Developing a GNSS data analysis tool to characterize the faulty event called Code-carrier incoherence

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The accuracy, availability and integrity of the Galileo system are of significant concern because of the intended benefits of this system in many applications in a near future, when the system will be fully operative. Thus, it is of critical importance that every satellite works and any potential error is minimized and bounded. This project analyzes the problem which a type of satellite failure, named code-carrier incoherence, generates and discusses how to overcome it with coherent multipath tracking, using the Galileo E1 frequency band as main frequency and the Galileo E5 frequency band as a secondary frequency. Then, variations with respect to the nominal Multipath receiver environment are detected and afterwards, data is combined to reduce the effect of measurements errors. For that, the antenna calibration has been performed, where the multipath mean computed as a function of elevation angle for a period of days. This work shows a way to effectively use Multipath and its standard deviation that avoids cycle slips and obtains well determined archs without phase ambiguities as a result. A tool is developed in C++ to compute a code-carrier coherence (CCC) value and a Gaussian error propagation of ccc. Finally, a CCC threshold value is established and when the CCC value overpasses it, the code carrier incoherence is detected. Details about the current and future status of Galileo, its data use in receiver stations and in the GPS Tool Kit, the multipath estimation algorithm for Galileo measurements are also noted to provide context for future improvements of this developed tool.

Code-Carrier Coherence | Multipath | Galileo

Introduction

In the navigation field there are many different sources of errors as satellite geometry, satellite orbits, multipath effect, atmospheric effects, clock inaccuracies and rounding errors. Some of them can alter the accuracy, availability, continuity or even the integrity. These feared events have been studied in static receivers to create models to avoid them in future events. They are cycle slips, multipath and code-carrier incoherence.

In the case of the cycle slip, one should know that it is a discontinuity in a receiver's continuous phase lock on a satellite's signal. Up to now, this project will focus in multipath and mainly in code-carrier incoherence.[1]
Multipath interference occurs when the user device receives reflected signals in addition to the direct line of sight (LOS) signal. These interference signals are generally reflected from the ground, buildings or trees in terrestrial navigation, while signal reflections from the host-vehicle body are more common in airborne and marine applications. [2]

Multipath signals are generally considered undesirable in the Global Navigation Satellite Service (GNSS) field because they destroy the correlation function shape used for time delay estimation, but can be useful in some cases e.g. for acquisition. Although some wireless communications techniques exploit multipath to provide signal diversity, the key point in GNSS is to efficiently mitigate the multipath effect because only the LOS signal is used for getting the satellite-receiver transit time offset for positioning. [2]

For a better understanding of what code-carrier incoherence event is, it is preferable to explain first, what the code-carrier coherence is. The code-carrier coherence reflects the coherence between the code phase and the carrier phase and plays a significant role in such applications as carrier phase ranging, carrier phase smoothed pseudorange, etc. For satellite navigation systems, guaranteed code-carrier phase coherence of the satellite transmitted signals is not only the premise of its ranging function, but also one of the main factors affecting the positioning accuracy of satellite navigation signals. By signal coherence, it is referred to the relationship between code phase and carrier phase, and by phase coherence, it is referred to stable relationship between the phases, i.e., the constant same phases or different phases. Code carrier incoherence introduces an additional time varying bias between the code and carrier observables, which will degrade the positioning accuracy when using code and phase data together. The main factors causing the failure in the code-carrier coherence are:

1. Failure in the satellite. Incoherence between the code emitted by the satellite and the carrier;
2. Ionosphere or error of the propagation path;
3. Anomalies of the code loop or carrier loop inside the receiver and other factors.

Accordingly, several receivers are employed to observe at the same time, therefore as to eliminate the measurement errors caused by the anomalies of the internal code loop or the carrier loop of the receivers through mutual calibration. The short relative distance difference between the two time points has excluded the non-instantaneous changes in the path and the instantaneous changes in the ionosphere. Finally, the code-carrier incoherence is mainly caused by the delay jitter of satellite signals. [3]

Material and Methods

The tool developed in this project is oriented to the Galileo satellite navigation system, thus, it is important having a deep knowledge of what Galileo offers to the world and taking a look of how its internal structure is formed.

The Galileo satellite navigation system will provide five different services: Open Service (OS), Commercial Service (CS), Safety of Life (SoL), Public Regulated Service (PRS), and Search and rescue (SAR). Each service has its application and focuses to a different public. OS is the most popular GNSS service, it is free of charge and it is not encrypted. It will have world-wide coverage and it is optimized for mass market applications. The OS is provided on three different frequencies (E1, E5a and E5b). In the Figure 1 it is shown the all the frequencies and also which type of service is provided within each frequency band. Because it is the most widely used, only the frequency bands available for the open service are chosen.

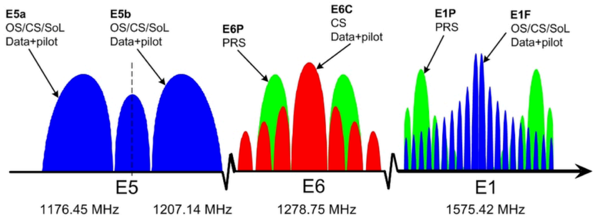

Figure 1: Galileo Frequency Spectrum [4]

GPSTK. The GPS Toolkit (GPSTK), developed to support GPS applications, is an open source library and suite of applications to the satellite navigation community, to researchers to focus on research and not lower level coding.
The GPSTk suite consists of a core library, auxiliary libraries, and a set of applications. Since its first release the GNSS world is evolving into a multi-constellation system: GLONASS has been revived, Galileo is a reality, the Chinese have launched Beidou, the Japanese QZSS, and GPS has slowly been adding the more types of signals to the existing constellation. None of these new systems or signals were operational at the time of the GPSTk's first release, when it was aimed at handling only GPS L1 and L2 signals. [5, 6, 7]

IGS. The International GNSS Service (IGS) global tracking network of more than 300 permanent, continuously-operating GNSS stations provides a rich data set to the IGS Analysis Centers, which formulate precise products such as satellite ephemerides and clock solutions. IGS Data Centers freely provide all IGS data and products for the benefit of any investigator.

Perhaps the most important prerequisite for a successful service and the ease of utilization of IGS products is the standardization of data and product formats. IGS has adopted and developed a number of standard formats. The formats used in this project: Receiver Independent Exchange Format (RINEX) and Standard Product 3 format (SP3) undergo regular revisions to accommodate receiver/satellite upgrades, or multi-technique solutions, respectively. [8]
Most geodetic processing software for GNSS data use a well-defined set of observables:

- The carrier-phase measurement at one or both carriers (actually being a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency);
- The code measurement (Pseudorange PR), equivalent to the difference of the time of reception (expressed in the time frame of the receiver) and the time of transmission (expressed in the time frame of the satellite) of a distinct satellite signal.

  $$PR = range + (rec\ clock\ offset - sat\ clock\ offset) * c \quad [1]$$

  where c is the light velocity;
- The observation time being the reading of the receiver clock at the instant of validity of the carrier-phase and/or the code measurements. Usually the software assumes that the observation time is valid for both the phase and the code measurements, and for all satellites observed.

Consequently all these programmes do not need most of the information that is usually stored by the receivers: They need phase, code, and time in the above mentioned definitions, and some station-related information like station name, antenna height, etc.
For the development of this project, has been mandatory, check several times if different type of RINEX files have or not the appropriate data. In this case, the required data is from the Galileo system. Two steps are important to follow to check if a RINEX file has or not Galileo data:

- First, the RINEX observable file has to have the type system as mixed or Galileo. It appears in the RINEX header as the letter M for Mixed and E for Galileo. Not only that, then one has to check if the data type need is in the list of keys;
- Second, this can seem not necessary but nowadays, most of the files are provide with capability to have Galileo data, even they say in the headers that they have that data, but sadly, at the end there is no data with that information in the body. For that, it is important to check if really there is any satellite in the body providing the proper data.

The Standard Product 3 format (SP3) has the main purpose of exchanging satellite related data (orbit and clock information). The basic format of an SP3 file is a header, following by a series of records containing the position and clock records for each satellite listed in the header. A second, optional, record contains the satellite velocity and clock correction rate-of-change.

One can find deeper information of the format and how it is composed in the NASA web page. As it is said about the problem of finding Galileo data in the RINEX observable files, there is a similar problem in the SP3 files. Some files have Galileo keys in the satellite list in the header, but then there is no data about Galileo satellites in the body.

Receiver stations. For developing this project, it is required to find receiver stations with some special features:

- Every chosen station has to be located close to the others. There is no a specific numerical limit but they should have the same satellites in view at the same time
- Every station has to be configured to manage Galileo data and to add it to their RINEX observable files.
- That data, stored in RINEX version 3 files, have to be uploaded online, if not it is not available and testable for everybody.

With the mentioned above features, It is found five receiver stations in the GPS/GNSS FTP Server Layout provided by UNAVCO from its main webpage. Then, one can search mostly every receiver position in the National Oceanic and Admospheric Administration main webpage. There is deeper information about every available receiver station. Clicking in each one, it is possible to access to photographs, site log, even data files as RINEX.

Five stations are selected to developing the tool. In Figure 2 one can see the position of this stations in a fragment of the world map.

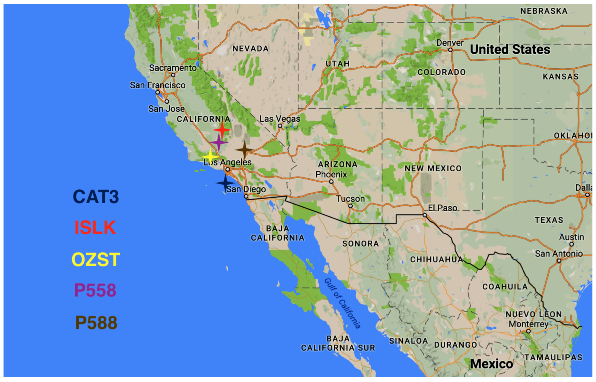

Figure 2: Map of the stations used in this project

Multipath. Combining the equations of the observables of carrier phase and code measurements, allows to avoid terms as the ionospheric and geometric terms [11]. Then, it is possible to focus on the main terms of this project.
The pseudorange measurements can be modeled as:

$$P_i = s + I_i + e_{MPi} \qquad [2]$$

$$P_j = s + I_j + e_{MPj} \qquad [3]$$

Where the P represents any GNSS code measurement, s is the term which includes the geometric ranges and the difference of clock offsets, I is the term due to the ionospheric delay and e_{MPi} represents the effect of multipath and noise in the code measurement. And the carrier phase measurement is represented as:

$$\Phi_i = s - I_i + A_i + \epsilon_{MPi} \qquad [4]$$

Where Φ_i is the measured carrier phase, A is the ambiguity term and ϵ_{MP} represents the carrier phase multipath and noise. Differencing P_i and Φ_i to find MP_i, where $MP_i = e_{MPi} - \epsilon_{MPi}$.

$$P_i - \Phi_i = 2I_i - A_i + MP_i \qquad [5]$$

$$MP_i - A_i = P_i - \Phi_i - 2I_i \qquad [6]$$

The following steps are required to avoid the ionospheric term Differencing Φ_i and Φ_j to solve for I_i:

$$\Phi_i - \Phi_j = Ij - Ii + A_i - A_j \qquad [7]$$

The Equations 5 and 7 are geometric-free combinations because the s term is removed with the geometric range inside. The ionospheric delay is proportional to the Ionospheric Electron Content (IEC) and depends on the signal wavelength.

$$I_i = \frac{A}{f_i^2} IEC, I_j = \frac{A}{f_j^2} IEC \qquad [8]$$

$$\frac{I_j}{I_i} = \frac{f_i^2}{f_j^2} = \alpha \qquad [9]$$

With the constant $A = 40.3 m^3 s^{-2}$.
Substituting $I_j = \alpha I_i$ into Equation 7:

$$\Phi_i - \Phi_j = I_i(\alpha - 1) + A_i - A_j \qquad [10]$$

$$I_i = \frac{\Phi_i - \Phi_j + A_j - A_i}{\alpha - 1} \qquad [11]$$

Where I_i is a function of the carrier phases, the ambiguities and the frequencies. As one can see above, the multipath can be obtain as a function of the other terms of the Equation 6, and as the ionospheric effect is not interesting in this project, this can be removed. Substituting 11 into 6:

$$MP_1 - \left\langle \frac{2}{\alpha - 1}(Aj - Ai) + A_i \right\rangle = P_i - \Phi_i - \frac{2}{\alpha - 1}(\Phi_i - \Phi_j) \qquad [12]$$

After processing MP_i for having a zero mean over elevation, the constant term in each arc $\frac{2}{\alpha-1}(Aj - Ai) + A_i$ can be removed by finding the average over a given orbital arc and then subtracted from the calculated MP_i for each epoch.

$$MP_i = P_i - \Phi_i - \frac{2}{\alpha - 1}(\Phi_i - \Phi_j) \qquad [13]$$

Where MP_i is the estimation of the code multipath error on a pseudorange P_i, while Φ_i and Φ_j are the carrier phase observables (in units of length) for a α which depends on the frequencies f_i and f_j. j represents any band which is different than i. With multi-frequency Galileo signals, several values of j are possible, but the particular selection of j does not significantly affect the results. [10, 11, 9]

Multipath Template Technique. The multipath effect on GNSS measurements depends on the physical environment and the receiver-satellite geometry. As the Galileo satellites are in nearly circular orbits at an approximate altitude of 23,222 km, they will again be over the same position on the earth's surface at the end of 10 sidereal day (approximately 23 hrs 56 mins in length). Thus the viewing geometry is the same each 10 days with respect to solar day, but with a shift of about four minutes per day. When the physical environment remains unchanged from day to day, then the multipath disturbance will be almost constant every 10 days.
This point is interesting from the point of view of forecasting and seeking anomalies. From the model based on several days of multipath measurements, the multipath values and curve shape should be similar, as it shown in [13].

Antenna Calibration. The linear combination of observable equations already shown eliminates the range, clocks, troposphere and the ionosphere delays from the observations. What remains (Equation 13) is a combination of code and carrier phase multipath, carrier phase ambiguities, noise, and finally, code and carrier antenna effects. The carrier multipath, noise, and antenna effects are much smaller than the corresponding effects for code, thus we can disregard the carrier multipath and noise. The presence of the carrier phase ambiguities means that it is not possible to perform an absolute calibration of the antenna effects. To eliminate this ambiguity it is used the variation of the multipath observable with elevation to retrieve the multipath measured for a specific angle. Thus, for observables in the same arc, it is computed:

$$dMP_{cx} = MP_{cx}(\varphi - \Delta\varphi) - MP_{cx} \qquad [14]$$

Where φ is the elevation angle and MP_{cx} is the multipath for a type of data called "cx" (e.g. c1 for L1 frequency or c5 for E5 frequency).
This removes the constant terms from the multipath combination, namely the ambiguities. Taking this into account, it is possible to define an approximate derivative with relation to the elevation angle as:

$$\frac{dMP_{cx}}{d\varphi} = \frac{MP_{cx}(\varphi + \Delta\varphi) - MP_{cx}(\varphi)}{\Delta\varphi} \qquad [15]$$

The derivative multipath data with the elevation angle can be binned into elevation bins. Every bin has the same width $\delta\varphi$, and it is centered on the a discrete set of angles, referred as φ_i. Moreover, the derivative will be modeled as a constant value on each bin. Averaging all the observations in the same nadir angle bin over time will reduce the effect of noise, and will provide a better estimate of the derivative of the Antenna Calibration for each nadir angle:

$$\frac{dAnt}{d\varphi}(\varphi_i) = \sum_{\varphi \in \varphi_i \pm \delta\varphi_{bin}} \frac{dMP_x(\varphi)}{d\varphi} \qquad [16]$$

Where N is the number of observations with nadir elevation angle.

After this step, we are left with a quantity that should have very little noise, but it is merely the rate of change with respect to the elevation angle. Integrating this we find the antenna effect for a given angle, affected by a constant value:

$$Ant(\varphi) = \int_{\varphi_{min}}^{\varphi} \frac{dAnt}{d\varphi}(\delta) d\delta + K \qquad [17]$$

The constant K is determined by an adequate boundary condition. It it considered a zero mean boundary condition, defined as:

$$\langle Ant(\varphi) \rangle = \frac{1}{\varphi - \varphi_{min}} \int_{\varphi_{min}}^{\varphi} \frac{dAnt}{d\varphi}(\delta) d\delta = 0 \qquad [18]$$

This means that the integration constant is defined as:

$$K = -\frac{1}{\varphi - \varphi_{min}} \int_{\varphi_{min}}^{\varphi} \frac{dAnt}{d\varphi}(\delta) d\delta \qquad [19]$$

Finally, note that because of dealing with bins, the above expressions are replaced by discrete sums. The Antenna bias at the bin j is given by:

$$Ant(j) == \sum_{i=i}^{j=1} \left(\left. \frac{dAnt}{d\varphi} \right|_i \Delta\varphi \right) + \left. \frac{dAnt}{d\varphi} \right|_j \frac{\Delta\varphi}{2} + K \qquad [20]$$

$$K = \frac{1}{N_{bins}} \sum_{j=1}^{N_{bins}} \left[\sum_{i=i}^{j=1} \left(\left. \frac{dAnt}{d\varphi} \right|_i \Delta\varphi \right) + \left. \frac{dAnt}{d\varphi} \right|_j \frac{\Delta\varphi}{2} \right] \qquad [21]$$

Code carrier coherence. Until this point, Multipath has been computing to track coherence, variations with respect to the nominal Multipath receiver environment has been detected and, at the end, data is combined from various receivers to reduce the effect of measurements errors. Now, all of mentioned above is joined to compute if there is any distortion in the data results.

Detection of this distortion is made difficult due to the fact that the ranging error caused by such distortion is dependent on the spread spectrum receiver discriminator type, correlator sparcing, and bandwidth. The importance of avoid it is because it is a threat to the integrity of the whole system.

$$ccc^i = \frac{\sum_j \left[\mu_j^i/(\sigma_j^i)^2\right]}{\sum_j \left[1/(\sigma_j^i)^2\right]} \qquad [22]$$

where μ_j^i is the multipath deviation for reference receiver j and SV i , and σ_j^i is the multipath error Standard Deviation for reference receiver j and SV i. A satellite failure is declared when the code-carrier coherence test statistic, ccc^i, exceeds a threshold. [12]

Gaussian error propagation for Code-Carrier Coherence. To compute the error propagation for CCC, variables of the CCC function have to have their own and independent Standard Deviation and they have to be the mean of Gaussian functions. Applying this procedure for CCC it is relatively simple, because in the Equation 22 CCC depends only on μ_j^i and its Standard Deviation.[14]

Since the individual leveled Multipath mean is zero, the mean CCC will be zero. As for the error, the variance is:

$$(\sigma_{ccc}^i)^2 = \sum_j \left(\frac{1}{\sum_k \frac{1}{(\sigma_k^i)^2}} \right)^2 \frac{(\sigma_j^i)^2}{(\sigma_j^i)^4} \qquad [23]$$

Simplifying, the variance deviation for the CCC becomes simply:

$$(\sigma_{ccc}^i)^2 = \frac{1}{\sum_j \frac{1}{(\sigma_j^i)^2}} \qquad [24]$$

If every receiver station have the same noise, the global variance would be the Standard Deviation divided by the number of satellites. In this project 5 satellites are used to compute ccc.

$$(\sigma_{ccc}^i)^2 \approx \frac{(\sigma^i)^2}{N} \qquad [25]$$

Tool explanation. First of all, it is important to make clear what is necessary for developing the tool.

- GPSTK is a dynamic library used as a support for managing GNSS data. It has many adventadges, because it has several classes to manage RINEX, use GNSS structures, etc. but it also has some limitations;
- The main objective, as it is said before is to compute the ccc. In that formula (Equation 22) first, the multipath and the Standard Deviation must be calculated;
- The multipath is calculated as it is explain in the procedure above. For that it is required the code and phase from Galileo system. The code is required in 1 band and the phase is required in 2 bands. In this project the Multipath is computed as function of elevation angle;
- The code and phase are collected from RINEX observable files. These RINEX observable files must have the convenient data. Not all the RINEX file versions can take Galileo data;
- For getting the RINEX observable files, one can find them in some FTP servers;
- The elevation angle is obtained from the data of the antenna position and the satellite position. The antenna position is obtained from the RINEX header and the satellite position from the SP3 files;
- The SP3 are obtain from FTP servers, these files have to have the appropriate data. They have to have the Galileo ephemeris;
- The Standard Deviation is computed from the Antenna Calibration and the leveled multipath data;
- Avoid cycle slips. They can provide wrong measurements of data (phase measurements) and the following error in the multipath estimation.

GPS Toolkit limitations. Most of the limitations found for using GPSTK are due to the fact that the tool is oriented to the Galileo System. This System is no completely operative, and many of the classes and functions of GPSTK are created to work with GPS (L1 and L2 bands). Thus, working with Galileo system and its bands may have limitations as it is shown further on.

Avoiding Cycle slip. First, it is mandatory to avoid cycle slip for computing multipath and the Antenna Calibration. In the Antenna Calibration procedure, the input is the derivative of multipath along elevation. Avoiding cycle slip is important here because that derivative in those points are extremely high due to the cycle slip.
To calculate that, there is a performed class which works for Galileo frequency bands. It is used a algorithm in GPSTK which will compute the bias between code and phase, and will compare it with a mean bias that is computed on the fly. If the current bias exceeds a given threshold, then a cycle slip is declared. Then, if a cycle slip is declared, then that epoch is considered invalid, and there is a gap in the elevation data. When there that gap appears, the arc is closed and the new data is added for the following arch.

Computing Antenna Calibration. The Antenna Calibration is what is called the mean multipath for a specific receiver station along a concrete number of days.

The GPSTK library let one work reading the observable file epoch by epoch and and adding the relevant data and avoiding every type of damaged or incorrect information to a data structure called gnssRINEX. What it is required to get this, it is specify the typeid (kind of data required), then a loop is developed for every present satellite in the available Galileo satellite list. For each satellite, the tool to compute the linear combination of equations and cycle slips is declared and defined. After that, the codes and phases are obtained and the Multipath computed. At the same time the elevation angle is calculated as the elevation angle from the antenna position and the satellite position. For representing plots for multpaths depending on elevation, the elevation was binned into integer numbers. As a result, the elevation angle is a discrete variable and thus, multipath values are represented against a range of numbers from 0 to 90 where there are only elevation integer values. To have a Multipath value for each elevation angle for every arc, while the satellite is in the range of the same whole elevation angle number, the mean of multipath is computed.

Computing Code-Carrier Coherence. To compute the CCC value, it is used the Equation 22. For accomplish that, the measured leveled multipath is used in place of μ_j^i , and the Standard Deviation of leveled Multipath as a function of elevation in place of σ_i:

$$ccc^i = \frac{\sum_j \left[\mu_j^i/(\sigma_j^i)^2\right]}{\sum_j \left[1/(\sigma_j^i)^2\right]}$$

Where:

- μ_j^i is the leveled multipath observed between station j and satellite i;
- σ_j^i is the calibrated Standard Deviation for the elevation corresponding to the observation μ_j^i ;
- ccc^i is the code carrier coherence metric for the satellite i.

The computed mean Multipath identifies any systematic effects in the data. That the Multipath is close to zero indicates that the systematic effect is mostly zero, which is to be expected given the requirements on IGS stations to have good quality.To compute the leveled Multipath is mandatory to compute, first, the Biased Multipath and then, the Mean Multipath

- To compute Biased Multipath: for each epoch in the pass, it is computed the Multipath linear combination for each frequency. This is called also raw Multipath;
- To compute Mean Multipath per pass for each frequency: For each pass and frequency the mean Multipath over the full pass is computed as:

$$\overline{MP} = \frac{\sum_t MP^i_{j,f}(t)}{N^i_{j,f}} \qquad \mathbf{[26]}$$

  Here N is the number of observations for the pass where f means that belongs to the same pass;
- Finally, to compute leveled Multipath: For each epoch, subtract $\overline{MP}$ from the MP at that epoch:

$$\mu_j^i(t) = MP_j^i(t) - \overline{MP} \qquad \mathbf{[27]}$$

For each epoch it is important to compute also the elevation, thus, from the leveled Multipath and elevation it is possible to organize the data in terms of leveled Multipath as a function of elevation.
This procedure provides the Multipath observable per pass.

Code-Carrier Coherence threshold. After computing the leveled Multipath and its deviation from the Antenna Calibration Multipath, every variable from the right part of the CCC equation (Equation 22) is know. Then, it is possible to compute CCC.

The CCC should be a function along time with zero mean and with shape of noise. Its Standard Deviation is computed through the procedure called Gaussian error propagation explained before. The value of the threshold depends on how safety the system is required, the safer the more false alarms are. If the threshold value is considered higher, the system would last longer to detect this feared event but there would be fewer false alarms. If the threshold is establish lower, it would happen the opposite.

To establish a criteria of what threshold is appropriate, a probability of having 95% of good data is chosen but using the worst case standard deviation, which means there is a much smaller probability than 5% of having a CCC value which overpass the threshold because most of the data will not have the highest Standard Deviation, they will have a lower one. If the Standard Deviation is lower, as it said above the probability of overpassing the threshold is lower than 5. [15]

$$PR(\mu - 2\sigma \leq X \leq \mu + 2\sigma) \approx 0.9545 \qquad \mathbf{[28]}$$

Where μ is the mean, σ is the Standard Deviation and X is an observation from a normally distributed random variable. Applying to this work, X is the ccc value, μ is the mean of CCC, which should be zero, and σ is the most extreme Standard Deviation of CCC obtained along the time.
The Equation 28 shows that the CCC threshold is $\mu \pm 2\sigma$.

Data Results

After computing Multipath for every epoch during a day, the Multipath results are a big amount of data with an elevation distance between two consecutive points of 0.03 degrees approx. and several points to choose to identify a precise Multipath to each elevation angle integer number. In the Figure 3 an example for the station OZST is shown.

As one can appreciate from the Figure 3 the Multipath values normally are noise and seem more or less constant with the elevation, also there is a jump in the satellite of the color purple, and the most remarkable feature is that the data lines are separated one from the other.
The cycle slip is taken into account for doing the program and it is avoidable using the appropriate algorithm, this is used

and works properly for getting further results. The separation between the curves is due to the term called ambiguity. This ambiguity term is a constant number for each arc but is different for different archs. Because of that reason, it is necessary to compute all the results shown later.

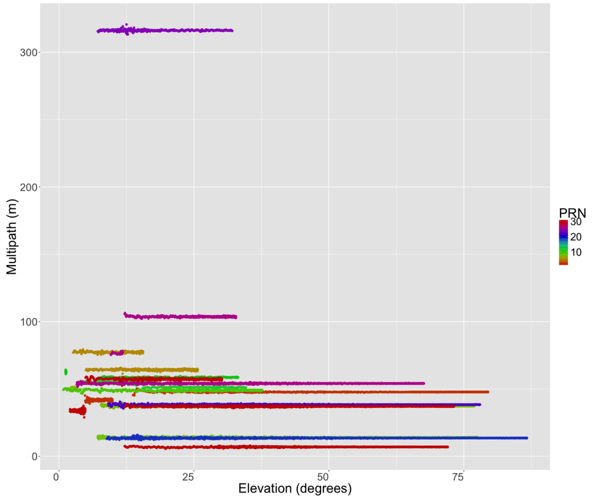

Figure 3: Continuous Multipath function of elevation

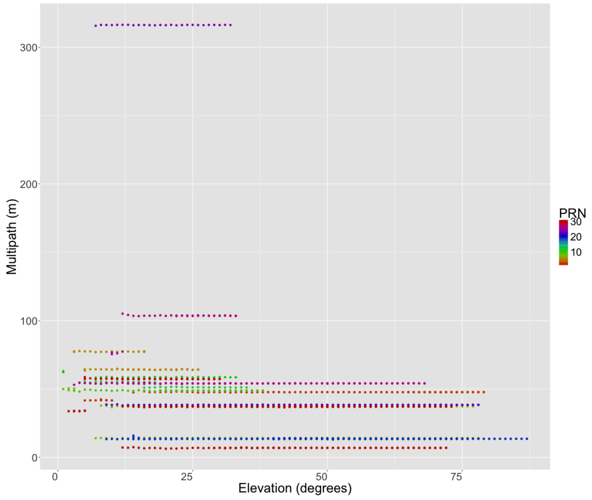

Figure 4: Discrete Multipath function of elevation

Antenna Calibration. To compute the discrete Multipath, it was chosen an elevation bin of 1 degree of elevation angle. Then, from the Figure 3, for every Multipath consecutive point which share the elevation angles, are collected to compute a discrete Multipath point. e.g. Every consecutive Multipath from the continuous function wich has an elevation value from 15.5 to 16.49 are collected to compute the mean and obtaining the discrete Multipath point for the elevation angle of 16.

As a result, the curves shown in Figure 4 are shown cleaner, and one can work with them to compute derivatives and treat them as discrete functions.

After computing the discrete Multipath, the derivative Multipath is calculated of each arc between consecutive points. Then, the mean is performed to have the derivative Antenna Calibration with elevation as a function of elevation.

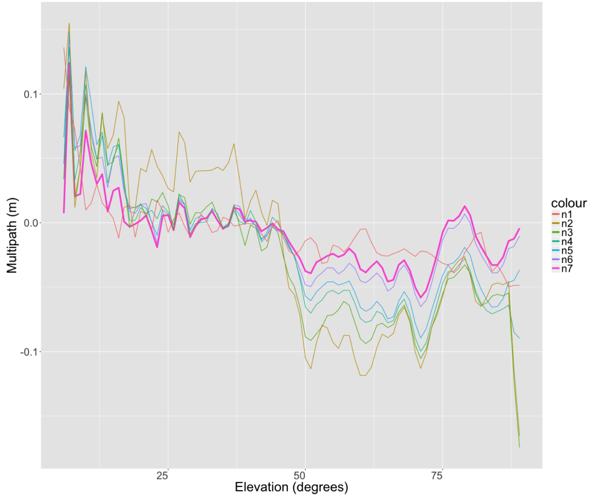

Figure 5: Multipath computed by Antenna Calibration from one to seven days, fuction of elevation.

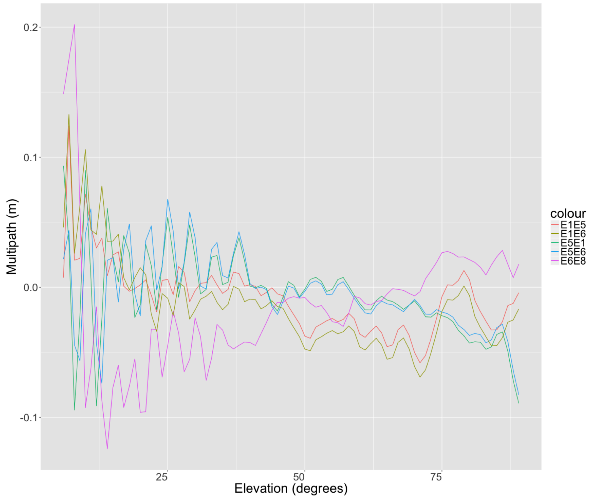

Figure 6: Multipath computed by Antenna Calibration for a different combinations of bands, fuction of elevation.

As final results for the Antenna Calibrations, some analysis are done. The previous Multipath results are done for a single day. That analysis can be done for as many days as is required. First, the Figure 5 shows the quantity of days used to compute the Antenna Calibration. One can check the fact that increasing the number of days, the functions tend to converge, for that it is used 7 days as an appropriate number of days, because it is enough to have good results. More days would increase the computational cost and would not provide more accurate results.

For one and two days, the values depends highly one what features of those days could change a little bit the Multipath values. More than 3 days provide repetitive results wich can be extrapolated to other dates.

Results for both Figure 5 and Figure 6 are got using the Galileo frequency band E1 (1575.4 MHz) for the main frequency (Then, the Multipath is called E1 Multipath) and E5 (1176.45 MHz) as the second frequency band for the day 85 of 2017.

In the Figure 6 it is shown the results of the Antenna Calibration for the receiver station called OZST. Here, it is shown a comparison of the Antenna Calibration using different combination of frequency bands.

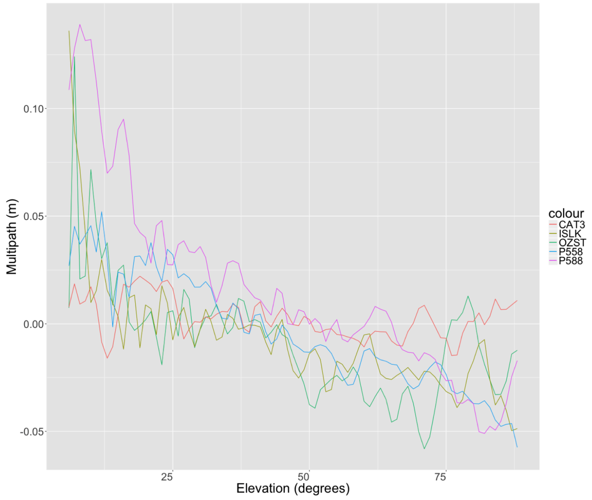

Figure 7: Multipath computed by Antenna Calibration for every station for seven days and for the band E1E5, fuction of elevation.

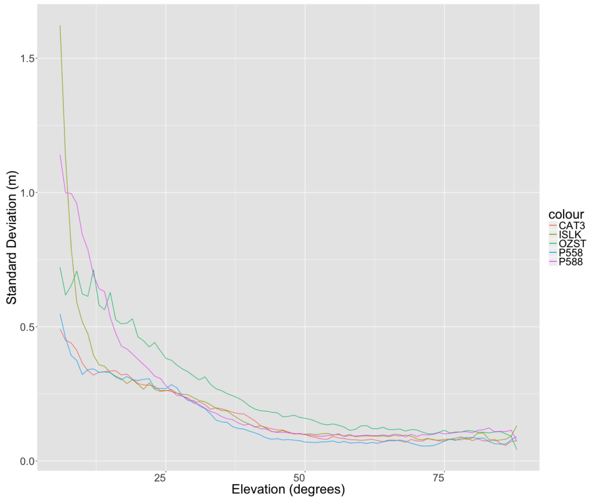

Figure 8: Standard Deviation computed by Antenna Calibration for every station for seven days and for the band E1E5, function of elevation.

As one can see, the Multipath is lower for E1- E5 and E1- E6, but it is also low for E5a as main frequency. In this project E1- E5 combination is chosen to compute the code-carrier coherence.

The reason of this choice is the effect of removing the ionosphere stronger when the carrier frequencies are further away. Moreover, it is the linear combinations that is more widely used.

The Figure 7 shows the results of the Antenna Calibration for different receiver stations. As one can see, the Antenna Calibration is a zero mean function, which has the property of having the sum of all Multipath values the result of zero.

Standard Deviation of the Antenna Calibration. This Standard Deviation is the deviation of the Multipath values during a week from the Antenna Calibration . Where the elevation is binned in whole numbers of elevation angles.

In the Figure 8 it is shown the standard deviation computed for the Antenna Calibration obtained in Figure 7. Despite of having very close curves for the Antenna Calibration, there are bigger differences in the standard deviation curves. The shapes of them are very similar but for lower elevation angles they are quiet different. At lower elevation, the terrain could be different and as it is considered the azimuth angle, could be a mountain in one side of the receiver station or other geographic feature on a single point.

Leveled Multipath. The leveled Multipath is obtained from the Equation 27. For the following plots the E1-E5 frequency band combination is used and it is shown the results of using the five receiver station mentioned above. Then, from the the RINEX observable files of the day 92 of the year 2017 and from the SP3 files from the day 0 and 1 of the week 1943,the Figure 9 shows the leveled Multipath for every satellite.

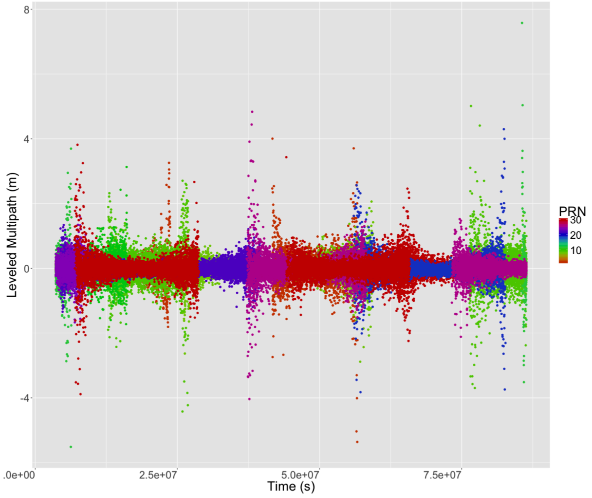

Figure 9: Leveled Multipath computed fuction of elevation for the day 92 of 2017 for every available satellite.

The Antenna Calibration is done for the days from 85 to 91. The research have been done to the days 92, 106 and 151 to compare the performance of using the Antenna Calibration for a test done 1 day later (day 92), 1 week later (day 106) and some months later (day 151).

CCC. This section provides the representation of the Equation 22.

The Figure 10 shows the code carrier coherence of every available station in the day 92 of 2017, using the Leveled Multipath represented in the Figure 9 and the standard deviation between this Multipath and the Antenna Calibration shown for every station in the Figure 7.

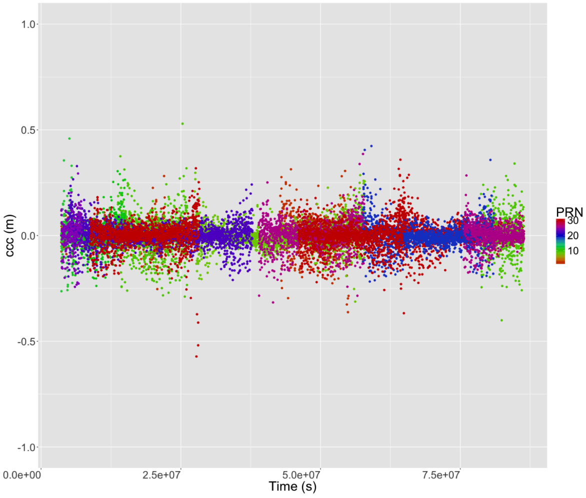

Figure 10: Code carrier coherence for the day 92.

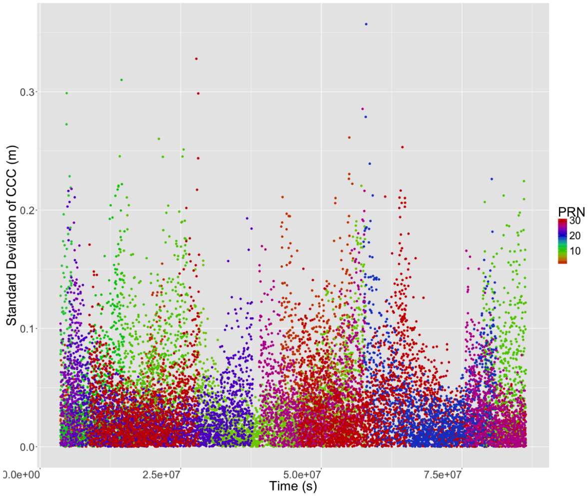

Figure 11: Standard deviation of CCC for day 92.

The Figure 10 shows CCC with a maximum value of 0.53 and a minimum of -0.57.

As one can appreciate, the values at the beginning and at the end of each pass are more scattered than at higher elevations. The satellite at the beginning of the pass raises from the horizon (because it is fixed an elevation mask of 5, the lowest elevation is supposed to be 5 degrees) and increases its elevation up to a maximum and then go down until it disappears again into the horizon (or 5 degrees).

Standard Deviation for Code-Carrier Coherence. To know how is evolving the code carrier coherence, it has been developed a Gaussian error propagation method. Now, this Gaussian error propagation is shown as the standard deviation of CCC. Again, the results are obtained for the days 92, 106 and 151, for frequency band combination of E1-E5 and with the use of 5 receiver station.

To establish a threshold of a flag for knowing when a carrier code incoherence is happening, this plots can help to appreciate how big the values can be and if the Antenna Calibration of the week from the day 85 to the day 92 worths for the day just after that week, the day of the week later and some day after some months.

The Figure 11 shows the standard deviation of CCC of the Figure 10. To have it clear the day 92 is the day just after the week used for computing the Antenna Calibration.

There are only three values shown in the Figure 11 overpass the value of 0.3.

Code-Carrier Coherence Threshold. After collecting the Leveled Multipath data, CCC data and CCC standard deviation data, it is possible to sum up some results:

- There are higher values of standard deviation of Multipath at lower elevation where the dispersion at the beginning and at the end of the pass are higher;
- Leveled Multipath plots show most of the values near zero;
- CCC is close to zero and with extreme values of around 0.53 as maximum and -0.57 as minimum;
- Standard Deviation of Multipath is close to zero;
- Only a few points of the Standard Deviation of Multipath are higher than 0.3 and have never been higher than 0.4.

Because the maximum Standard Deviation of CCC is around 0.3, this is considered the most extreme Standard Deviation for the procedure of computing the threshold. The threshold for CCC is:

$$\Theta_{ccc} = \overline{CCC} \pm 2\sigma_{ccc} \qquad [29]$$

Where Θ_{ccc} is the CCC threshold, $\overline{CCC}$ is the CCC mean and σ_{ccc} is the Standard Deviation for CCC. The mean can be considered zero as it shown in Figure 10. Then, the threshold depends only in the extreme value of Standard Deviation which is considered 0.3

$$\Theta_{ccc} = \pm 2\sigma_{ccc} = \pm 0.6 \qquad [30]$$

Discussion

As a result of this project, the seeking of detecting the failure of a satellite because of code carrier incoherence has been concluded successfully.

During the project, Galileo data has been deeply searched, analyzed, rejected and finally used carefully. The main problems of using Galileo RINEX and SP3 files are based on the lack of completion of the Galileo system and the inviability of the systems in general and the receiver stations in particular to hold this "recent" data. On the other hand, although the system requirements are covered to hold Galileo data, the benefits of using a underdeveloped GNSS may be for them not interesting at all. It depends on a balance of adventadges and disadvantages. One of the main disadvantages is adjust a global format as RINEX or SP3 from a specific receiver station to hold Galileo data for just obtaining the data from a few satellites.

As the Galileo system is underdeveloped, new satellites become available continuously. Although they can be operative, their data broadcast could be not good enough for the filters imposed to compute the CCC value. From the day 92 to the day 151 the number of satellites has increased in three, having 14 for the days 92 and 106 and 17 for the day 151. Fortunately the number of satellites will increase until having the Galileo constellation fully operative. Nicole, Zofia and Alexandre will be launch in the year 2017. [1]

As one of the main features of the project, Multipath has been computed along the project many times. That is because it appears in the main equation, Equation 22, as the mean of Multipath values, as standard deviation, and even as a result of the antenna calibration. For that, before knowing if the code-carrier coherence results have been properly computed, it is interesting, test multipath results first.

There is a big difference between the leveled Multipath, the biased or raw Multipath and the discrete Multipath. While the raw Multipath shows the Multipath for a not binned elevation angles and the values are got with ambiguity, leveled Multipath is binned and has no ambiguity because the mean has been removed and although discrete Multipath has included the ambiguity term, it is binned.

The results obtained from Antenna Calibration Multipath values are lower than 0.2 meters from the mean, which is in coherence with [16] and with [17] because they show similar multipath results.

On the other hand, the Multipath data used to compute the Antenna Calibration shows a Standard Deviation lower than 2 meters as it is shown in the Figure 8 can be compared with [18] Their Standard Deviation for Multipath L1 is lower than 1.6 meters. In both cases, there are higher values of Multipath Standard Deviation at lower elevation, as it is shown before where the dispersion at the beginning and at the end of the pass is higher. In this project, E1 has been used, which is the same frequency band as L1.

The test to compute the ccc values is done for three different days. The first one is the day after the week chosen to compute the antenna calibration, the second is the day just after a week after the antenna calibration and the third is some day after three several months. All of them show quiet similar results, for that, if there are no any appreciable physical change in the terrain nor in the own receiver station the same Antenna Calibration can be used for longer time than some days or a week as long as it is safe to trust that there are no changes in the above mentioned.

As the CCC is a value with a near zero mean and great dispersion at low elevation angles, it is used an error propagation to measure how to detect whenever the values go away from the normal environment. In that case, it is said that a code-carrier incoherence exists. To know that, it is a good idea to establish a threshold to know if a value, or a group of them overpass it, and turn on a flag to alert the dependent authority. As it is shown in [12] the aim is to establish a threshold which depends on the user differential range error values that are broadcast by each satellite.

This threshold value have to be computed for every new work which uses different receiver stations and satellites and times. Indeed the threshold value depends on the number of receiver stations. The CCC Standard Deviation is inversely proportional of the square root of the number of satellites. That means that the threshold would decrease with the number of receiver stations.

The threshold obtained is ± 0.6. This value means that if a CCC value along the time goes higher than 0.6 or lower than -0.6 a flag would become on. This threshold values gains coherence due to there is no CCC value which exceed those bounds in the shown plots above. As it is said there, the maximum is 0.53 and the minimum -0.57.

Conclusion

This project has developed a method to find code-carrier incoherences in satellites. Specifically, this method has been applied in the current underdeveloped Galileo system. The lack of research around Galileo compared to the whole GPS ecosystem remarks the importance and innovation of the method described. Throughout the project, ambiguities in the carrier phase observable equation have been cleared and arches have been detected, to accomplish that, data with cycle slips has been removed and Multipath has been computed, analyzed and used to track coherence. The E1 frequency band is used as the main frequency and the E5 frequency band as a secondary frequency.

The first part of the tool consists in obtaining the Antenna Calibration of different receiver stations. This Antenna Calibration gets its value by measuring a mean multipath in a seven-day time frame, which allows to reduce out of range value effects and to know how the multipath performance is along elevation angle. This Antenna Calibration is the base to compute the variations in a posteriori computed leveled Multipath. This procedure is done for five different receiver stations. Then, the second part of the tool computes the leveled Multipath for a specific day and its Standard Deviation from the Antenna Calibration. The code-carrier incoherence tracking can be done thanks to the plots of CCC where the values can be considered correct if never exceed from the normal environment. But a better method is to compute the error propagation of CCC and set a threshold. To sum up, the method consists on establish from the error propagation of CCC, a flag which would become "on" whenever this feared event appears.

It is studied for how long is permissible to use the Antenna Calibration for a specific week. It has been chosen a day, a week and some months later and the results can be considered good for this three test days. In conclusion, if there is no remarkable change in the receiver station nor in the satellite, there would not be problem of using the same week to compute the Antenna Calibration for a test day method some months later.

The fact of using five receiver stations located in a small area results in a dependency on the elevation. For every single time, every satellite is at similar elevation angle of view for every receiver station chosen in this work. That makes easier the computation of CCC due to every receiver station is viewing the same satellites. On the other hand, the number of receiver stations is important to establish the threshold, as it is explained in this project, the Standard Deviation of CCC is inversely proportional of the square root of the number of satellites. In conclusion, increasing the number of receiver stations would decrease the threshold. What has coherence because the CCC values become noisy reduced.

The threshold chosen is ± 0.6, what means that any time a CCC value overpasses it, a possible code-carrier incoherence can be occurring or there is a value which is out of range. On the other hand, if actually this feared event is occurring, there would be many values overpassing the selected threshold.

In my personal opinion, this value should evolve with experience, depending on how many out of range values are during a period of time, and how better it is to receive many false alarms versus catching this feared event on time(e.i. if the threshold is lower than the optimal value, there will be many false alarms, but if the threshold is higher, it will be difficult to catch the code-carrier incoherence on time).

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[1] `http://space.skyrocket.de/doc_sdat/galileo-foc.htm`

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