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BACHELOR'S THESIS

TITLE: Analysis of scintillation measurement errors in GNSS signals

DEGREE: Bachelor's Degree in Aerospace Engineering

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DATE: February 20, 2019

Title: Analysis of scintillation measurement errors in GNSS signals

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Abstract

The goal of this project is to demonstrate the presence of errors in the measures of scintillation indices on the GPS L1 C/A signal due to the presence of multipath reflection at the receiver, and to propose a method to reduce such errors.

Scintillation is a disturbance induced by the ionosphere, the farther layer of the atmosphere in which free ions (electrons) are present. These electrons vary in quantity according to many factors related to Solar activity and affect instantaneously and simultaneously both in amplitude and in phase the radio navigation signal. Therefore, the impact of scintillation is typically assessed by means of amplitude and a phase scintillation index. However, multipath reflections induce a signal amplitude variation very similar to what scintillations do, leading to potentially wrong scintillation indices estimations.
In the thesis, a technique for clearing out the amplitude scintillation index from the multipath effect is presented and analyzed.

For the demonstration, data collected during the first ten days of the month of September of 2017, at Polar latitudes during a solar storm, were used. The data were collected at one Hertz (1 Hz) interval for periods of fifty (50) minutes; and include the amplitude scintillation index and the phase scintillation index of GPS L1 C/A signal.

With these data, the behavior of the signal has been analyzed during the twenty-four hours of the day, and together with another detector of scintillation, the data have been compared during the days and the most conclusive hours of the week.

The results obtained have been divided by time slots and blocks of signal behavior, differentiated into three different blocks depending on the amount of scintillation present.

The data processing confirmed that in selected cases multipath induces a considerable growth of the value of the amplitude scintillation index, and that there is a correlation in this trend between consecutive days. It has been shown that by properly aligning measurements time series, it is possible to remove the contribution of multipath and thus to underline the sole contribution of true scintillation. Furthermore, the necessity of a big data programming approach to analyze all the data acquired has been faced.

Títol: Detecció d’errors de posicionament amb GPS L1CA degut a scintillation

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Data: 20 de Febrer de 2019

Resum

L'objectiu d'aquest projecte és demostrar la presència d'errors en les mesures d'índexs de scintilaltion en el senyal GPS L1 C / A a causa de la presència de reflexió multipath al receptor i proposar un mètode per reduir aquests errors.

La scintilaltion és una perturbació induïda per la ionosfera, la capa més llarga de l'atmosfera en la qual estan presents els ions lliures (electrons). Aquests electrons varien en quantitat segons molts factors relacionats amb l'activitat solar i afecten instantàniament i simultàniament tant en amplitud com en fase de senyal de radiocomunicació. Per tant, l'impacte del scintilaltion sol avaluar-se mitjançant amplitud i un índex de scintilaltion de fase. No obstant això, els reflectors de múltiples vies indueixen una variació d'amplitud de senyal molt similar a la que fan els scintilaltions, donant lloc a estimacions d'índexs de scintilaltion potencialment incorrectes.
En la tesi es presenta i analitza una tècnica per eliminar l'índex de scintilaltion d'amplitud de l'efecte multipath.

Per a la demostració, es van utilitzar les dades recollides durant els primers deu dies del mes de setembre de 2017, a latituds polars durant una tempesta solar. Les dades es van recollir a un interval d'Hertz (1 Hz) per a períodes de cinquanta (50) minuts; i inclou l'índex de scintilaltion d'amplitud i l'índex de scintilaltion de fase del senyal GPS L1 C / A.

Amb aquestes dades, el comportament del senyal s'ha analitzat durant les vint-i-quatre hores del dia i, juntament amb un altre detector de scintilaltion, s'han comparat les dades durant els dies i les hores més concloents de la setmana.

Els resultats obtinguts han estat dividits per block de temps i blocs de comportament del senyal, diferenciats en tres blocs diferents segons la quantitat de scintilaltion present.

El processament de dades va confirmar que en els casos seleccionats multipath indueix un creixement considerable del valor de l'índex d'escintilació d'amplitud i que hi ha una correlació en aquesta tendència entre dies consecutius. S'ha demostrat que al alinear correctament les sèries temporals de mesuraments, és possible eliminar la contribució de la ruta múltiple i, per tant, subratllar l'única contribució del scintilaltion real. A més, s'ha enfrontat la necessitat d'un gran enfocament de programació de dades per analitzar totes les dades adquirides.

Título: Detección de errores de posicionamiento con GPS L1 CA debido a scintillation

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Fecha: 20 de Febrero de 2019

Resumen

El objetivo de este proyecto es demostrar la presencia de errores en las medidas de los índices de scintilaltion en la señal del GPS L1 C / A debido a la presencia de reflexión multipath en el receptor, y proponer un método para reducir dichos errores.

El scintilaltion es una perturbación inducida por la ionosfera, la capa más alejada de la atmósfera en la que están presentes los iones libres (electrones). Estos electrones varían en cantidad de acuerdo con muchos factores relacionados con la actividad solar y afectan instantáneamente y simultáneamente tanto en amplitud como en fase la señal de radionavegación. Por lo tanto, el impacto del scintilaltion suele evaluarse por medio de la amplitud y un índice de scintilaltion de fase. Sin embargo, las reflexiones por trayectos múltiples inducen una variación de la amplitud de la señal muy similar a la de los scintilaltions, lo que lleva a estimaciones de índices de scintilaltion potencialmente erróneas.
En la tesis, se presenta y analiza una técnica para eliminar el índice de scintilaltion de amplitud del efecto multipath.

Para la demostración, se utilizaron los datos recopilados durante los primeros diez días del mes de septiembre de 2017, en las latitudes polares durante una tormenta solar. Los datos se recolectaron en un intervalo de Hertz (1 Hz) por períodos de cincuenta (50) minutos; e incluye el índice de scintilaltion de amplitud y el índice de scintilaltion de fase de la señal GPS L1 C / A.

Con estos datos, el comportamiento de la señal ha sido analizado durante las veinticuatro horas del día, y junto con otro detector de scintilaltion, los datos se han comparado durante los días y las horas más concluyentes de la semana.

Los resultados obtenidos se dividieron por intervalos de tiempo y bloques de comportamiento de señal, diferenciados en tres bloques diferentes según la cantidad de scintilaltion presente.

El procesamiento de datos confirmó que, en casos seleccionados, las rutas múltiples inducen un crecimiento considerable del valor del índice de scintilaltion de amplitud, y que existe una correlación en esta tendencia entre días consecutivos. Se ha demostrado que al alinear correctamente las series de tiempo de las mediciones, es posible eliminar la contribución de las rutas múltiples y, por lo tanto, subrayar la contribución única del scintilaltion verdadero. Además, se ha enfrentado la necesidad de un enfoque de programación de big data para analizar todos los datos adquiridos.

Titolo: Analisi di errori nella misura degli indici di scintillazione di segnali GNSS

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Data: 20 febbraio 2019

Sommario

L'obiettivo di questo lavoro è di dimostrare la presenza di errori nelle misure degli indici di scintillazione sul segnale GPS L1 C / A a causa della presenza della riflessione multipath sul ricevitore e di proporre un metodo per ridurre tali errori.

La scintillazione è un disturbo indotto dalla ionosfera, lo strato più lontano dell'atmosfera in cui sono presenti ioni liberi (elettroni). Questi elettroni variano in quantità in base a molti fattori legati all'attività solare e influenzano istantaneamente e contemporaneamente sia in ampiezza che in fase il segnale di navigazione radio. Pertanto, l'impatto della scintillazione viene tipicamente valutato mediante un indice di scintillazione di ampiezza e un inidce di scintillazione di fase. Tuttavia, le riflessioni di multipath inducono una variazione di ampiezza del segnale molto simile a quella delle scintillazioni, portando a stime di indici di scintillazione potenzialmente sbagliati.
Nella tesi, viene presentata e analizzata una tecnica per eliminare il contributo del multipath dall’indice di scintillazione di ampiezza.

Per la dimostrazione sono stati utilizzati i dati raccolti durante i primi dieci giorni del mese di settembre del 2017, alle latitudini polari durante una tempesta solare. I dati sono stati raccolti ad un intervallo di Hertz (1 Hz) per periodi di cinquanta (50) minuti; e includono l'indice di scintillazione di ampiezza e l'indice di scintillazione di fase del segnale GPS L1 C / A.

Con questi dati, il comportamento del segnale è stato analizzato durante le ventiquattro ore del giorno e, insieme ad un altro rivelatore di scintillazione, i dati sono stati confrontati durante i giorni e le ore con piú attività della settimana.

I risultati ottenuti sono stati divisi per intervalli di tempo e blocchi di comportamento del segnale, differenziati in tre blocchi diversi a seconda della quantità di scintillazione presente.

L'elaborazione dei dati ha confermato che in casi selezionati il multipath induce una crescita considerevole del valore dell'indice di scintillazione dell'ampiezza e che esiste una correlazione in questa tendenza tra giorni consecutivi. È stato dimostrato che, allineando correttamente le serie temporali delle misurazioni, è possibile rimuovere il contributo del multipath e quindi sottolineare l'unico contributo della vera scintillazione. Inoltre, è stata affrontata la necessità di un approccio di programmazione di tipo *Big Data* per analizzare tutti i dati acquisiti.

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Grazie Nicola, per la tua pazienza e i tuoi idee per fare di questa tesi un progetto completo, grazie anche per tenere la porta dell tuo ufficio sempre aperta per risolvere i miei dubbi e errore.

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Y como no, Kika, por todas las risas y los momentos que no olvidaré desde que nos conocimos. Ha pasado tiempo ya, pero parece que fue hace un par de días pero con mil recuerdos y de veras se agradece poder contar con vosotras.

Tzakzo, no sé en qué idioma podría escribir estos agradecimientos, pero sé que no cabrían en esta página y probablemente tampoco en un audio. Pero bueno, no sé, simplemente, gracias.

Gràcies a BEST Barcelona per fer veure que només depèn de nosaltres convertir-nos en allò que volem ser. SpACemen sempre us portaré amb mi i sempre recordaré els àudios de 20 minuts nomes jo rient-me, les altres tantes *risas* i sobretot a nosaltres.

Gracias, Merci, Ви благодарам,Grazie to all of you C·O·M·A·L·A, I can’t think of a better group of people to share this experience with. I will never forget this. The pigeon, the *shut ups* or the “Fellas I’m late” as a lot of other stuff you all know. And I promise I will come back and we will meet soon.

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Y por último, y más importante, Hèctor, papá y mamá, ya sabéis que sin vosotros estos comentarios son absurdos y que gracias por siempre, siempre estar ahí. Gracias.

“La educación es lo que sobrevive,
Cuando todo lo aprendido se olvida”

“We keep feeding forward the advanced of the human spirit,
Because we stand on the soulders of giants
To go farther than we have ever been.”

“If you need inspirational words,
Don’t do it”

CONTENTS

LIST OF FIGURES

ACRONYMS AND ABBREVIATIONS

C/A	Coarse Acquisition
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
PRN	Pseudo-Random Noise
SANAE	South African National Antarctic Expedition
SANAP	South African National Antarctic Program

NOMENCLATURE

C/N_0	Signal to Noise power density ratio
Phi60	Phi 60 index (phase scintillation)
S4	S4 index (amplitude scintillation)
TEC	Total Electron Content
ROT	Rate of TEC

INTRODUCTION

Worldwide, the Global Navigation Satellite System (GNSS) is currently providing information of positioning and location to any part of the globe and in the past decades, the receivers have been moving from a rather passive data collection to a more active filter improvement-based one. Placing the spotlight on the question “what causes the errors in positioning?” has unearthed new sources of bias, and with the new urge of quick centimeter-accurate positioning even at user level, the smallest details are being examined. This has, in turn, highlighted the need for further optimization of the receiving phase. Several variables can affect the final output of the receiving phase: clock offset, artificial interferences, natural interferences, signal loss, etc.; and the natural interference **scintillation** is one of the most challenging and discussed topic in the field currently, because of its rapid phase changes in a simultaneous and random manner and the introduction of amplitude errors that become a bias of meters in the final output of the receiver. Scintillation is a form of space-based multipath, measured by means of an amplitude index (S4) and of a phase index (Phi60). The phase index depends on the irregularities of the ionosphere and the amplitude index can fade or be increased during the downward towards the ground station due to the constructive and destructive phase changes.

The synchronization in GNSS receivers is typically carried out following a two-steps approach: acquisition and tracking. The first stage gives a coarse estimation of the parameters, and the second one refines the estimation, filtering out noise and tracking any possible time-variation. During the tracking stage, an optimized-based filtering is applied in some parameters of the scintillated data; those parameters are usually introduced by Kalman filters, which it has been demonstrated that successfully provides an accurate and precise positioning output.

However, this approach has already been studied by Vilà, Salcedo and Granados [1] when studying GNSS carrier phase tracking. On the other hand, our study will not aim the positioning question and it will remain with the objective of detecting scintillation in strong multipath scenarios. *Multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths at a ground level due to the environment surrounding the antenna.* This presence of multipath induces an increase of the amplitude scintillation index even though scintillation may not be present.

Our approach will be from the data collected, analyze the signal amplitude. We analyze the data with a simple technique, detailed in *Section 2.1,* and we will be able to detect, in the amplitude timeseries, the effect of multipath due to the environment in the signal amplitude values and discrete the values of S4 due to effect of multipath, remaining with the values of the index S4 due to the effect of scintillation.

By the time of this thesis’ writing, no other work had specifically assessed the discretization of multipath against scintillation on the post-processing stage, due to the fact that this solution implies Big Data Analysis. This is why in this project a simplified model has been applied to observe the amplitude variation between a multipath induced error and a scintillation induced error.

The first chapter introduces the basic definitions and the values and conditions behind: the data acquired from the ground station, the environmental conditions and the acquiring period time.

The second chapter explains and justifies the code created and how data was retrieved and processed in order to get the results outlined in the third chapter. These results, in form of plots and data tables are discussed in the end of the third chapter, and are the source of the conclusions of the project, in which the results are compared with the data a high-accuracy scintillation receiver provides.

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CHAPTER 1. Background

The aim of this chapter is to introduce the basic concepts, definitions and numbers behind the object of this study as the data of the ground station and the acquisition period time.

1.1. Ionospheric scintillation.

The ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere [1]. The ionosphere is the ionized layer of Earth's upper atmosphere, from about 50 km to 1,000 km altitude, a region that includes the thermosphere and parts of the mesosphere and exosphere. The ionosphere’s gases are ionized by solar radiation and in this layer, electrons and ions move freely, the quantity of electrons depends on the solar radiation and the propagation speed of a radio signal depends upon the number of free electrons along the path; an example of atmospheric scintillation is shown in **¡Error! No se encuentra el origen de la referencia.**1.
The quantity of electrons, calculated for a hypothetic tube of 1m^2 cross-section between the satellite and the receiver, at the ionosphere is commonly known by the TEC number (Total Electron Content).

Ionization is caused by the sun’s radiation. TEC depends on sunlight and is greatest in the middle of the day and lowest at the night. Furthermore, the ionospheric scintillation has more presence in some parts around the globe than on others, for instance, the Polar zones are more affected by phase-changing scintillation and the Equatorial region is affected averagely by amplitude and phase-changing scintillation. The scintillation index S4 measured the variation in amplitude given by the scintillation effect, in a sixty (60) seconds interval and follows the formula below:

$S_4^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$ where I is the signal intensity at the correlators output.

A fading in the signal due to scintillation can be monitored by means of two indices:

- The S4 index which gives the information of the variation of the amplitude of the signal induced by scintillation for each sample of time.
- The Phi60 index that gives information of the variation of the phase of the signal induced by scintillations.

An example of S4 timeseries in the presence of scintillation is the shown in Figure 2.

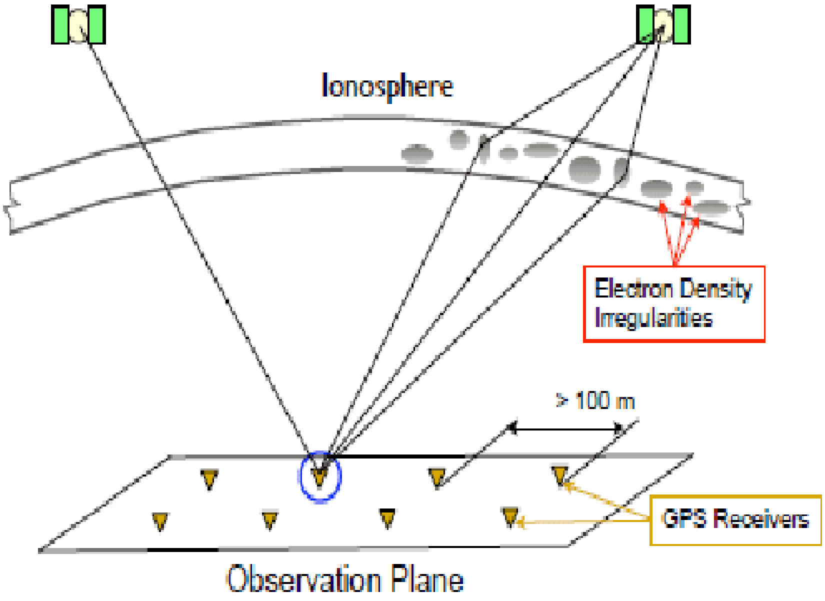

Figure 1 Example of atmospheric scintilaltion

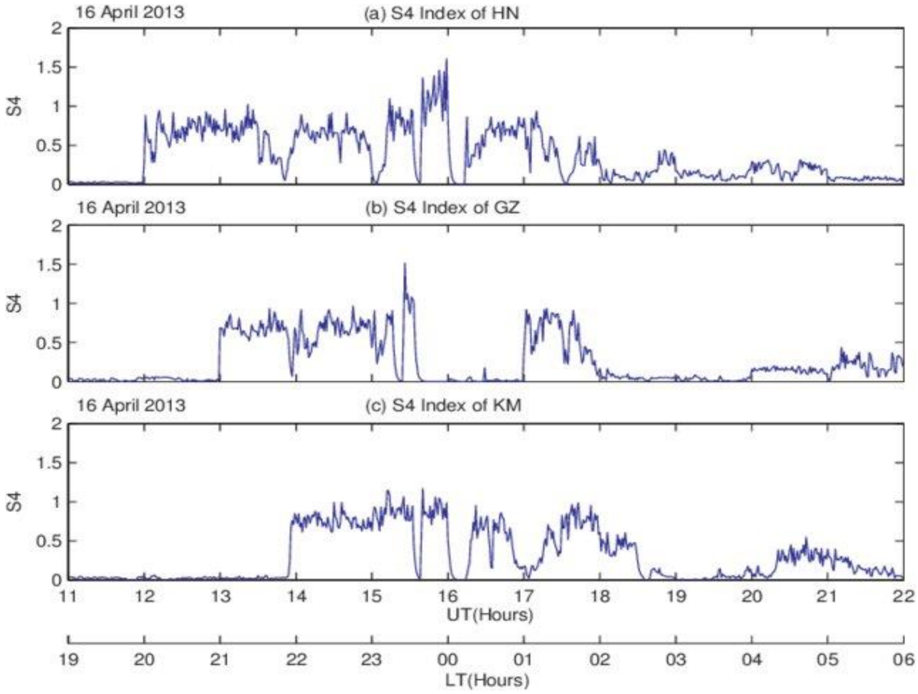

Figure 2 Example of S4 index in the presence of scintillation

1.1.2. Multipath

In wireless telecommunications, multipath is the propagation phenomenon that results in radio signals reaching the receiving antenna by two or more paths. Causes of multipath are mainly due to the environment surrounding the receiver, as reflection from water bodies and terrestrial objects such as mountains and buildings. Shown in Figure 3

Multipath causes interference on the signal, including constructive and destructive interference, and phase shifting of the signal. Destructive interference causes fading, where the magnitudes of the signals arriving by the various paths have a distribution known as the Rayleigh distribution.

The main characteristic of multipath is, because the changes on the environment that surrounds the receiver are negligible by the study period time, the effect on the signal becomes cyclic each sidereal day. That makes the multipath effect very distinguishable at sight, as we can observe on **¡Error! No se encuentra el origen de la referencia.**

Our main problem with multipath is that the error produced by it interferes in the process of estimating the amplitude scintillation index due to the fact that the estimation of S4 is biased by the presence of multipath.
Due to the fact that the values of the scintillation index induced by the ionosphere are lower than the values induced by multipath or thermal noise, without a wide dataset is impossible to detect scintillation.

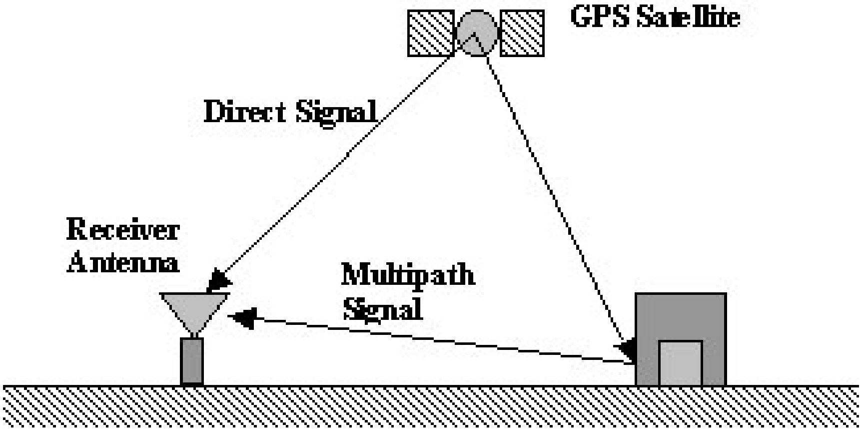

Figure 3: Multipath sketch

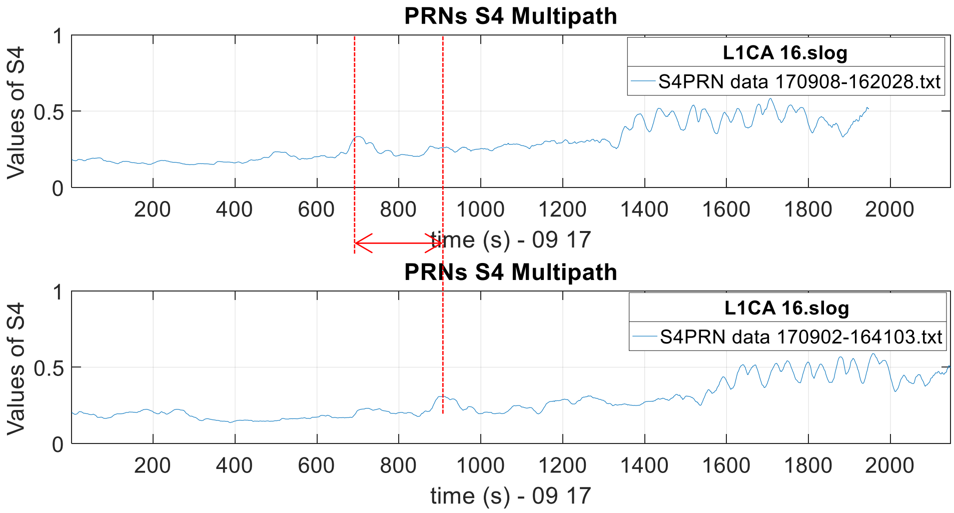

Figure 4 Multipath effect between two siderial days showing the same patern after 4 minutes (240 s.)

1.2. Radiation storm September 2017

During the month of September of the year 2017, the space weather was changing; a solar radiation storm was forecasted, for the 4th and the 10th.

This storm affected directly the ionosphere electron content thus the ionospheric scintillation would be in its highest peaks during that period.

This interval was one of the most flare-productive periods of now-waning solar cycle 24. Solar active regions (AR) 2673 and 2674 both matured to complex magnetic configurations as they transited the disk. AR2673 transformed from a simple sunspot on 2 September to a complex region with order-of-magnitude growth on 4 September, rapidly reaching beta-gamma-delta configuration. [2]
(BIBLIO: https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1542-7390.SW-SEPT2017)

1.3. Antarctica Ground Station: SANAE IV

SANAE IV is the South African Antarctic research base located in Vesleskarvet, Queen Maud Land. The base is part of the South African National Antarctic Program (SANAP) and is operated by the South African National Antarctic Expedition.
Latitude and longitude:71º 40’ 22’’ S; 2º 50’ 26’’ W

Since 2015, in the frame of the DemoGRAPE project, the NavSAS group of Politecnico di Torino is managing a GNSS installation at SANAE IV station and continuously collecting GNSS data, by means of a Septentrio professional receiver and of a customized experimental software-defined data acquisition system and GNSS receiver.
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Figure 5: SANAE IV Ground Station

1.4. Data and variables

Time block:

The data in which we focus is the one corresponding to the solar storm, from 1st September to September 10th.

Each day is considered to have 24 hours of data. The theoretical 24 hours become less due to the fact that the receiver needs a gap of 10 minutes to post-process the data. Thus the block of data for the 24 hours will be of 50 minutes each hour, leaving a gap of 10 minutes to post-processing.

Then, for each day, and for each block of 50 minutes, we consider all the GPS L1 C/A signals of satellites in view

Finally, for each day, for each block of 50 minutes, for each satellite in view, we consider the S4 index, sampled at 1 Hz..

The time blocks taken during the acquisition comprehend from the hour 00:00 of the first day to approximately the hour 23:50 of the tenth day, during fifty (50) minutes each block. The data used in this study have been collected through the experimental receiver: as about ten (10) minutes of post-processing are required to process the data acquired, in order to have a new acquisition starting every each hour, chunks of data of length fifty minutes are considered.

The S4 index, at a sampling rate of 1 sample per second, is considered over these intervals

The Time block diagram is shown in Diagram 1.4.1.

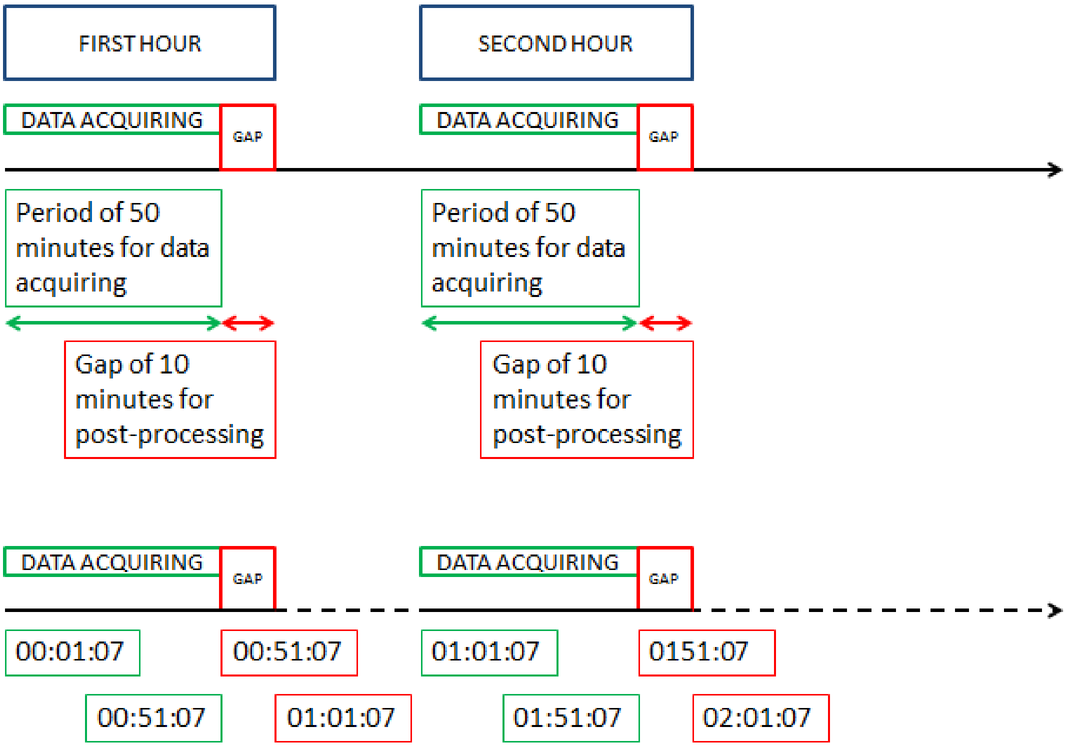
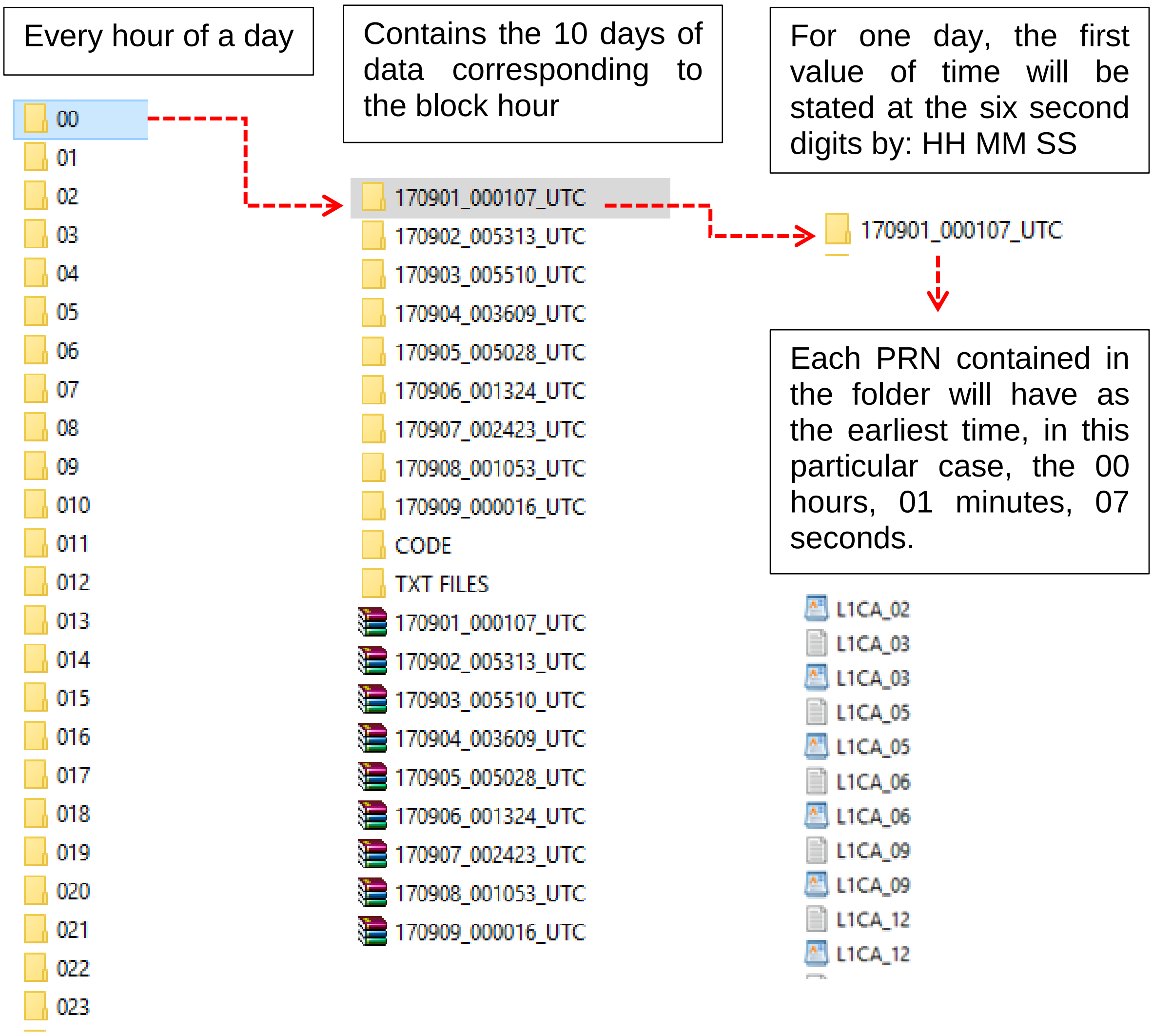


Diagram 1.4 1 Time Block diagram of the receiver

As an example, for day 2017/09/01 we will have a folder in which the first six digits correspond to the date “170901”, and the other six digits correspond to the initial time of acquisition, in this case “000107” corresponds to hour 00, minute 01, second 07; this folder will have data from 00:01:07 to 00:51:07. As explained in the Diagram 1.4.2.



Every hour of a day

Contains the 10 days of data corresponding to the block hour

For one day, the first value of time will be stated at the six second digits by: HH MM SS

Each PRN contained in the folder will have as the earliest time, in this particular case, the 00 hours, 01 minutes, 07 seconds.

Diagram 1.4. 2 Structure of data

L1CA_XX

The L1CA archive has the information in the name of the PRN (Pseudo Random Noise) of GPS satellites. For example: L1CA_02 will correspond to the satellite 2 out of 32 of GPS and consequently the PRN number 2.

The information gathered for one PRN is split in one archive, with .slog ending.

- L1CA.slog: The L1CA.log archive is a SLOG file composed by four columns. Each one of them gives different information:
    - Time: The acquisition time in seconds (50 minutes fractions related to a sidereal of a day)
    - C/N_0: Signal to Noise ratio between of the signal.
    - S4: amplitude scintillation value.
    - Phi60: Phase scintillation value.

1.4.1. Variables chosen

As we have commented before, a fading in the signal due to scintillation can be monitored by means of two indices and the scintillation effect causes a simultaneous phase-changing on the signal, and thus these two values give the main information of the data we will analyze.

The information gathered for one PRN is split in two archives, one with the .log ending, and the other with .slog ending.
Focusing on the creation of a code able to analyze the data, we have chosen the variables of the .slog file, because in order to acquire visual plots of scintillation, the S4 index giving us the amplitude of the signal is key to understand the behavior of the signal; the acquisition time, in order to plot the data with an equal reference for each PRN. And finally the Phi60 index we will use it in the end of our thesis to double check the results obtained.

The size of the dataset is composed by zip files separated by days (from 1 to 10), each with 24 folders corresponding to the hours of each day, and each time folder with a mean of 12 .slog files of PRN data, due to the mean amount of satellites in view during an hour. The data of index was taken each second during 50 minutes, about 3000 values each variable of the file.

In addition to the results of the fast post-processing, we have the plots of CN_0, Phi60 and S4 of the PRNs contained in the block hour for each day, each block hour, which we will use as an orientation to lead our code to a meaningful conclusion and to focus on a certain day and time.

CHAPTER 2. Development

2.1. Technique

This section will explain the technique used to conduct the objective experiment: the final result expected is detecting the presence of scintillation in the scintillation index S4 time series and conclude the effect of multipath to the creation of false values of S4 inducing an erroneous reading. Shown in Figure 6

The technique we apply bases on the mathematical method of reduction, having two functions in which a simple rule is applied in order to have a simpler function as an output.

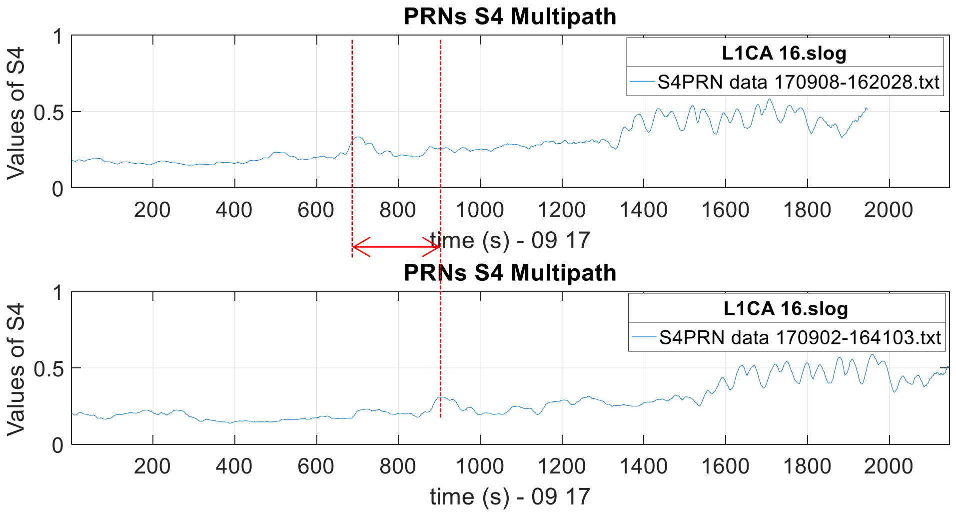


Figure 6: PRN 16 for day 8 and day 2 for the block hour 16.

In our case the two complex functions will be the values of S4 of the same PRN in two different days affected by scintillation and multipath and we will apply the rule of subtraction between them in order to isolate the contribution of scintillation. We will be able to do the subtraction because the values of S4 affected by multipath follow easy-spotting pattern cyclically repeated at the same block hour in subsequent days as we have seen above.

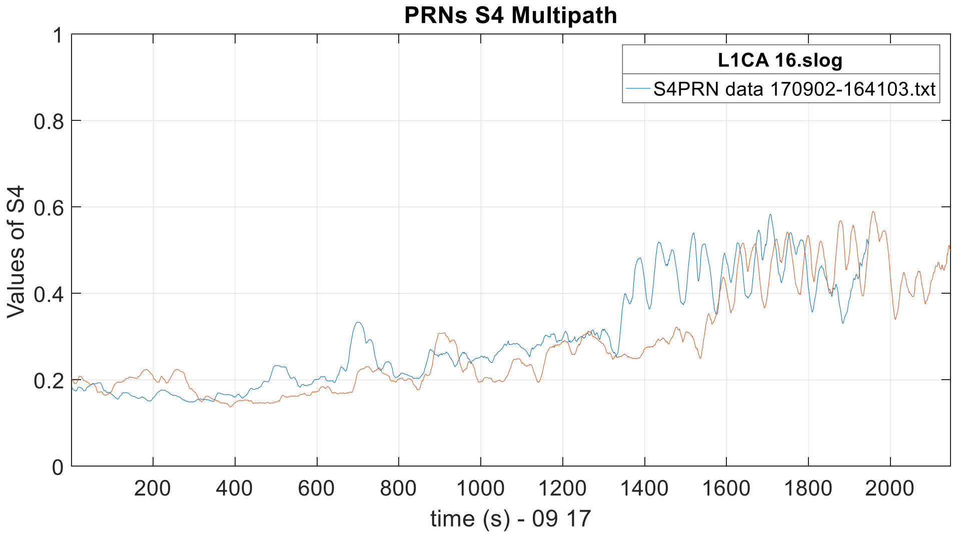


Figure 7: PRN 16 for day 8 and day 2 for block hour 16 one above the other.

Obviously, in our case it will be an extra step due to the fact that the two signals will not be aligned as shown in Figure 7; if they are not aligned we cannot apply the subtraction method, so in order to align them we can exploit a correlation procedure between the signals.

Computing a correlation between signals usually results in a curve with values close to zero and a differentiate peak value; the x-component of the peak offers the delay between the two signals. δt.

$$\delta t \simeq 4\, minutes \cdot \#\ \text{days of difference}$$

With this value, we complete the shorter signal with Not a Number (NaN) values so the two signals have the same length. The two signals will be aligned in time and already having taken into consideration the differences of days δt and the difference between the acquisition times of the two days. Shown in Figure 8

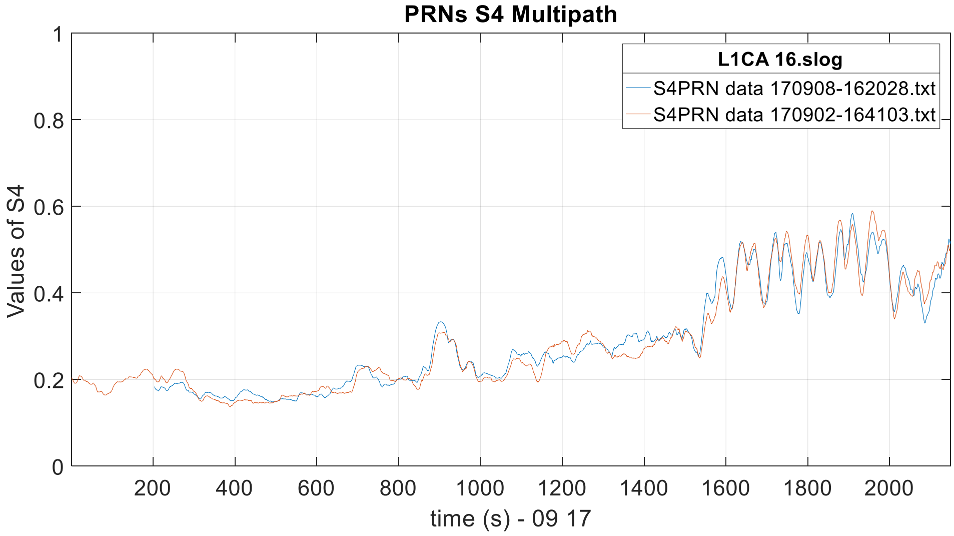


Figure 8: PRN 16 for day 8 and day 8 for block hour 16 aligned

Now, the two signals we have created with NaNs have the same length and we can apply the subtraction method. The subtraction of PRNs will give us the values of S4 in the time series only affected by scintillation; the values of these plots will be named *Lambda* (λ). As it shows Figure 9.

$$\lambda(t) = S4_i(t) - S4_j(t - \delta t)$$

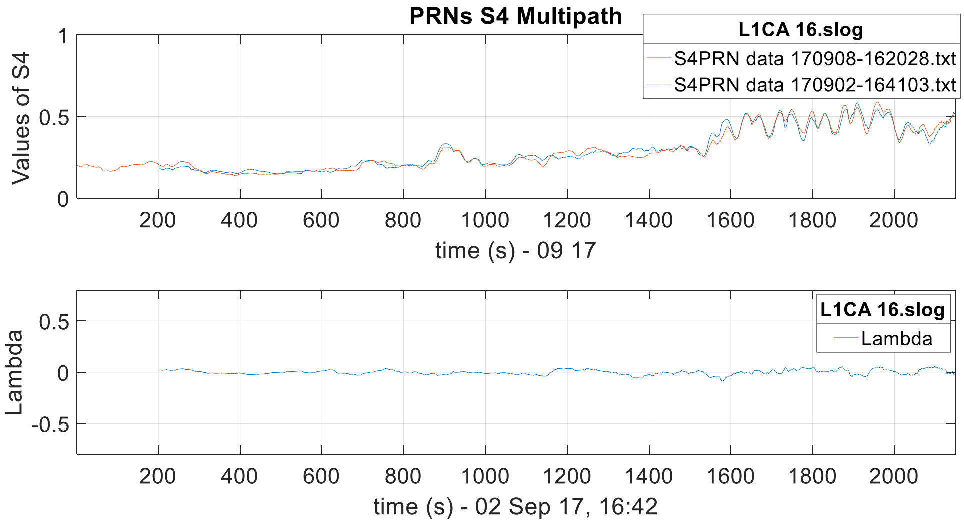
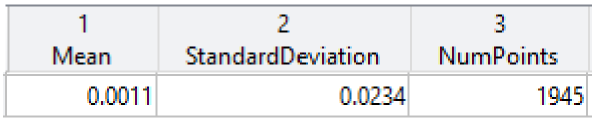


Figure 9: Lambda of the PRN 16 for day 8 and day 2

Of this new data, we will compute the mean, in order to prove that multipath is cancelled out from S4, the standard deviation, in order to tune a new scintillation threshold with the data left of the subtraction, and the number of points of the signal, which will show numerically the amount of data we have of the scintillation.

With these three variables we can explain how the signal behaves. With the mean we observe the tendency of the signal. The standard deviation tells us how much the points of the signal move from the mean, telling us the quantity and the size of the peaks of Lambda. These peaks are the main reason of this project, because the peaks are the scintillation effect on the S4 index. Finally the number of points tells us if we can trust the values before, if we have more points it means that the two signals we have subtracted had been a lot of time overlapped. The Table 1 below shows the data of the Lambda plot of Figure 9.



1 Mean	2 StandardDeviation	3 NumPoints
0.0011	0.0234	1945

Table 1: Data of plot above.

2.2. Code

This section will explain the code created to conduct the objective experiment: applying the technique stated at the section 2.1.

2.2.1. First steps

The code created for this study aims the detection of the scintillation effect in the amplitude index of the data. Despite this main objective, for the first steps of coding the decision was to gather all the data of the .slog files so we could compare the data we were plotting with the code, with the data that we had, to check the values of S4 and to confirm the functionality of the code.
In order to do so we created two principal functions:

- Give Me log Data: This function has an input of a PRN (L1CA_XX) and as output gives the variables in vectors:

- Give Me Slog Data: This function has an input of a PRN (L1CA_XX) and as output gives the variables in vectors:

Once we had the data in Matlab variable, we also created a function (PlotMeS4) to plot each variable, S4, CN_0 and Phi60.

These functions were governed by one main program which its function was basic; calling the other functions and to be sure that the basic requirements were fulfilled.

The basic requirements were:

- S4 index needs to be above 0.4 to be considered a scintillation event.
- Phi60 index needs to be above 60 to be considered a scintillation event.

The Main_Mark3:

- Read the folder
- Call the functions with the requirements
- Plot function

This first approach to the whole dataset finished with the plots of one PRN for one block hour. That allowed us to check that the data was correct and corresponding to the plots we had, but the plots in fact, were not relevant to our final aim. Furthermore, the code was not optimized.

2.2.2. Main Development

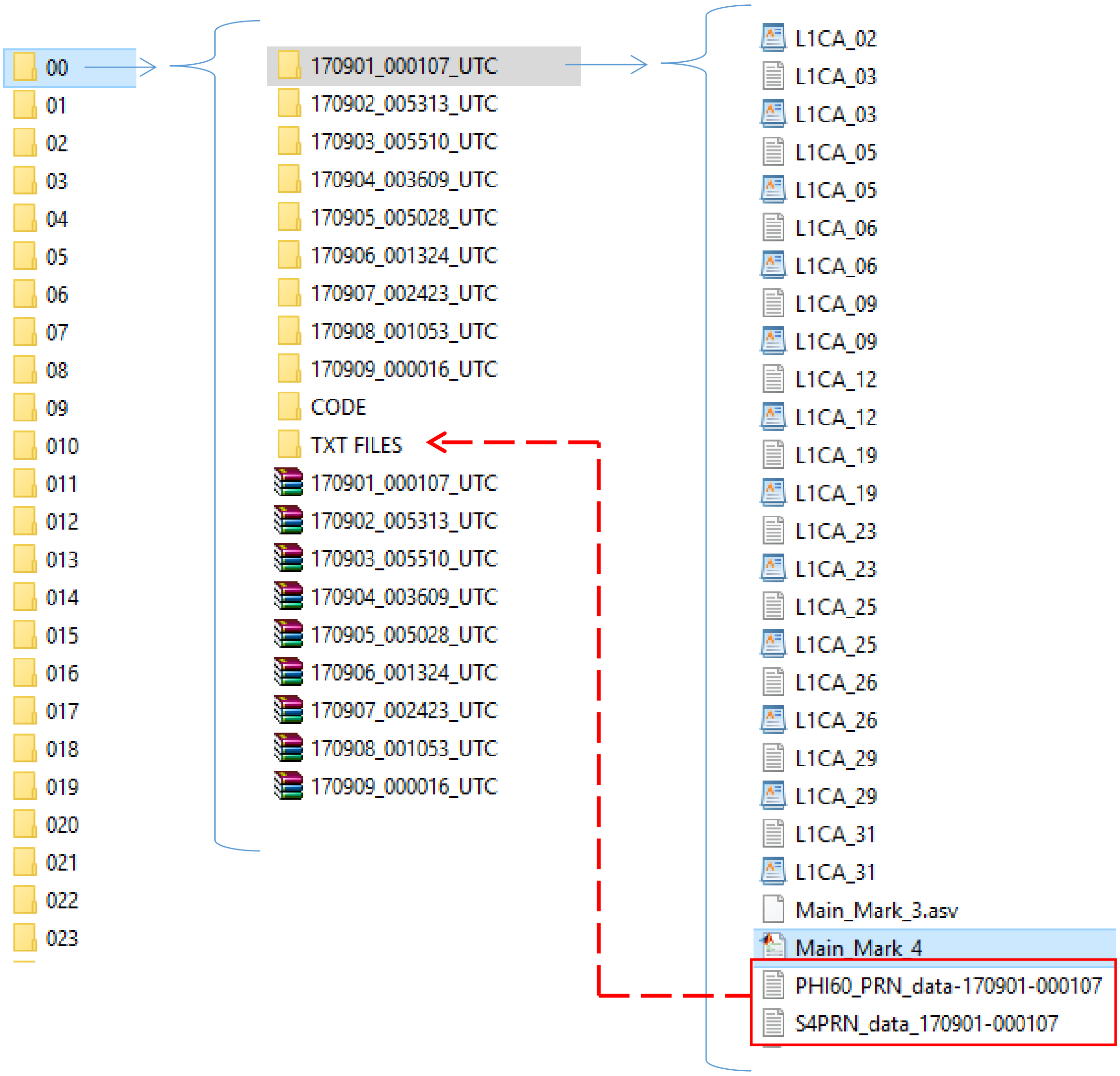
2.2.2.1. S4 and Phi 60 TXT Files

Since the first approach of the code did not work as expected, we changed the approach and decided to gather all the data of the PRNs for each day each time block in one .txt file. On the txt file we will save the PRN number, the values of S4 and the values of time. For the other .txt file, instead of saving the S4 index we will save the Phi60 index values.

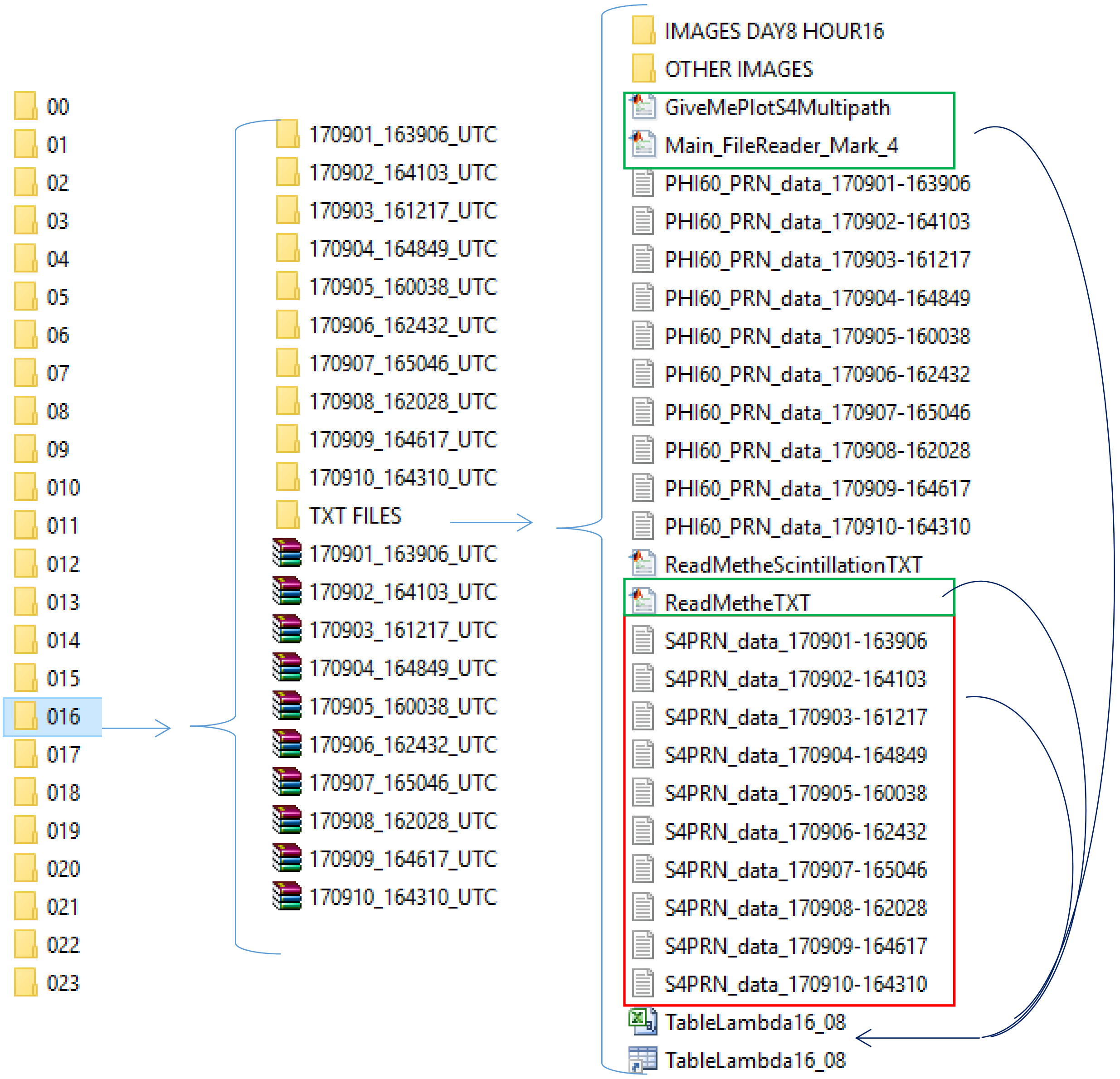
To create the .txt file, we read the .slog file and applying a transient of 100 values, in order to avoid the first received values affected by other factors of the initialization of the receiver, and we write the txt as shown in the diagram below.

2.2.2.2. Save all the TXTs in the folder TXT FILES

With this code we obtain two txt files corresponding to the S4 index and the Phi60 index for day X between the hour block of ZZ. (Being X one day of the 10 and ZZ one block hour of the 24)



One of the milestones of this thesis was to decide how to organize the files in order to obtain results in which we could clearly observe the scintillation effect. Our solution was to organize all the days in block times, so for the block hour from 00:00 to 01:00 approximately, you will plot each day against the other days, so if we are looking for an anomaly in the plot, we can spot in which day it happens and in which block hour.
Once we have obtained the txt files for S4 and for Phi60 of one day and one block hour, we will save them in the folder TXT files for later.



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019
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022
023

170901_163906_UTC
170902_164103_UTC
170903_161217_UTC
170904_164849_UTC
170905_160038_UTC
170906_162432_UTC
170907_165046_UTC
170908_162028_UTC
170909_164617_UTC
170910_164310_UTC
TXT FILES
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170902_164103_UTC
170903_161217_UTC
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170905_160038_UTC
170906_162432_UTC
170907_165046_UTC
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170909_164617_UTC
170910_164310_UTC

IMAGES DAY8 HOUR16
OTHER IMAGES
GiveMePlotS4Multipath
Main_FileReader_Mark_4
PHI60_PRN_data_170901-163906
PHI60_PRN_data_170902-164103
PHI60_PRN_data_170903-161217
PHI60_PRN_data_170904-164849
PHI60_PRN_data_170905-160038
PHI60_PRN_data_170906-162432
PHI60_PRN_data_170907-165046
PHI60_PRN_data_170908-162028
PHI60_PRN_data_170909-164617
PHI60_PRN_data_170910-164310
ReadMetheScintillationTXT
ReadMetheTXT
S4PRN_data_170901-163906
S4PRN_data_170902-164103
S4PRN_data_170903-161217
S4PRN_data_170904-164849
S4PRN_data_170905-160038
S4PRN_data_170906-162432
S4PRN_data_170907-165046
S4PRN_data_170908-162028
S4PRN_data_170909-164617
S4PRN_data_170910-164310
TableLambda16_08
TableLambda16_08

Having created the txt files for S4 index and Phi60 index for each day at each hour and save them at the TXT folder, it is time to do the plots on amplitude, thus we will take the information gathered on the S4 txt files.

To read and plot the TXT files we will need the function that reads the txt (*ReadMeTheTXT*), the function that plots the data (*GiveMePlotS4Multipath)* and a main program to execute those functions *(Main_FileReader_Mark_4).*

The structure will go as follows, the main opens the txt files, calls the function GiveMePlotS4Multipath, which at the same time calls the function *ReadMetheTXT* to read the data that puts in a matrix. Once read and in a matrix, the first function computes the plots of S4 in amplitude for Multipath and Scintillation; explained on the following section.

Proceeding with the code creation and taking into consideration the structure explained previously, once we are located in the folder TXT Files, we run the main program.

2.2.2.3. Read me the TXT

With these lines of code we call the function *GiveMePlotS4Multipath* fixing the first day and plotting with the other nine days. The next iteration of the loop will fix the day number two and plot it against the next 8 days, because with day one is already plotted.

The first step for the function *GiveMePlotS4Multipath* is calling the function *ReadMetheTXT*:

As an input is receiving the two files, being the first the one fixed and the second the iteration of the other X days, and he list of all files, that for the final version of the code this last input was useless.

Reading the files is in charge of the function *ReadMetheTXT*, it is easy to read the TXT because we decided to save it the data in rows in which the first one is the name of the PRN, the second one are the values of S4 and the third are the values of time (in seconds).
We just repeat this reading for the length of the file.

2.2.2.4. Give Me Plot S4 Multipath

This part is the most important part of the thesis; in this function we apply the technique explained in section 2.1. computing the plots of the S4 time series with the two PRNs for all the block hours and the plots of *Lambda* (λ).

Once the plot is read we go back to *GiveMePlotS4Multipath* and start computing the plots.

When we receive the data of one day vs the next, we first check if in both of them we have S4 index going above the threshold, checking if one of them is empty.

Secondly, we check if the PRNs coincide, if they do not coincide we go for the next iteration, if they do we go for the next step.

Then, due to the fact that the block of time is 50 minutes but the start acquisition time is different between days, we have one code that is shorter than the other. So we define the PRN, the time and the values that compose the shorter PRN. Consequently, the other file will be the one corresponding to the largest amount of data.

```
cont=1;
acquisitiondelay = [];
contTXT = 1;
if ~isempty(C) && ~isempty(C2)
for n=2:3:numel(C)
for i=2:3:numel(C2)
if(strcmp(C{n-1,1},C2{i-1,1})==1)
if length(C2{i}) > length(C{n})
longC  = C2{i};
fileOneDate = datenum(regexprep(fileSecond(12:24),'-
',''),'yymmddHHMMSS');
timelongC = C2{i+1} + fileOneDate ;
shortC = C{n};
timeshortC = C{n+1};
shortFile = regexprep(fileOne,'_',' ');
longFile = regexprep(fileSecond,'_',' ');
namePRN = regexprep(C{n-1},'_',' ');
L = length(C2{i}); %length of the long dataset
D = L - length(C{n}); %length of the short dataset
else
longC  = C{n};
fileOneDate = datenum(regexprep(fileOne(12:24),'-
',''),'yymmddHHMMSS');
timelongC = C{i+1} + fileOneDate ;
shortC = C2{i};
timeshortC = C2{i+1};
shortFile = regexprep(fileSecond,'_',' ');
longFile = regexprep(fileOne,'_',' ');
namePRN = regexprep(C{n-1},'_',' ');
L = length(C{n}); %length of the long dataset
D = L - length(C2{i});%length of the short dataset
end
```

Program Listing 1: Give Me Plot S4 Multipath: Defining short and long variables.

Once we know which one of them has the shortest dataset, we fill this dataset with NaNs until the length of the long dataset and we compute the correlation between the two functions. The position of the minimum of the correlation will be the delay between the two PRNs.

Having done the correlation, we add NaNs, corresponding to the delay between the signals, to the short dataset and now we have the two PRNs perfectly aligned. Not caring how many sidereal days have passed nor the difference between the acquisition times.

```
%Filling the short dataset with NaNs and doing the
%autocorrelation between the two functions to check the
%delay.
for j=1:L
cc = abs([shortC; NaN(D, 1)] - circshift(longC, -j));
corr(j) = sum( cc(~isnan(cc)) );
end
timelong = timelongC*60*24;
timeshort = timeshortC*60*24;
timeshortCstr = datestr(timeshortC,'MMSS');
timelongCstr = datestr(timelong, 'MMSS');

%Finding the xvalue for the minimum of the corr and
%shifting the long.
[tmp, acquisitiondelay(cont)] = min(corr);
```

Program Listing 2: Give Me Plot S4 Multipath: Filling the short data set with NaNs

We compute the plots of the two PRNs aligned and the plots of Lambda (the subtraction of PRNs.

```
% Plotting the two PRNs
figure;
subplot(2,1,1);
shortCzeros = [ NaN(acquisitiondelay(cont),1); shortC];
plot(shortCzeros);
hold on
longCzeros = [longC; NaN(acquisitiondelay(cont)-D,1)];
plot(longCzeros);
hold off
grid on
lgd = legend(shortFile, longFile);
title(lgd,regexprep(C{n-1},'_',' '))
xlim([1 length(longCzeros)])
ylim([0 1])
xlabel(['time (s) - ' datestr(timelongC(1),'mm
yy')],'FontSize',13)
ylabel('Values of S4','FontSize',13);
if (length(longCzeros)-length(shortCzeros) ~= 0)
NANdelay = length(longCzeros)-length(shortCzeros);
shortCzerosNAN = [shortCzeros; NaN(NANdelay,1)];
else
shortCzerosNAN = shortCzeros;
end

%Plotting Lambda (being Lambda the subtract of PRNs)
subplot(2,1,2);
lambda{contTXT} = shortCzerosNAN-longCzeros;
plot(-(shortCzerosNAN - longCzeros));
lgd = legend('Lambda'); %Being Lambda the subtract of PRNs
title(lgd, regexprep(C{n-1},'_',' '))
xlabel(['time (s) - ' datestr(timelongC(1),'dd mmm yy,
HH:MM')],'FontSize',13)
ylabel('Lambda','FontSize',13);
grid on
ylim([-0.8 0.8])
xlim([1 length(longCzeros)])
```

Program Listing 3: Give Me Plot S4 Multipath: Plotting the PRNs aligned and Lambda

For each day of one block hour, the plots will have a Table in which each row corresponds to each plot and contains the information of the:

- Mean: Average of the values of S4 index
- Standard Deviation: Value that quantifies the amount of dispersion of the values compared to the mean.
- Number of points: Total number of samples of the signal Lambda.

The last two rows of the table correspond to the Total of each variable and the Average of each variable.

```
matrix3 = 1;
for matrix1=1:numel(Files)
for matrix2=1:numel(Files{matrix1})
if ~isempty(Files{matrix1}{matrix2}) &&
(length(Files{matrix1}{matrix2}) > 2)
PRN1 = Files{matrix1}{matrix2}(1);
PRN2 = Files{matrix1}{matrix2}(2);
namePRN = Files{matrix1}{matrix2}(3);
FileScint{matrix2} = [PRN1 PRN2 namePRN];
FileScintVector= FileScint{matrix2};

SubMatrixVector = submatrixs{matrix1}{matrix2};
TimeVector = Times{matrix1}{matrix2};

lambdavector = Lambda{matrix1}{matrix2};
MeanLambda = mean(lambdavector,'omitnan');
DevStdLambda = std(lambdavector,'omitnan');
NumPoints = length(lambdavector(~isnan(lambdavector)));

NewLambda{matrix3,1} = MeanLambda;
NewLambda{matrix3,2}= DevStdLambda;
NewLambda{matrix3,3} = NumPoints;
matrix3=matrix3+1;
end
end
end

TotalMean = 0;
TotalStdDev = 0;
TotalNumPoints = 0;
for counter=1:length(NewLambda)
if ~isnan(NewLambda{counter})
TotalMean = TotalMean + (NewLambda{counter,1});
TotalStdDev = TotalStdDev + NewLambda{counter,2};
TotalNumPoints = TotalNumPoints + NewLambda{counter,3};
end
end
```

Program Listing 4: Main File Reader Mark 4: Creating the table for the variables Mean, Std Dev, Num Points.

With an example of the plots we finish the Main Development of our code, and on the following section we will show the results and comment them.

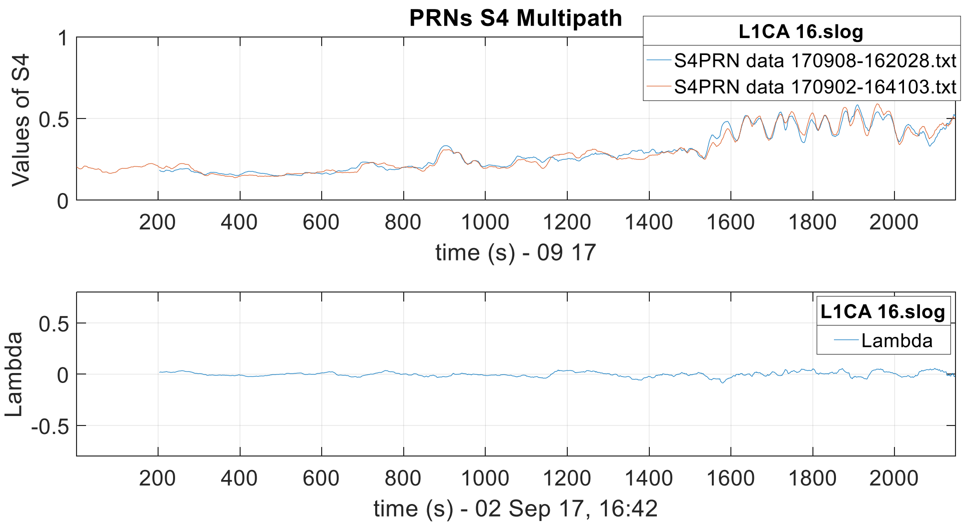

Figure 10: Example of final plot of PRNs and Lambda.

All the results obtained will follow the same structure. In the plot of above we will observe two signals, corresponding to the same PRN and the same block hour but for different days. The signals are aligned in time; although that does not mean they will be overlapped always as we will see in the results section.

With the plot above with the two signals it's with the one we do the subtraction to obtain Lambda. Lambda is the plot below and is the subtraction between the two signals above and is in which we have get rid of the multipath masking effect and we obtain the scintillation effect. As the legend of both plots describe:

Legend Plot S4 (above):

- Blue line: Day and block hour of the short PRN
- Red Line: Day and block hour of the long PRN.
- X Axis: Time in seconds
- Y-Axis: Value of S4.
- Title Legend: name of the PRN.

Legend Plot S4 Lambda (below)

- Blue line: Lambda.
- X Axis: Time in minutes
- Y-Axis: Value of S4.
- Title Legend: name of the PRN.

CHAPTER 3. Results

In this chapter, the different plots resulting from section 2.2.2. are shown. The information retrieved after analysing those figures is available in the discussion (section 3.1.).

As commented in the section1, the type of analysis we are doing is a simplified big data analysis, although is a simplified version, the amount of data gathered and plots created are large enough to not be able to analyse one by one. So to solve this problem, we rely on the *Septentrio ISMR Data*, a high accurate receiver focused on scintillation measurements.

This receiver gave us the plots for the solar storm regarding the TEC and the ROT. Checking the plots, we saw an anomaly the day 8th of September of 2017 on both indexes (see Fig 3.1.)

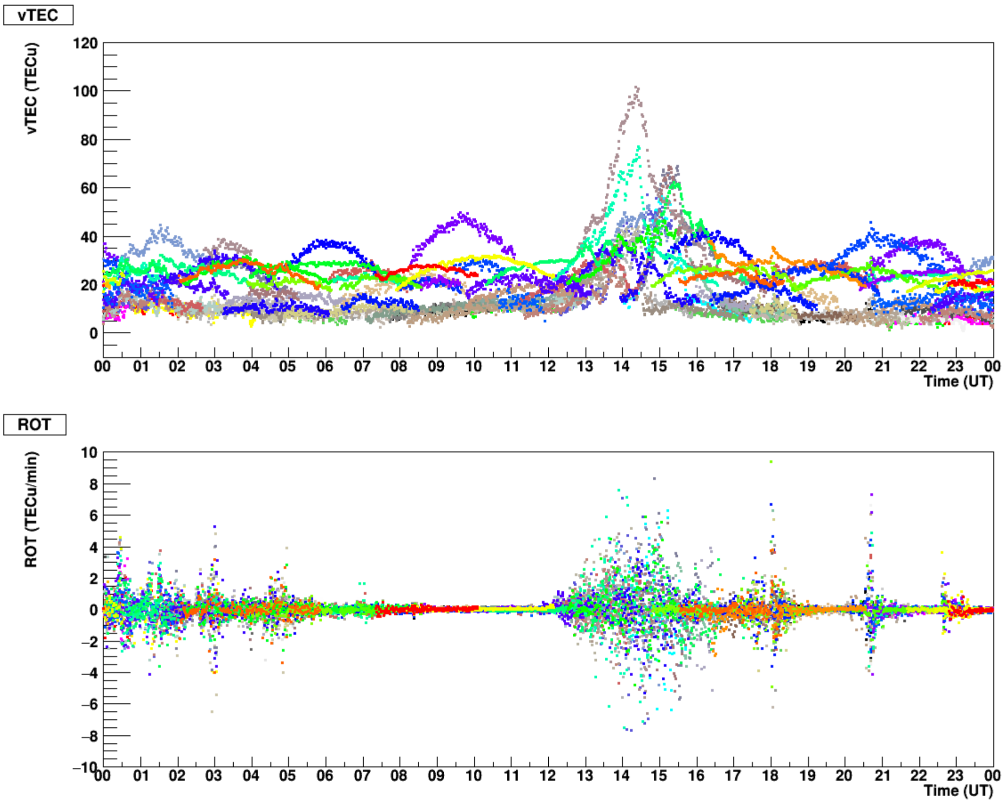

Figure 11 Vertical TEC and Rate of TEC (ROT) for day 8 plotted with the Septentrio recevier data

As we can see and as expected, the anomaly in TEC and ROT is higher at the solar peak hours, between 12 and 16 for the day 8 of September. That’s why; the following plots and the plots we will discuss and differentiate by blocks are the ones from day 8 versus all the other days, between the hours 10 and 16.

Add that we choose day 8 because the TEC and ROT for other days did not present this anomaly, as we can observe in Figure 12.

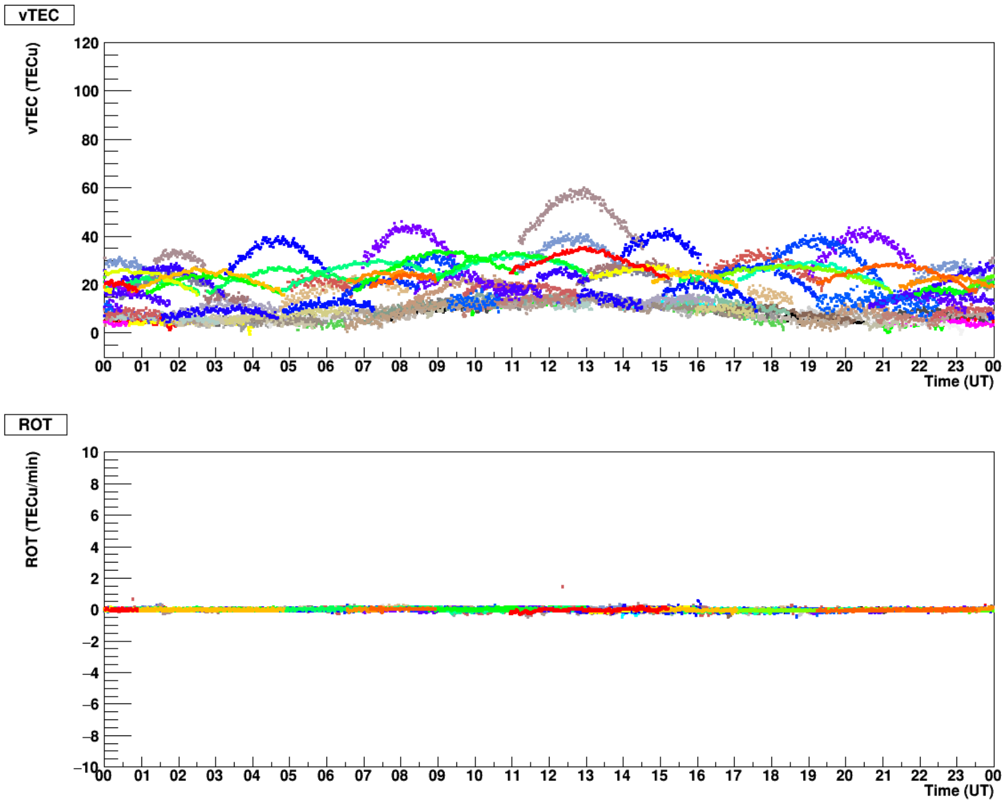

Figure 12: TEC and ROT for day 9.

3.1. Plots

These plots show PRNs for different days versus time in seconds; and the subtraction of these PRN versus time in minutes. In order to ease the analysis of data, three types of plots were differentiated: The first block in which the PRNs are perfectly aligned in y-axis, thus without any scintillation; a second block with the PRNs with a misalignment but without the assurance to label the difference as a scintillation error. Finally the ones that we consider they have scintillation.

3.1.1. Scintillation free:

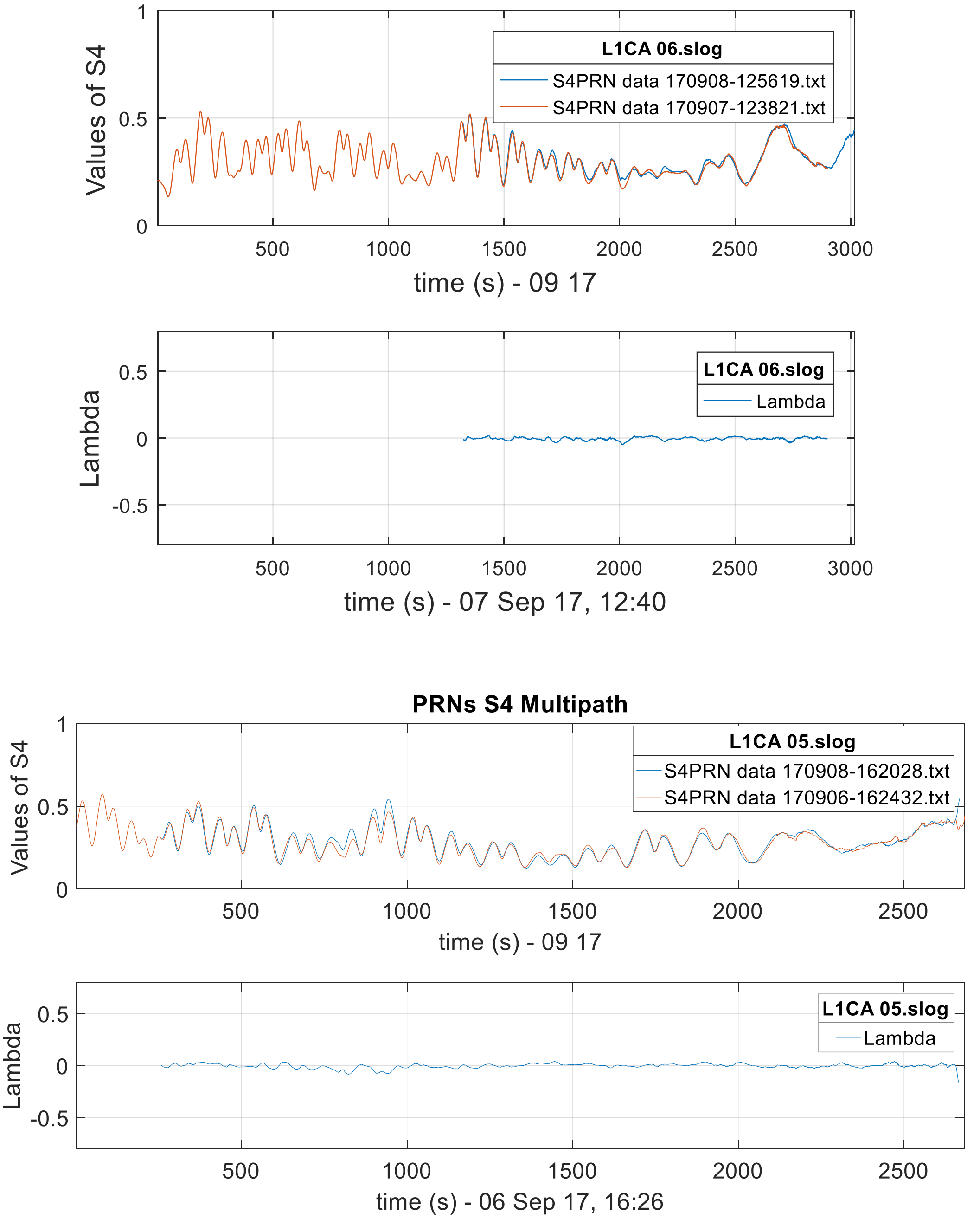

Figure 13: Scintillation Free examples. PRN 6 and PRN 5 for day 8 against day 7 and day 6.

The table with the mean, the Standard deviation and the number of points of these two plots is the following:

	Mean	**Std Deviation**	**Num. Points**
Lambda PRN 06	0.00036980	0.0235	1947
Lambda PRN 05	0.0045	0.0227	2413

Table 2: Values of variables. Each row correspoding to each plot.

Discussion:

The plots of Lambda in this section have a mean close to zero. Once we have subtracted the two PRN of the different days, we obtain *Lambda*, a plot in which the multipath effect, inducing the non-true values of S4, is perfectly removed.

In this section, we obtain a plot of *Lambda* with a mean and a standard deviation close to zero. This means that the S4 that remains exhibit from the subtraction is nearly zero. This value of S4 is the true value of the scintillation effect to the S4 index during that hour to that PRN.

These plots build the base of our project, being used as a benchmark to show that the technique applied to obtain the results of *Lambda* work properly and to show how multipath effect masks the true effect of scintillation. Based on these plots and the data of other similar behavior plots, we will analyze the plots in which we have consider there is a presence of scintillation and why there are different from the scintillation-free plots.

3.1.2. Presence of Scintilaltion.

On the following pictures we observe all the plots between hours 12 and 16 that we have considered to have the presence of Scintillation.

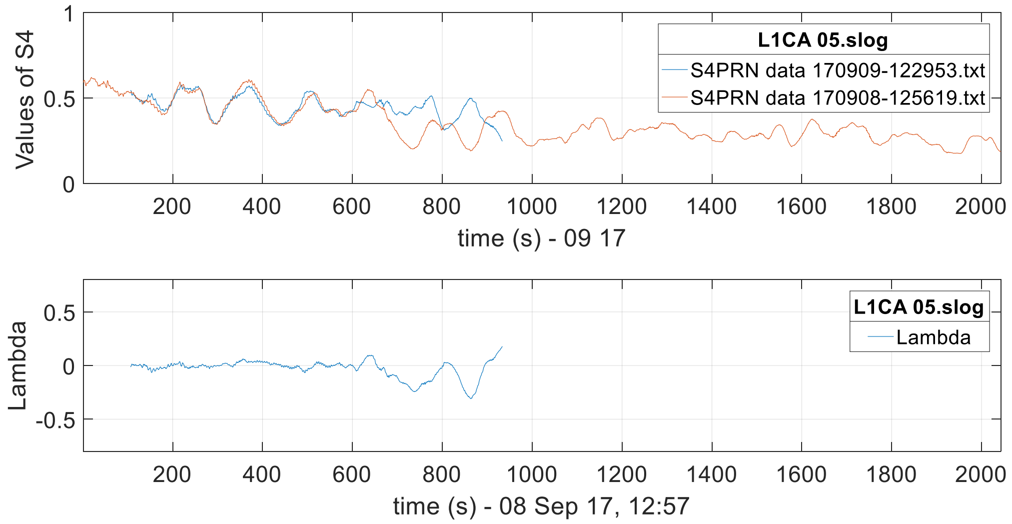

Figure 14: PRN 5, Day 8 against Day 9. Block hour 12

This first plot, regarding the PRN 05 during the gap hour 12 between days 8 and 9 it is considered to have the presence of scintillation because we can observe an overlapped signal with a result of zero-mean Lambda, but after ten (10) minutes (600 seconds) we observe a misalignment between the two signals. This misalignment is due to scintillation effects because we still have changes in the value of S4 after the removal of multipath effect.

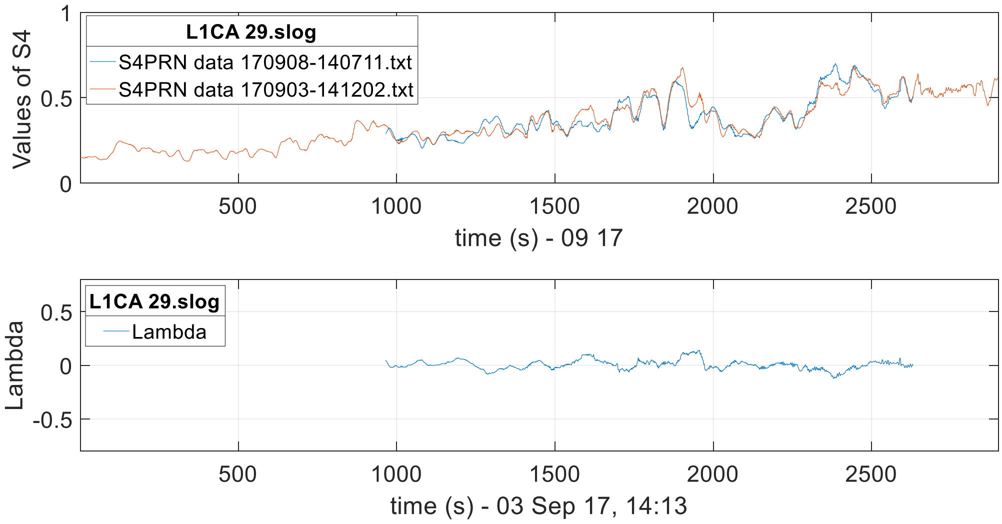

Figure 15: PRN 29, Day 8 against Day 3. Block hour 14

This first plot, regarding the PRN 29 during the gap hour 14 between days 8 and 3 it is considered also to have the presence of scintillation because we can observe that Lambda oscillates between the values 0.1 and -0.1. This oscillation could be considered a difference due to Gaussian Noise, but since we can check the TEC and ROT of that block hour and confirm a high scintillation event was happening, we can consider this oscillation as an effect of scintillation.

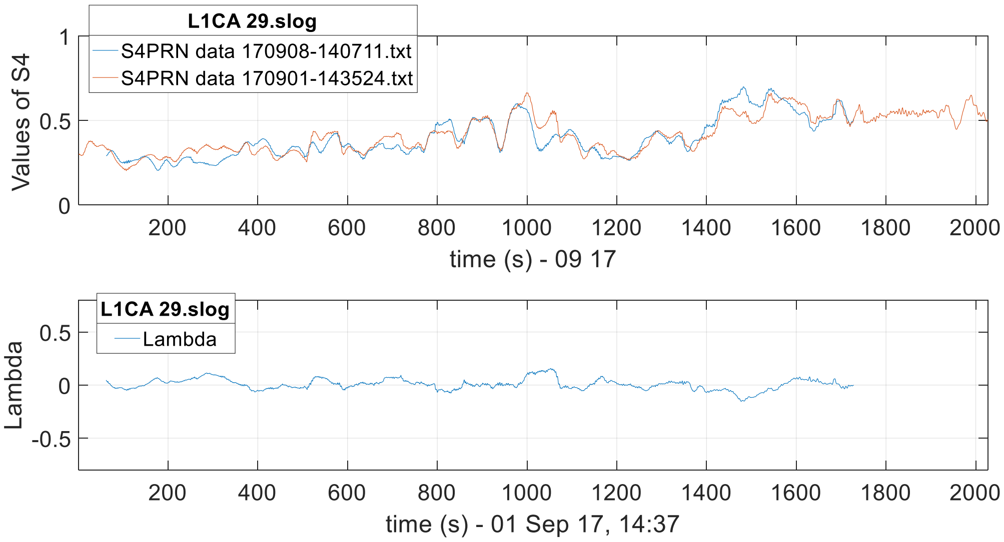

Figure 16: PRN 29, Day 8 against Day 1. Block hour 14

This plot is really similar as the one obtained in Figure 15, and the reasons are the same. After the subtraction, we still have irregularities on the signal and we have considered that these irregularities come from a scintillation event, checking the presence of scintilaltion with the ROT at hour 14.

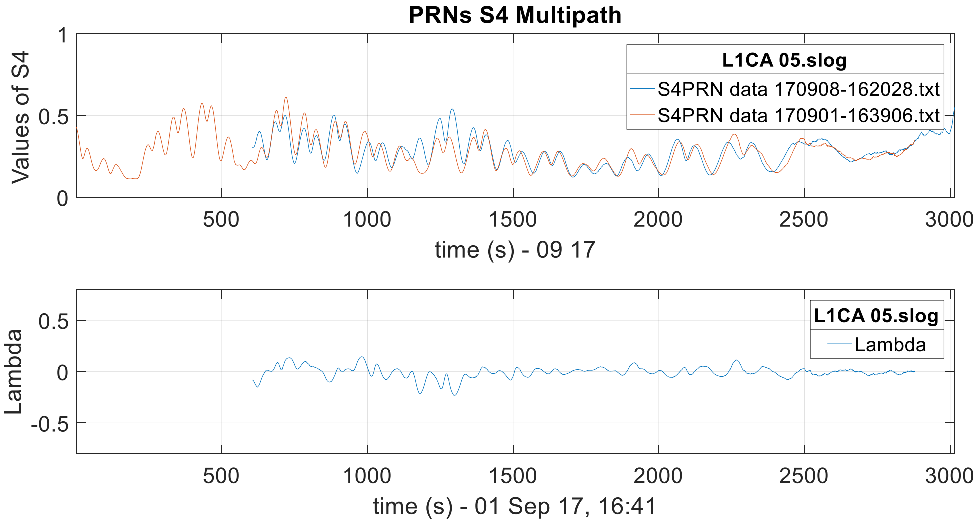

Figure 17: PRN 5, Day 8 against Day 1. Block hour 16

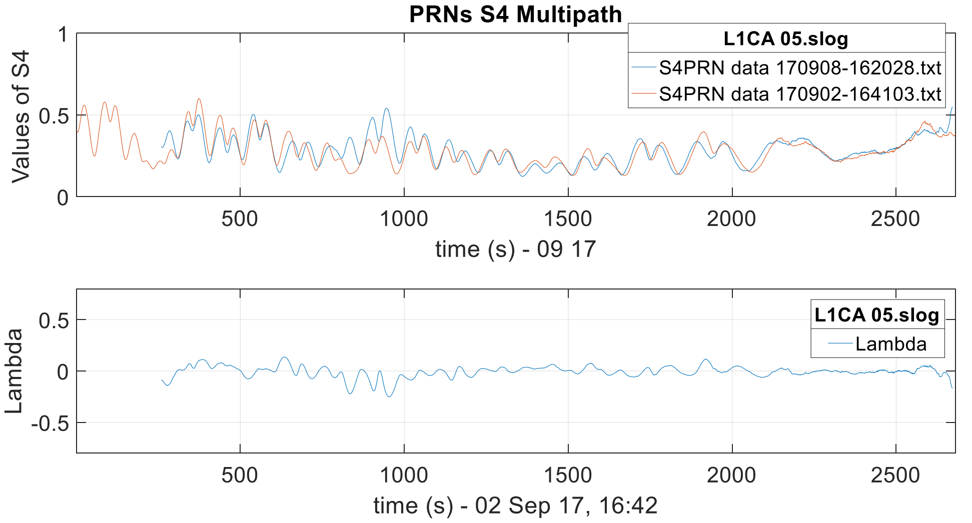

Figure 18: PRN 5, Day 8 against Day 2. Block hour 16

Plots of Figure 17 and Figure 18 are related because the block hour is the same and the PRN is the same (PRN 05); and we are subtracting day 8 against day 1 and day 2 respectively. In both *Lambda* we can observe there is a misalignment and we conclude is due to scintillation effect, since if we plot the PRN 05 for day 1 against day 2 we obtain a scintillation-free lambda.

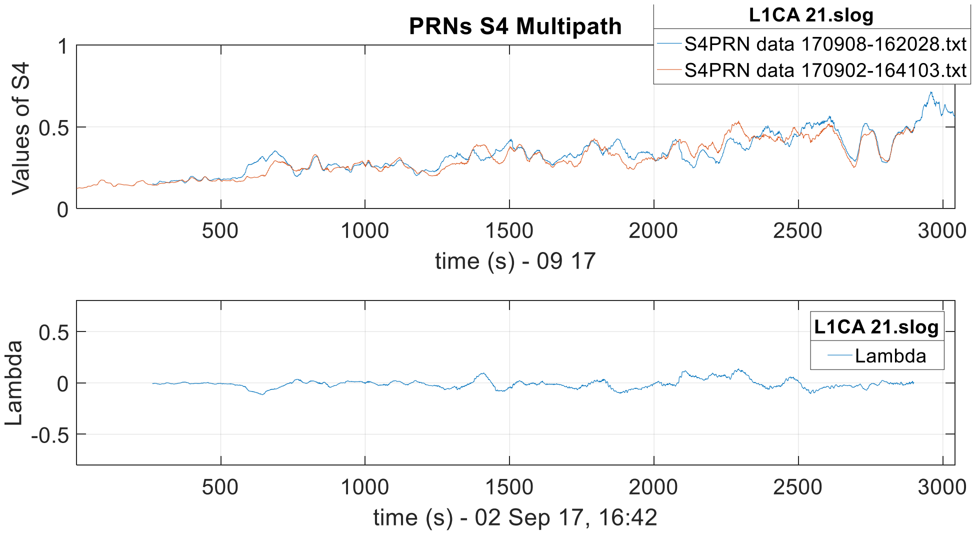

Figure 19: PRN 21, Day 8 against Day 2. Block hour 16

This plot regarding the PRN 21 during the gap hour 16 between days 8 and 2 it is considered to have the presence of scintillation because as in Figure 15 and Figure 16, we can observe irregularities in the Lambda behaviour and we know by checking the ROT that can be due to a scintillation event.

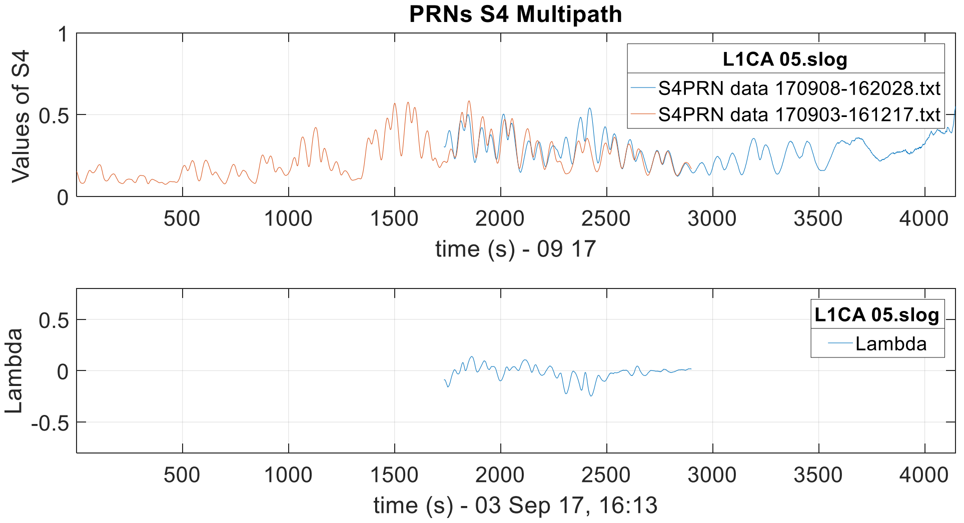

Figure 20: PRN 5, Day 8 against Day 3. Block hour 16

This plot we have considered as a scintillation present due to the fact that the PRN 05 during hour 16 of day 8 have already presented a scintillation behaviour, thus although the lower number of points of overlapping, we have considered this plot as a scintillation present one.

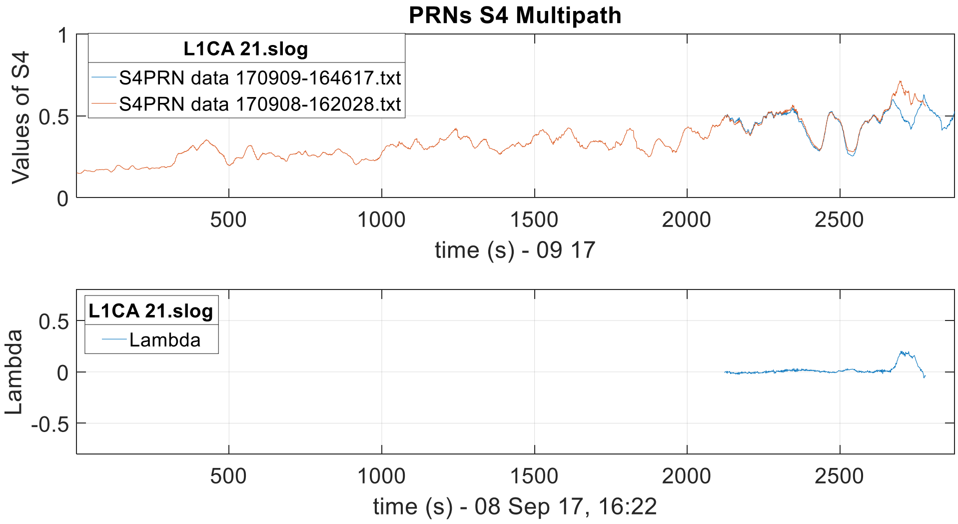

Figure 21: PRN 21, Day 8 against Day 9. Block hour 16

This last plot, similar to the plot we have seen in Figure 14, shows an overlap during a considerable amount of time, and after that the signal on day 8 presents a misalignment respect to the other signal. Although this is the plot with less number of points, the misalignment is easy-spotting once the multipath effect is gone.

Following, we show the table with the Mean, Standard deviation and Number of Points for each Lambda plot.

	Mean	**Std. Deviation**	**Num. Points**
Figure 14	0.0300	0.0843	829
Figure 15	0.0070	0.0514	1667
Figure 16	0.0043	0.0432	1667
Figure 17	0.0067	0.0564	2276
Figure 18	0.0080	0.0569	2413
Figure 19	0.0104	0.0425	2638
Figure 20	0.0189	0.0702	1168
Figure 21	0.0210	0.0491	659

Table 3: Mean, Std Dev and Number of Points for plots with presence of scintilaltion.

General Discussion:

In the plots above we can observe a presence of misalignment between the PRNs of different days in the same block hour. Due to the fact that we are sure that the alignment is correct, subtracting and obtaining lambda (λ) will make appear the values of S4 affected by scintillation, in all the cases above the misalignment is not large but is visible.

The misalignment is consequence of a high rate of TEC (ROT) during the day and block hour analyzed, and as expected, scintillation adds an increment in the values of S4, once the multipath effect is removed.

Regarding the table for each plot, we observe that the standard deviation is larger than for the scintillation-free post, meaning that the variations on the signal are larger.

In conclusion of this section, with our technique we have detected scintillation during day 8 between the block hour of 12 and 16; event that would have been masked by the multipath effect if we would have used a standard technique of detection.

3.1.3. Data affected by other nuisances

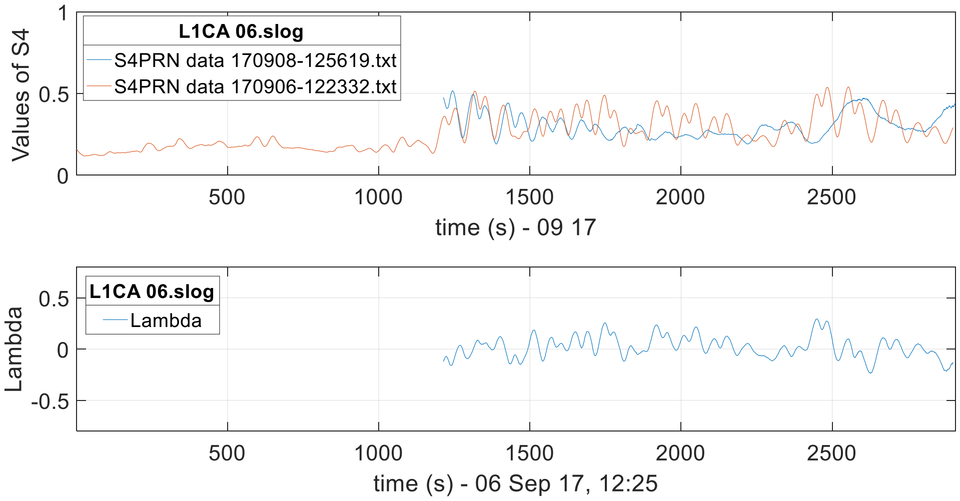

Figure 22: PRN 06, Day 8 against Day 6. Block hour 12

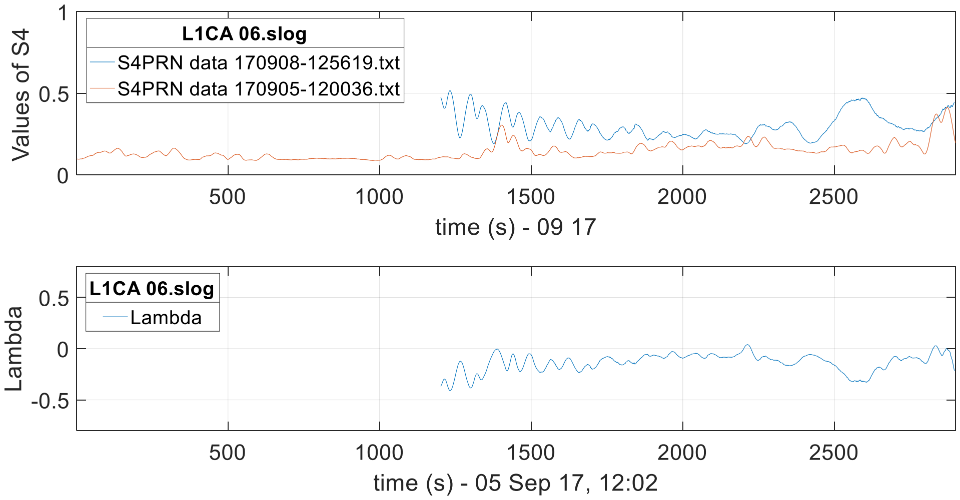

Figure 23: PRN 06, Day 8 against Day 5. Block hour 12

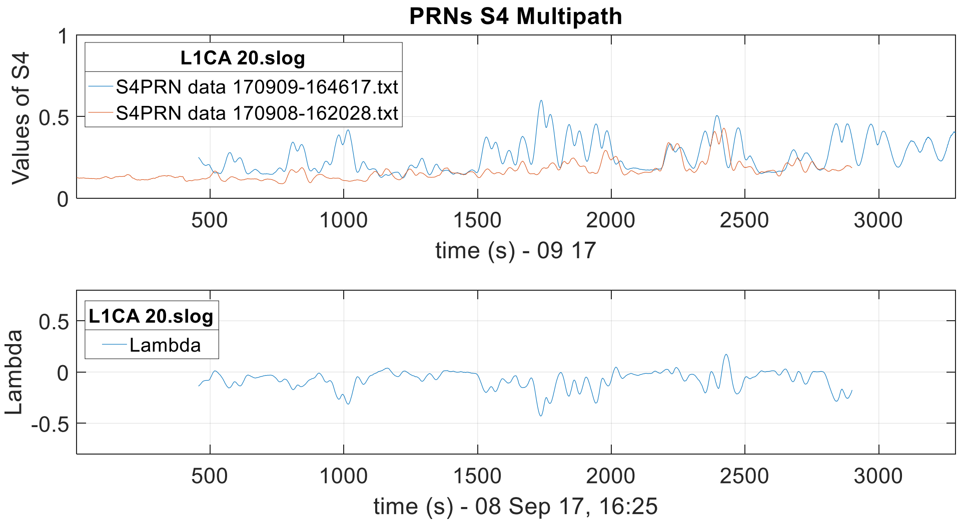

Figure 24 PRN 20, Day 8 against Day 9. Block hour 16

	Mean	Std. Deviation	Num.Points
Figure 22	0.1349	0.0880	1695
Figure 23	0.0198	0.1029	1687
Figure 24	0.0788	0.0883	2445

Table 4: Mean, Std Dev, Num. Points for the three plots.

Discussion:

The plots we have observed in this section are the ones that suffer from a misalignment but we have not considered that the misalignment is due to a scintillation effect.

The other possible effects that might affect the signal to have this behaviour are:

- Non repetitive multipath: objects being moved manually from one day to the other around the installation.
- Thermal noise driving the computation of the S4.
- Un-correct alignment: Correlation between the signals gone bad.
- Receiver specific artifacts.

CONCLUSIONS

In spite of the first expected simplicity of the experiment, the final experiment conducted in this study has permitted the confirmation of the hypothesis that the multipath affects the values of S4 in amplitude, and that during a high rate of TEC the values of S4 vary, in this case, due to scintillation.

Firstly, we created the code that would allow us to analyze the data of the .slog files in which the values of S4 and time were saved. Once the values were read, we computed the correlation to align the signals and subtract the signals masked by multipath to obtain the signal, which we called Lambda, affected by scintillation.

The main results obtained, compressed in section 3.1. were relevant and proved the masking effect of multipath on the scintillation effect to the S4 index.

Although the results in which scintillation was present were only eight (8) out of two-hundred (200), it can be concluded that the technique used to detect multipath and scintillation can be applied to other cases, and most importantly, in cases in which the scintillation can be stronger. In this experiment of detection, the amount of data we had of that period of time is only Polar data; scintillation is also strong in Equatorial areas in which if we had the data we could apply the technique.

The realization of this first experiment has also highlighted the need for further applications in cases of other strong solar storms or the data of other regions of the globe in which the presence of amplitude scintillation is strong. Also, during periods of time larger than the one analyzed in this experiment.

The need of this amount of data to prove the true viability of our technique, calls out the need of a Big Data analysis.

BIBLIOGRAPHY AND REFERENCES

[1] N. Linty, F. Dovis, and L. Alfonsi, "Software-defined radio technology for GNSS scintillation analysis: Bring Antarctica to the lab", GPS Solutions, vol. 22, no. 4, p. 96, Jul. 2018, issn: 1521-1886. doi: 10.1007/s10291-018-0761-7.

[2] L. Alfonsi, P. J. Cilliers, V. Romano, I. Hunstad, E. Correia, N. Linty, F. Dovis, O. Terzo, P. Ruiu, J. Ward, and P. Riley, "First observations of GNSS ionospheric scintillations from DemoGRAPE project", Space Weather, vol. 14, no. 10, pp. 704–709, 2016, issn: 1542-7390. doi: 10.1002/2016SW001488.web

[3] A.J. Fernandez, J.A. Pulido, M. Wis; P.Closas, C. Fernández-Prades, F. Zanier, R. Prieto-Cerdeira, M.Crisci: *ARTEMISA: New GNSS receiver processing techniques for positioning and multipath mitigation.*

[4] Peter Joosten, Markus Irsigler: *GNSS ambiguity resolution in presence of multipath:* DOI: 10.1.1.596.8341

[5] Christian Rost, Lamber Wanninger: *Carrier phase multipath mitigation based on GNSS signal quality measurements:* DOI: 10.1515

[6] Yedukondalu Kamatham: *Estimation, Analysis and Predictions of Multipath Error for static GNSS applications.*

[7] Diego M. Franco-Patiño, Gonzalo Seco-Granados, Fabio Dovis: *Signal Quality checks for Multipath detection in GNSS.*

[8] Brian Schipper: *Multipath Detection and Mitigation Leveraging the Growing GNSS Constellation*

[9] Rodrigo Romero, Fabio Dovis: *Effect of Interference in the Calculation of the Amplitude Scintillation Index S4.*

[10] Yang Liu, Lianjie Fu, Junling Wang, Chunxi Zhang: *Study of GNSS Loss of lock characteristics under Ionsophere scintillation with GNSS data at Weipa (Australia) During Solar Maximum Phase.*

[11] Surenda Sunda: *GPS Signal fading due to scintillation and multipath and its impact on satellite geometry and postioning over the Appleton Anomaly Region.* DOI: 7.665

[12] Jordi Vilà-Valls, Pau Closas, Carles Fernandex Prades, James Thomas Curran: On the mitigation of Ionospheric Scintillation in Advanced GNSS Receivers (pages from 1692 to 1709) from IEEE.

[13] Jordi Vilà Valls, J.A. Lopez-Salcedo, G. Seco Granados.: *An interactive multiple model approach for robust GNSS carrier phase tracking under scintillation conditions.*

[14] Observations and modeling of UHFband scintillation occurrence probability over the low latitude region of China during the maximum activity of solar cycle: https://www.researchgate.net/publication/273304962_Observations_and_modeling_of_UHF-band_scintillation_occurrence_probability_over_the_low-latitude_region_of_China_during_the_maximum_activity_of_solar_cycle_24/figures?lo=1

APPENDIX A. Code

MAIN FILEREADER MARK4

```
%% READ TXT FILES PROGRAM
clear all;
close all;
clc;

%% Get a list of all files in the folder with the desired file name
pattern.

d = dir;
fn = {d.name};
% [indx,tf] = listdlg('PromptString','Select a file:',...
%                             'SelectionMode','single',...
%                             'ListString',fn);

%% Create
n = 1;
TXTFiles = [];
for i=1:1:numel(d)
     if(d(i).bytes>=10000)
         TXTFiles{n} = d(i).name;
         n = n + 1;
     end
end
%
i=18;
n=11;
cont = 1;
while i<=18 %Because S4 index start at 10
%     n=n+1;
    while n<=20 %Because S4 index start at 10
        [File, Time, submatrix, lambda] =
GiveMePlotS4Multipath(TXTFiles{i}, TXTFiles{n}, TXTFiles);
        Files{cont} = File;
        Times{cont} = Time;
        submatrixs{cont} = submatrix;
        Lambda{cont} = lambda;
        n=n+1;
        cont = cont + 1;
    end
    i=i+1;
    n=11;
end
%[Files, Time, submatrix]= GiveMePlotS4Multipath(TXTFiles{15},
TXTFiles{18}, TXTFiles);


%% Scintillation TXT
% Read the cell of Files, Time and subtractionmatrix and put it in a
TXT

% FileScintillation = fopen('Scintillation016-DAY8','wt');
matrix3 = 1;
for matrix1=1:numel(Files)
    for matrix2=1:numel(Files{matrix1})
```

```
        if ~isempty(Files{matrix1}{matrix2}) &&
(length(Files{matrix1}{matrix2}) > 2)
            PRN1 = Files{matrix1}{matrix2}(1);
            PRN2 = Files{matrix1}{matrix2}(2);
            namePRN = Files{matrix1}{matrix2}(3);
            FileScint{matrix2} = [PRN1 PRN2 namePRN];
            FileScintVector= FileScint{matrix2};

            SubMatrixVector = submatrixs{matrix1}{matrix2};
            TimeVector = Times{matrix1}{matrix2};

            lambdavector = Lambda{matrix1}{matrix2};
            MeanLambda = mean(lambdavector,'omitnan');
            DevStdLambda = std(lambdavector,'omitnan');
            NumPoints = length(lambdavector(~isnan(lambdavector)));

            NewLambda{matrix3,1} = MeanLambda;
            NewLambda{matrix3,2}= DevStdLambda;
            NewLambda{matrix3,3} = NumPoints;
            matrix3=matrix3+1;
        end
    end
end

TotalMean = 0;
TotalStdDev = 0;
TotalNumPoints = 0;
for counter=1:length(NewLambda)
    if ~isnan(NewLambda{counter})
        TotalMean = TotalMean + (NewLambda{counter,1});
        TotalStdDev = TotalStdDev + NewLambda{counter,2};
        TotalNumPoints = TotalNumPoints + NewLambda{counter,3};
    end
end

AvgMean = TotalMean/length(NewLambda);
AvgStdDev = TotalStdDev/length(NewLambda);
AvgNumPoint = TotalNumPoints/length(NewLambda);

lambdaTable = cell2table(NewLambda,...
    'VariableNames',{'Mean','StandardDeviation','NumPoints'});

AddTableTotal = table(TotalMean, TotalStdDev, TotalNumPoints,...
     'VariableNames',{'Mean','StandardDeviation','NumPoints'});

AddTableAvg = table(AvgMean, AvgStdDev, AvgNumPoint,...
    'VariableNames',{'Mean','StandardDeviation','NumPoints'});

TableDataLambda = [lambdaTable; AddTableTotal; AddTableAvg];

save('TableLambda12_08.mat','TableDataLambda');
save('TableLambda12_08.csv','TableDataLambda');

%% Save all plots:

FolderName = 'C:\Users\Usuario\Desktop\TFG\CODES\CODE DATA
STORM\DATA\Sep2017storm\MULTIPATH\012\TXT FILES\IMAGES DAY8 HOUR12';
% Your destination folder
FigList = findobj(allchild(0), 'flat', 'Type', 'figure');
```

```
for iFig = 1:length(FigList)
  FigHandle = FigList(iFig);
  FigName   = num2str(get(FigHandle, 'Number'));
  set(0, 'CurrentFigure', FigHandle);
  savefig(fullfile(FolderName, [FigName '.fig']));
end
```

FUNCTION GIVE ME PLOT S4 MULTIPATH

```
function [ Files, Time, submatrix, lambda ] =
GiveMePlotS4Multipath( fileOne, fileSecond, TXTFiles )
%GiveMES4Multipath plots the PRN of S4, the ones above 0.4 and with
the
%same PRN. Also, applies the correction of the delay.
format long

%limits = [0 0.04];
C = ReadMetheTXT( fileOne );
C2 = ReadMetheTXT( fileSecond );

%% DELAY

cont=1;
acquisitiondelay = [];
contTXT = 1;
if ~isempty(C) && ~isempty(C2)
    for n=2:3:numel(C)
        for i=2:3:numel(C2)
            if(strcmp(C{n-1,1},C2{i-1,1})==1)
                if length(C2{i}) > length(C{n})
                    longC  = C2{i};
                    fileOneDate =
datenum(regexprep(fileSecond(12:24),'-',''),'yymmddHHMMSS');
                    timelongC = C2{i+1} + fileOneDate ;
                    shortC = C{n};
                    timeshortC = C{n+1};
                    shortFile = regexprep(fileOne,'_',' ');
                    longFile = regexprep(fileSecond,'_',' ');
                    namePRN = regexprep(C{n-1},'_',' ');
                    L = length(C2{i}); %length of the long dataset
                    D = L - length(C{n}); %length of the short dataset
                else
                    longC  = C{n};
                    fileOneDate = datenum(regexprep(fileOne(12:24),'-
',''),'yymmddHHMMSS');
                    timelongC = C{i+1} + fileOneDate ;
                    shortC = C2{i};
                    timeshortC = C2{i+1};
                    shortFile = regexprep(fileSecond,'_',' ');
                    longFile = regexprep(fileOne,'_',' ');
                    namePRN = regexprep(C{n-1},'_',' ');
                    L = length(C{n}); %length of the long dataset
                    D = L - length(C2{i});%length of the short dataset
                end
                %Filling the short dataset with NaNs and doing the
                %autocorrelation between the two functions to check
the
                %delay.
                for j=1:L
                    cc = abs([shortC; NaN(D, 1)] - circshift(longC, -
j));
                    corr(j) = sum( cc(~isnan(cc)) );
                end
        %       figure,plot(corr)
                timelong = timelongC*60*24;
                timeshort = timeshortC*60*24;
                timeshortCstr = datestr(timeshortC,'MMSS');
                timelongCstr = datestr(timelong, 'MMSS');
```

```
                %Finding the xvalue for the minimum of the corr and
                %shifting the long.
                [tmp, acquisitiondelay(cont)] = min(corr);
                longShifted = circshift(longC,-
(acquisitiondelay(cont)));


                % Plotting Multipath
                figure;
                subplot(2,1,1);
%                 t_temp = [ linspace(timelongC(1)-
( acquisitiondelay(cont)/24/60/60) , timelongC(1)-(1/60/60/24) ,
acquisitiondelay(cont))'; timelongC];
                shortCzeros = [ NaN(acquisitiondelay(cont),1); shortC];
                plot(shortCzeros);
                hold on
                longCzeros = [longC; NaN(acquisitiondelay(cont)-D,1)];
                plot(longCzeros);
                hold off
                grid on
%                 datetick('x',15)
%                 title('PRNs S4 Multipath');
                lgd = legend(shortFile, longFile);
                title(lgd,regexprep(C{n-1},'_',' '))
                xlim([1 length(longCzeros)])
                ylim([0 1])
                xlabel(['time (s) - ' datestr(timelongC(1),'mm
yy')],'FontSize',13)
                ylabel('Values of S4','FontSize',15);
                set(gca,'FontSize',20);

               vector = length(-(shortC - circshift(longC(1:L-D),-
(acquisitiondelay(cont)))));

               if (length(longCzeros)-length(shortCzeros) ~= 0)
                    NANdelay = length(longCzeros)-length(shortCzeros);
                    shortCzerosNAN = [shortCzeros; NaN(NANdelay,1)];
               else
                   shortCzerosNAN = shortCzeros;
               end

                %Plotting Scintilaltion
                subplot(2,1,2);
                % plot(timeshort(1:vector), -(shortC -
longShifted(1:L-D)));
                % plot([NaN(acquisitiondelay(cont),1); -(shortC-
longShifted(1:L-D))]);
                lambda{contTXT} = shortCzerosNAN-longCzeros;
                plot(-(shortCzerosNAN - longCzeros));
%                 title('Subtract of PRNs');
                lgd = legend('Lambda'); %Being Lambda the subtract of
PRNs

                title(lgd, regexprep(C{n-1},'_',' '))
                xlabel(['time (s) - ' datestr(timelongC(1),'dd mmm yy,
HH:MM')],'FontSize',13)
                ylabel('Lambda','FontSize',15);
                grid on
                ylim([-0.8 0.8])
                xlim([1 length(longCzeros)])
```

```
                set(gca,'FontSize',20);

                % Saving the data in matrix
                Files{contTXT} = [shortFile longFile namePRN];
                Time{contTXT} = timeshortC;
                submatrix{contTXT} =(-(shortCzerosNAN - longCzeros));
                lambda{contTXT} = shortCzerosNAN-longCzeros;
                contTXT = contTXT + 1;

               cont = cont+1;

            elseif (strcmp(C{n-1,1},C2{i-1,1})==0)
                acquisitiondelay(cont) = 0;
                Files{contTXT} = 0;
                Time{contTXT} = 0;
                submatrix{contTXT} = 0;
                lambda{contTXT} = 0;
                contTXT = contTXT + 1;
                cont = cont+1;
            end
        end
    end
else
    acquisitiondelay(cont) = 0;
    Files{contTXT} = 0;
    Time{contTXT} = 0;
    submatrix{contTXT} = 0;
    lambda{contTXT} = 0;
end

end
```

FUNCTION READ ME THE TXT

```
function [ Cnew ] = ReadMetheTXT( fileID )
% abrir archivo para leerlo
id=fopen(fileID,'r');
if id==-1
    error(sprintf('El archivo "%s" no pudo abrirse para
lectura.','nombre_archivo'));
end

% mientras no llegue al final del archivo seguirá leyendo
Lineas={ }; % cell array que contendrá las líneas
while ~feof(id)
    linea = fgetl(id); % lee toda la línea
    Lineas{end+1,1}=linea;
end

C = cell(numel(Lineas),1);
for i=1:3:numel(Lineas)
   C(i) = textscan(Lineas{i,1},'%q',...
'Delimiter',' ','EmptyValue',-Inf);
end
for i=2:3:numel(Lineas)
   C(i) = textscan(Lineas{i,1},'%f',...
'Delimiter',' ','EmptyValue',-Inf);
end
for i=3:3:numel(Lineas)
   C(i) = textscan(Lineas{i,1},'%f',...
'Delimiter',' ','EmptyValue',-Inf);
end

n=1;
value = {};
for i=2:3:numel(C)
    value{i}= find(C{i,1} > 0.4);
    if ~isempty(value{i})
        Cnew(n) = C(i-1);
        Cnew(n+1) = C(i);
        Cnew(n+2) = C(i+1);
        n = n + 3;
    end
end

Cnew = Cnew';
% for k=3:3:numel(Cnew)
%     Cnew{k,1} = Cnew{k,1};
% end


fclose(id); % cierra el archivo leído


end
```