GPS time). In hours, 39777 seconds of a day is $39777s * 1h/3600s = 11.049...h$, around 11AM.

The ti files provided contained data from 10.5h to 11.5h (with a sampling rate of 30 seconds), so that we could see the VTEC distribution throughout the day.

With this data we can obtain the two parameters that will yield the plot shown in figure 4.2: the **VTEC value** and the **cosine of the solar-zenith angle**.

4.2 Vertical Total Electron Content (VTEC)

Fisrt we wanted to obtain VTEC distribution throughout the day, to visually see if any spikes appeared confirming that the moment we were going to study based on the paper [8] was correct.

For each epoch in our data set (from 10.5 to 11.5 with a sampling rate of 30 seconds) we needed to compute an estimation of the VTEC value.

4.2.1 Computing the VTEC

As we have mentioned before, one of the main paramenters relevant to the computation is the **double derivate of LI**, the d2li field in the ti file. The Li is the "ionospheric combination of carrier phases" [8], a direct measurement of TEC. Because this is a derivative it is the increment in VTEC, this will be observed in figure 4.3.

The VTEC can be estimated using the following approach:

$$\frac{d^2V}{dt^2} = \frac{d^2Li}{M} \quad (4.1)$$

Where $M = \frac{1}{\cos Z}$ is the "ionospheric mapping function", the inverse of the cosine of the satellite-zenith angle that we have for each IPP. [8]. This is the **xmappingion** field in the ti file.

Therefore, we can estimate the VTEC of an IPP by dividing the two given parameters:

$$VTEC \approx \frac{d^2Li}{M} \quad (4.2)$$

4.2.2 Distribution throughout the day

Because the only operation that had to be performed was the previous division, a simple AWK script was used to filter out the two necessary fields from the data file and print the resulting value as a function of time.

```

1 {
2   /a/
3   d2li = $21;
4   mappingFunc = $43;
5   vtec = d2li/mappingFunc;
6   print $3 " " vtec
7 }
```

Listing 4.2: AWK script to estimate the VTEC

```
1 #!/bin/bash
2 tiDataFile="../data/ti.2003.301.10h30m-11h30m.gz"
3
4 zcat "$tiDataFile" | gawk -f previewVTECDistribution.awk > vtecValues
5 gnuplot -e "set terminal png; set output 'vtecDistribution.png'; set
    title 'VTEC Distribution'; set xlabel 'Time of the day (hours)';
    set ylabel 'VTEC'; set grid; plot \"vtecValues\" using 1:2 with
    point"
6 rm vtecValues
```

Listing 4.3: Bash script to execute the procedures

The bash script executes the AWK process with the data as the input and outputs n rows with two columns: the time of the day and the calculated VTEC, plotting the results using Gnuplot. This results can be seen in figure 4.3(a), where we can see how the VTEC value evolves throughout the day. Visually, a spike can be seen between 11 and 11.2 hours.

As mentioned before this value is estimated using the derivative of li , because this is the increment in VTEC, we can see that the value becomes negative after the spike, due to the VTEC value decreasing (negative gain).

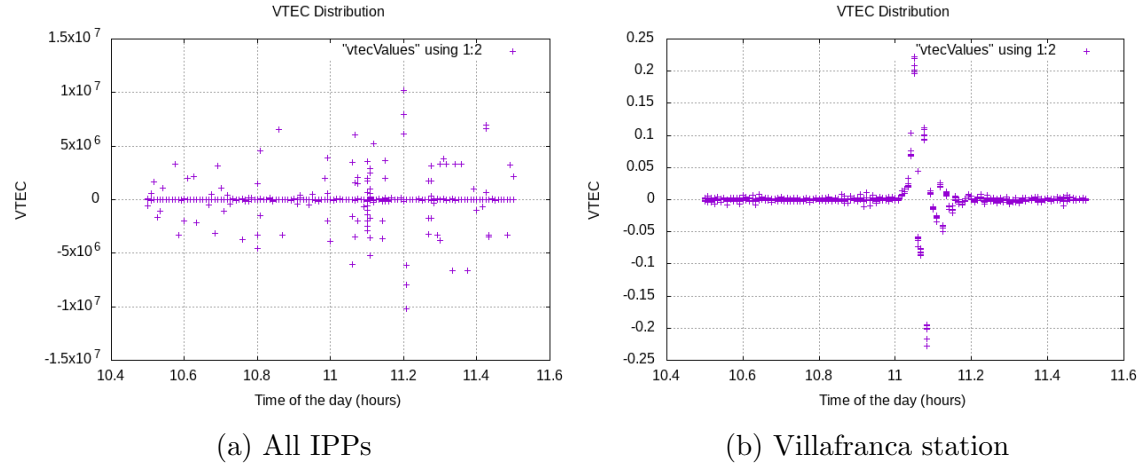


Figure 4.3: VTEC distribution throughout the day for all IPPs (a) and for IPPs that have Vill as the receiver (b)

To see the event more clearly, though, we can focus on one specific receiver (which will still yield multiple IPPs, as the receiver works with different satellites). For the particular case of the Villafranca, Spain station (identified as Vill), we obtain the plot from figure 4.3(b). At this time of the day around 11:00h the Sun would have a greater effect on the IPPs of this station, so the spike can be seen more clearly.

As mentioned before, the flare took place at 11.05, so we could proceed using the studied data range and this epoch in particular.

4.3 Solar-zenith angle

The solar-zenith angle (denoted χ from now onward) plays a major role when studying this event: it is the angle formed by the Sun and the Earth's zenith and indicates the effect the flare is having on a particular IPP. It is expected that this variable presents a correlation with the increase in VTEC, which is what we aim to observe in this chapter.

Figure 4.5, at the end of the chapter, provides a visual representation of this variable that along with the results depicts how it can affect the VTEC value.

Obtaining the angle between two celestial objects has been shown in the previous section by means of equations 4.3, 4.4 and 4.5, when calculating the angle between the Sun and a detected GRB.

$$unitVectorObjectA = \begin{bmatrix} \cos \delta_g * \cos \alpha_g \\ \cos \delta_g * \sin \alpha_g \\ \sin \delta_g \end{bmatrix} \quad (4.3)$$

$$unitVectorObjectB = \begin{bmatrix} \cos \delta_s * \cos \alpha_s \\ \cos \delta_s * \sin \alpha_s \\ \sin \delta_s \end{bmatrix} \quad (4.4)$$

$$\cos \beta = unitVectorObjectA \cdot unitVectorObjectB \quad (4.5)$$

For this case, though, the angle is computed using the IPP's Right Ascension and Latitude (equivalent to declination), yielding the cosine of χ , the **solar-zenith angle**. The previous dot product can be simplified to:

$$\cos \chi = \sin \delta_{IPP} * \sin \delta_{Sun} + \cos \delta_{IPP} * \cos \delta_{Sun} * \cos(\alpha_{IPP} - \alpha_{Sun}) \quad (4.6)$$

The following Fortran code is the function that implements equation 4.6 and returns $\cos \chi$:

```

1  real function computeSolarZenithAngle (raIPP, decIPP, raSun, decSun)
2      implicit none
3
4      real, intent(in) :: raIPP, decIPP, raSun, decSun
5      real :: solarZenithAngle
6
7      solarZenithAngle = sin(decIPP)*sin(decSun) + cos(decIPP)*cos(
8          decSun)*cos(raIPP - raSun)
9      return
10     end function computeSolarZenithAngle

```

Listing 4.4: Computation of the solar-zenith angle's cosine

4.4 Results

Taking 212.338° and -13.060° as the Sun's right ascension and declination, respectively, and the measurements of all IPPs at 11.05 hours, figure 4.4 shows the plot of the output of our program.

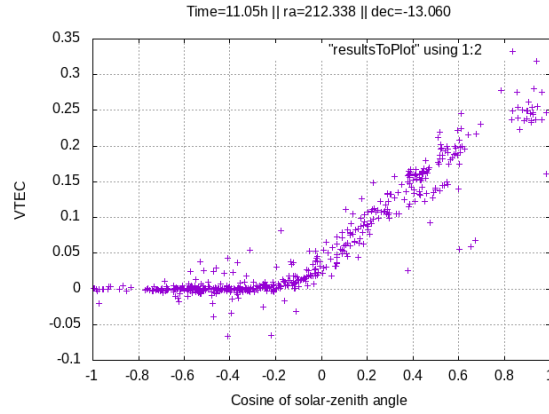


Figure 4.4: VTEC value as a function of the solar-zenith angle cosine

As we can observe, the resulting plot, similar to the one from figure 4.2, shows a strong correlation between the cosine of the solar-zenith angle and the VTEC content, which increases from $\cos \chi = 0$ (90°) to $\cos \chi = 1$ (0°) and it doesn't seem to affect it from $\cos \chi = -1$ (180°) to $\cos \chi = 1$ (0°).

Visually, this can be seen as follows:

TODO: SOLO FALTA ESTO, DIBUJO Y EXPLICACION DE PORQUE SUCEDE ESTO

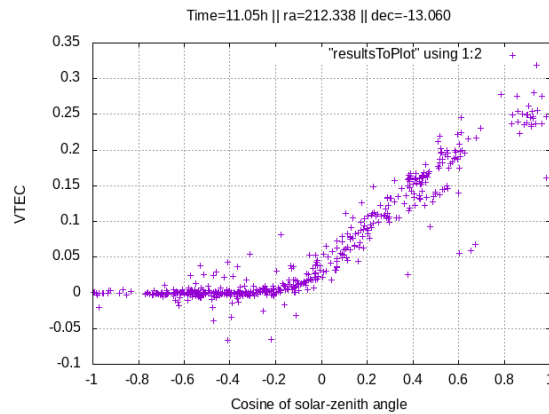


Figure 4.5: Visual representation of the solar-zenith angle

When the Sun is vertically on the.....TODO

In conclusion, we can see that there appears to be correlation between the two variables. This correlation will be studied in more detail in the following section, where a first approach of the algorithm will be presented to detect the flare without knowing the location of its source.

Chapter 5

Brute Force Approach

In the previous chapter the correlation between the solar-zenith angle's cosine and the estimated VTEC value was seen. In this section we aim to provide a first, brute force approach, for an algorithm able to estimate the Sun's location based on this study. This first approach is done as a first approximation to be problem to see more clearly how the algorithm will work, regardless of the performance.

5.1 Key elements

5.1.1 Correlation

explain, formulas, references, etc

explain R and compare to show the computation is correct

5.1.2 Moment of the flare

The first part of the algorithm was, without going into the actual computations regarding the position of the IPPs, the possible Sun locations, etc, finding out when to perform the study, that is, detecting a spike in the VTEC content in general, for any IPP. In the previous chapter we knew the specific moment of the flare (11.05h), but the algorithm has to determine which moment is going to be studied.

A first approach to detecting this we first wanted to detect a spike in the VTEC content throughout the day in a simple way. For each epoch ¹ we computed the mean VTEC of all IPPs and inserted it into a priority queue. We did this because we wanted to see thbut a simple single-pass max-value finder would work

explicar buscar pico por hill climbing o algo asi usando la grafica de la distribucion. Al encontrar un momento exacto en el que centrarnos empezar a estudiar

¹In our data set the epochs ranged from 10.5 to 11.5, that it is, 10:30AM to 11:30AM with a sampling rate of 1/120 hours or 30 seconds

ahi

5.1.3 Linking C++ and Fortran

explicar aqui que la logica se hace con c++ y la computacion numerica con Fortran

```

1 import numpy as np
2
3 def incmatrix(genl1, genl2):
4     m = len(genl1)
5     n = len(genl2)
6     M = None #to become the incidence matrix
7     VT = np.zeros((n*m,1), int) #dummy variable
8
9     #compute the bitwise xor matrix
10    M1 = bitxormatrix(genl1)
11    M2 = np.triu(bitxormatrix(genl2),1)
12
13    for i in range(m-1):
14        for j in range(i+1, m):
15            [r,c] = np.where(M2 == M1[i,j])
16            for k in range(len(r)):
17                VT[(i)*n + r[k]] = 1;
18                VT[(i)*n + c[k]] = 1;
19                VT[(j)*n + r[k]] = 1;
20                VT[(j)*n + c[k]] = 1;
21
22    if M is None:
23        M = np.copy(VT)
24    else:
25        M = np.concatenate((M, VT), 1)
26
27    VT = np.zeros((n*m,1), int)
28
29    return M

```

Listing 5.1: Python example

5.2 Brute force approach

explicar que es para entender que debemos hacer

5.2.1 Pseudocode

primero pseudocodigo, explicar for each dec for each ra

Algorithm 1 My algorithm

```

1: procedure BRUTEFORCEALGORITHM
2:    $stringlen \leftarrow \text{length of } string$ 
3:    $i \leftarrow patlen$ 
4: top:
5:   if  $i > stringlen$  then return false
6:    $j \leftarrow patlen$ 
7: loop:
8:   if  $string(i) = path(j)$  then
9:      $j \leftarrow j - 1$ .
10:     $i \leftarrow i - 1$ .
11:    goto loop.
12:   close;
13:    $i \leftarrow i + \max(\delta_1(string(i)), \delta_2(j))$ .
14:   goto top.

```

entonces explicar aqui lo de los polos, in a first approach to this in which to visually see ourselves the differences between possible Sun positions we obtained a plot for each possibility (figure 5.1), we could see this happening:

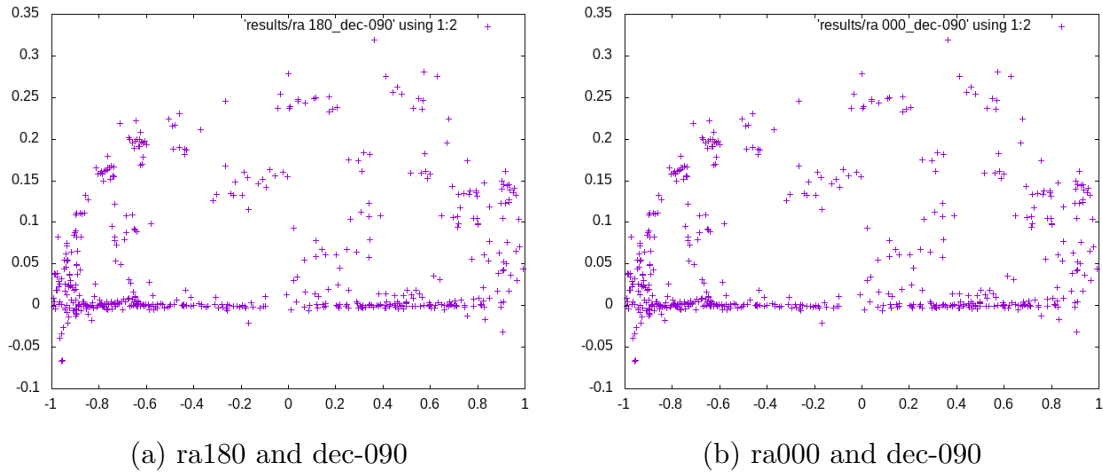


Figure 5.1: dasdasdasda

The two images are equivalent using the diff

5.2.2 Results

Comparison of precision and time here

```
1 [C++: Finding a spike in the VTEC distribution]
2 [AWK: Filtering all data by best epoch: 11.05]
3 [C++ -> Fortran: Finding the Person coefficients for possible Suns |
   Epoch = 11.050000]
4 [C++ -> R: Computing correlation coefficient for each possible Sun with
   R]
5 [R: RESULTS]
6 Largest correlation coefficient: 0.9073422
7 Estimated Sun's location: ra210_dec-010
```

Listing 5.2: Brute force approach algorithm output

As we can see this approach provides the expected results, but has a large computational complexity that increases with the precision we want to obtain in our results. In the next chapter, an algorithm is presented to perform this computations with several optimizations to reduce its complexity.

Chapter 6

Sun flare detection algorithm

6.1 Correlation computation

Same vtec

6.2 Decrease range of the search

testing [9] [14] [6]

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