Ionospheric delay estimation in a single frequency mode for Civil Aviation

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BIOGRAPHIES

Christophe OUZEAU graduated in 2005 with a master in astronomy at the Observatory of Paris. He started the same year his Ph.D. thesis on degraded modes resulting from the multi constellation use of GNSS, supported by DTI and supervised by ENAC.

Christophe MACABIAU graduated as an electronics engineer in 1992 from the ENAC in Toulouse, France. Since 1994, he has been working on the application of satellite navigation techniques to civil aviation. He received his PhD in 1997 and has been in charge of the signal processing lab of the ENAC since 2000.

Benoît ROTURIER graduated as a CNS systems engineer from Ecole Nationale de l'Aviation Civile (ENAC), Toulouse in 1985 and obtained a PhD in Electronics from Institut National Polytechnique de Toulouse in 1995. He was successively in charge of Instrument Landing Systems at DGAC/STNA (Direction Générale de l'Aviation Civile/Service Technique de la Navigation Aérienne), then of research activities on CNS systems at ENAC. He is since 2000 head of GNSS Navigation subdivision at DGAC/DTI (Direction de la Technique et de l'Innovation, formerly known as STNA) and is involved in the development of civil aviation applications based on GPS/ABAS, EGNOS and GALILEO. He is also currently involved in standardization activities on future multiconstellation GNSS receivers within Eurocae WG62 and is the chairman of the technical group of ICAO Navigation Systems Panel.

Mikaël MABILLEAU graduated in 2006 as an electronics engineer from the Ecole Nationale de l'Aviation Civile (ENAC) in Toulouse, France. He is currently working for EGIS AVIA as a consultant engineer in the GNSS Navigation domain.

Laurent AZOULAI is Radionavigation R&T Leader within Navigation Department at Airbus Design Office. He is involved in Research activities on Navigation Architectures for future Airbus A/C, focusing on the foreseen extended use of GNSS including Galileo and GBAS. He has been in charge of development and certification of the first MMR with GLS function on Airbus A/C. He graduated in 1996 of Institut Supérieur d'Electonique de Paris as an engineer specialized in automatic systems and joined first an inertial navigation systems supplier before joining Airbus. He has more than ten years experience in Navigation domain.

Jacqueline LEVAN and Frédéric BESSE will graduate in 2009 as electronics engineers from the Ecole Nationale de l'Aviation Civile (ENAC) in Toulouse, France.

ABSTRACT

Ionosphere is a dispersive medium that can strongly affect GPS and GALILEO signals. It is the largest source of ranging error in GNSS. In future GNSS civil aviation context, to remove this effect from pseudoranges, it is necessary to use two different frequencies to obtain "ionospheric-free" measurements, in a dual frequency mode of operation. A receiver can lose one or more frequencies, for instance in the case of disturbance due to RFI leading to the use of only one frequency to estimate ionospheric delay in a degraded mode of operation.

Therefore, it is felt by the authors as an important task to identify and determine the performance of techniques that would try to sustain multi-frequency ionospheric delay estimation performance when a multi-constellation receiver installed in an aircraft is losing one frequency component, during critical phases of flight. This problem is identified for instance in [NATS, 2003].

Those single frequency techniques can be based on the fact that the ionospheric delay encountered in GNSS may be estimated by using the remaining code and phase measurements thanks to the dispersive effect of the ionosphere on GNSS electromagnetic waves crossing this medium.

Indeed, ionosphere generates a delay in code measurements as well as an advance in carrier phase with the same amplitude.

Making the difference between the two measurements at the same frequency, it is consequently possible to estimate ionospheric delay instead of using "ionospheric-free" pseudorange measurements as in a dual frequency mode. Nevertheless, carrier phase ambiguities must be estimated before estimating single frequency ionospheric delay. Indeed, the difference between code and carrier phase measurements provides twice the ionospheric delay plus phase ambiguity, residual noise and multipath.

However, carrier phase measurements are subject to cycle slips that would result in a variation of the phase ambiguity and so in an additive error on the ionospheric delay estimation. Consequently, cycle slips in carrier phase measurements must be monitored to comply with civil aviation requirements to ensure integrity of the system. This is done in [Ouzeau, 2006], the availability of such a technique is also discussed and evaluated in [Ouzeau, 2007]. To estimate code minus carrier ionospheric delay, a Kalman filter is implemented, whose states are both ionospheric delay and carrier phase ambiguities. This allows estimating ionospheric delay and monitoring cycle slips thanks to ambiguities for each satellite in view [Ouzeau, 2007].

During simulations on actual measurements, the filter behavior is studied and the accuracy of the estimation is discussed. This algorithm is expected to bridge a gap between one nominal mode of operation and a degraded mode and thus to try to maintain the level of performance during the degraded mode as long as possible after the degradation occured. In particular, in this paper, the accuracy of the technique is studied. The particular case of APV phase of flight requirements is discussed and actual aircraft measurements are used to validate the model and to observe the filter behavior under actual conditions.

The main goals of this paper are then to describe the methodology used to estimate ionospheric delay and in particular the settings of the Kalman filter used, and to present the accuracy of the ionospheric delay estimation obtained. The paper starts with a description of the proposed algorithm and the settings of the Kalman filter. The accuracy of single and dual frequency estimations will be then compared.

INTRODUCTION

Future GNSS combined receivers will have to be compliant with requirements that are defined by means of performances specified in terms of integrity, continuity, availability and accuracy for Civil Aviation community. The architecture of those receivers is currently defined from investigations about the advantages and risks linked to the multiple constellation use of GNSS signals.

GNSS components (constellations, frequencies) combinations are expected to provide different levels of performance compared with the targeted phase of flight requirements.

From the level of performance that can be reached by the proposed GNSS components, operational combinations are classified into modes of operation. Each mode is identified by taking into account the fact the level of performance is compliant or not with the requirements for each phase of flight.

Thus, nominal, alternate and degraded modes characterize the identified associations. Combinations that allow reaching the specified requirements linked to a phase of flight are included in nominal and alternate modes. Nominal means are preferred to alternate ones for various reasons as explained in [EUROCAE, 2007].

If all those nominal and alternate combinations are unavailable, the use of remaining components is identified as a degraded mode.

Consequently, to take full benefits of all available GNSS components, WG 62 proposed a switching architecture between nominal, alternate and degraded combinations [Mabilleau, 2007].

Ionosphere delay mitigation requires the use of a minimum of two frequencies transmitted by one satellite in view.

In a civil aviation nominal case, dual frequency measurements allow to directly estimate ionospheric code delay from pseudorange measurements.

Ionospheric delay can be obtained via a linear combination of the pseudoranges at two different frequencies (defined by the index 1 and 2):

$$P = \frac{f_1^2}{f_1^2 - f_2^2} P_1 - \frac{f_2^2}{f_1^2 - f_2^2} P_2$$

$$\phi = \frac{f_1^2}{f_1^2 - f_2^2} \phi_1 - \frac{f_2^2}{f_1^2 - f_2^2} \phi_2$$

Those new expressions are called « ionospheric-free » combinations.

However, in case of radiofrequency interference (RFI) for instance, the loss of one frequency may be a problem if one wants to keep the same performance as in the nominal dual frequency case and so we need to use alternate techniques to estimate the ionospheric delay.

1. IONO FREE MEASUREMENTS

In the dual frequency civil aviation case, smoothed ionospheric-free range measurements are used. The ionospheric delay is estimated and

corrected thanks to the use of dual frequency. Indeed, in a nominal mode, the pseudo range measurements that are available to the aircraft receiver are the GPS L1, GPS L5, Galileo L1, Galileo E5a, Galileo E5b code and phase measurements. In order to get rid of ionospheric delay in the measurements, a hybrid ionospheric-free pseudo range measurement is derived from the multi-frequency measurements available.

Indeed, the ranging error due to ionosphere is proportional to the ratio of the Total Electron Content (TEC) encountered by the signal when propagating through the ionosphere, divided by the squared carrier frequency and multiplied by a factor 40.3 which depends upon the medium crossed by electromagnetic waves.

Therefore, dual-frequency measurements can be used to sample the TEC, and that estimated TEC value can be used in turn to predict the ionospheric delay on one specific frequency. For future civil aviation GNSS receivers complying with EUROCAE requirements, dual frequency measurements will be combined into a single composite measurement called the ionospheric-free measurement, corrected for ionospheric delay.

Once elaborated, these two GPS and Galileo ionospheric-free measurements are then smoothed to reduce the influence of noise and multipath.

With the availability of multiple frequencies, it is likely that ionospheric delay will not be a major threat for code and phase measurements under nominal Galileo and modernized GPS conditions. Thus, multipath remains as the main source of error for code measurements under low interference environment.

The code and carrier phase measurements are smoothed to reduce the influence of noise and multipath, because carrier phase measurements are less affected by noise and multipath than code pseudorange measurements. The smoothing filter used is a Hatch filter with 100 seconds time constant [RTCA, 2001]. This smoothing step allows reducing the measurements standard deviation of the filter by an amount evaluated by [Hegarty, 1993]:

$$\frac{\sigma^2_{raw}}{\sigma^2_{smoothed}} = \frac{\alpha}{2}$$

Where α is the filter weighting function (unit less), equal to the sample interval in seconds divided by the time constant, σ_{raw} being the raw pseudo range sigma and $\sigma_{smoothed}$ the smoothed one.

From GPS L1 – L5, and from Galileo E1 – E5b, two distinct ionospheric-free code measurements are built, together with two ionospheric-free phase measurements:

$$P_{L1-L5}(k) = \frac{f_{L1}^2}{f_{L1}^2 - f_{L5}^2} P_{L1}(k) + \frac{f_{L5}^2}{f_{L5}^2 - f_{L1}^2} P_{L5}(k) \quad \text{(GPS)}$$

$$P_{E1-E5b}(k) = \frac{f_{E1}^2}{f_{E1}^2 - f_{E5b}^2} P_{E1}(k) + \frac{f_{E5b}^2}{f_{E5b}^2 - f_{E1}^2} P_{E5b}(k) \quad \text{(Galileo)}$$

$$\varphi_{L1-L5}(k) = \frac{f_{L1}^2}{f_{L1}^2 - f_{L5}^2} \varphi_{L1}(k) + \frac{f_{L5}^2}{f_{L5}^2 - f_{L1}^2} \varphi_{L5}(k) \quad \text{(GPS)}$$

$$\varphi_{E1-E5b}(k) = \frac{f_{E1}^2}{f_{E1}^2 - f_{E5b}^2} \varphi_{L1}(k) + \frac{f_{E5b}^2}{f_{E5b}^2 - f_{E1}^2} \varphi_{E5b}(k) \quad \text{(Galileo)}$$

In this application:

$$\frac{f_{L1}^2}{f_{L1}^2 - f_{L5}^2} \approx 2.261, \quad \frac{f_{L5}^2}{f_{L5}^2 - f_{L1}^2} \approx -1.261, \text{ and}$$

$$\frac{\frac{f_{L5}^2}{f_{L5}^2 - f_{L1}^2}}{\frac{f_{L1}^2}{f_{L1}^2 - f_{L5}^2}} = -\frac{f_{L5}^2}{f_{L1}^2} = -0.5576$$

$$\frac{f_{E1}^2}{f_{E1}^2 - f_{E5b}^2} \approx 2.422, \quad \frac{f_{E5b}^2}{f_{E5b}^2 - f_{E1}^2} \approx -1.422, \text{ and}$$

$$\frac{\frac{f_{E5b}^2}{f_{E5b}^2 - f_{E1}^2}}{\frac{f_{E1}^2}{f_{E1}^2 - f_{E5b}^2}} = -\frac{f_{E5b}^2}{f_{E1}^2} = -0.5871$$

The obtained code and carrier phase standard deviations are then:

$$\sigma_{L_1-L_5} = \sqrt{\left(\frac{f_{L_1}^2}{f_{L_1}^2 - f_{L_5}^2}\right)^2 \sigma_{L_1}^2 + \left(\frac{f_{L_5}^2}{f_{L_5}^2 - f_{L_1}^2}\right)^2 \sigma_{L_5}^2}$$

$$\sigma_{E_1-E_5} = \sqrt{\left(\frac{f_{E_1}^2}{f_{E_1}^2 - f_{E_5}^2}\right)^2 \sigma_{E_1}^2 + \left(\frac{f_{E_5}^2}{f_{E_5}^2 - f_{E_1}^2}\right)^2 \sigma_{E_5}^2}$$

2. SINGLE FREQUENCY MODE

The objective of this paper is to evaluate ionospheric delay measurements in a single frequency mode identified as alternate (NPA) or degraded (APV) mode of operation. Different kinds of investigations can be processed. One way to use single frequency measurements is to use code and carrier phase measurements to deduce ionospheric delay from the dispersive behavior of the medium and the derived properties on electromagnetic waves. Another way to estimate ionosphere thanks to only one frequency, is to use the broadcasted parameters used by ionosphere models to calculate TEC. Another solution can consist in using other available GNSS components such as SBAS as proposed in [Shau-Shiun Jan, 2003]. Through a ionospheric threat model technique, the receiver can use a ionospheric grid that can provide a bound for ionospheric delay standard deviation value. This estimation depends upon the aircraft position around the reference geoids. However, this system is only regional. First, the used SBAS depends upon the area crossed by the aircraft. Indeed, it may be located in WAAS or EGNOS coverage area. Secondly, the SBAS coverage is not sufficient to protect the user everywhere on the Earth. This

system robustness against ionosphere irregularities generated by storms must be studied in details. Indeed, magnetic storms are characterized by abnormal variations in the magnetic field of the Earth. It causes free electrons distributions to be disturbed. The use of a storm detector is consequently required. Fourthly, the case when an aircraft flies in border line the SBAS coverage has to be studied in details to know the availability of the component.

In this study, the problem of estimating ionospheric code delay in single frequency mode is addressed without use of SBAS.

Several cases can be encountered due to a loss of frequency after an RFI area crossing for instance. For example, for a dual frequency GPS L1 C/A / L5 receiver, the loss of L1 or L5 implies the use of the remaining L1 or L5 frequency.

Single frequency situation can be classified as alternate mode if an augmentation is used for NPA as mentioned in Table 1, [Eurocae, 2007].

	En route to NPA	APV I
Nominal	• Galileo SoL • Galileo E1 E5b + SBAS • GPS L1 L5 + SBAS	• Galileo SoL • Galileo E1 E5b + SBAS • GPS L1 L5 + SBAS
Alternate	• GPS single frequency + SBAS • Galileo single frequency + SBAS • Galileo single frequency + SoL • Combination of all available pseudoranges + RAIM	• GPS single frequency + SBAS • Galileo single frequency + SBAS
Degraded	No integrity information	• Galileo single frequency + SoL • Combination of all available pseudoranges + RAIM

Table 1 : nominal, alternate and degraded combinations identified by Eurocae WG 62.

It appears that Code Minus Carrier divergence technique is the most promising technique that may be used as mentioned in [NATS, 2003]. This technique is described further in this paper. The characteristics of this technique are that it doesn't need an ionospheric model but carrier phase ambiguities have to be removed from the estimation to get ionospheric delay. If a cycle slip occurs, phase measurements are biased in consequence and estimations must be corrected so as to provide a good estimation of ionospheric code delay. In the following parts, Code Minus Carrier divergence estimations are calculated through a Kalman filter.

The Code Minus Carrier divergence technique is described in the following.

3. CODE MINUS CARRIER DIVERGENCE TECHNIQUE AND KALMAN FILTERING

After a loss of several frequencies leading to a single frequency degraded mode, resulting from a perturbation like interference, a receiver can use code and carrier phase pseudoranges made on only one frequency. To estimate ionospheric code delay, the difference between code and carrier phase measurements can be used. Indeed, this is modelled as (x frequency):

$$P_x - \phi_x = 2I_x - N_x\lambda_x + w_x + v_x$$

Where:

- P is the code pseudorange measurement in meters
- ϕ is the phase measurement in meters
- I is the ionospheric delay in meters
- N is the integer ambiguity
- λ is the carrier wavelength in meters
- w is the code multipath and noise error
- v is the phase multipath and noise error

Indeed the difference between code delay and phase advance provides us two times the shift caused by the ionosphere propagation of the electromagnetic waves.

The ionospheric delay can therefore be extracted from this difference assuming N is constant. The assumption made is that v_x and w_x only depend upon noise and multipath i.e. that clock errors at the receiver and satellite levels, tropospheric errors get cancelled in the difference computation.

The ionospheric delay can be extracted from that difference, provided the ambiguity is known and constant, i.e. no cycle slip occurs.

If a cycle slip occurs, the code carrier divergence method is not adapted to this situation as phase measurements are biased differently. It is therefore necessary to be able to determine exactly when this type of phenomenon occurs, whatever atmospheric conditions.

Cycle slips may have various causes, for instance multipath and ionospheric scintillation, or receiver dynamics as mentioned previously.

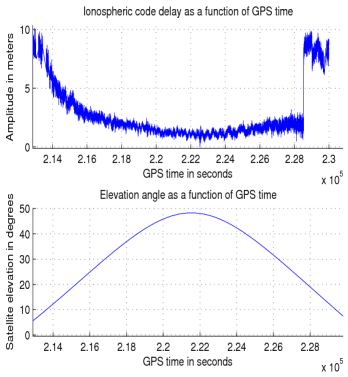

Figure 1: Amplitude of L1 ionospheric delay for a receiver located at ENAC, Toulouse, France, on 14/03/2006. A cycle slip occurs for a low elevation angle of about 20 degrees, which may correspond to a multipath.

Figure 1 shows the estimation of ionospheric code delay using single frequency CMC estimation on L1, we can note that a cycle slip occurs for a low elevation angle.

Those examples are known to generate cycle slips, but the amplitudes of the generated ruptures strongly vary from case to case. It would be possible to detect high amplitude cycle slips but it is really hard to detect small ones that don't allow estimating correctly ionosphere code delay with regards to civil aviation requirements in terms of integrity, for critical phases of flight.

Cycle slips are studied in details in [Ouzeau, 2006] and it appears the simplest way to monitor cycle slips is a method using Doppler predictions of phase measurements described in the mentioned reference.

A Kalman filter is used in order to evaluate the ionospheric code delay and to follow the evolution of ambiguities of all satellites in view. The observation and state propagation models are described in the following. Each ambiguity value is not expected to vary along each corresponding satellite course from the receiver point of view. The acquisition and loss of each satellite are taken into account in the estimation algorithm by updating the states according to the different satellites in view.

When a cycle slip occurs, the ambiguity on the corresponding phase measurement varies abnormally.

As a consequence, the state vector is defined in the following, as in [Nisner, 1995] or [Lestarquit, 1997]:

$$X = (I_0 \quad N_1 \quad \cdots \quad N_n)^T$$

The filter is initialized thanks to dual frequency ionospheric delay estimation. Indeed, in reality, the filter will not have to run before loss of frequency, only dual frequency ionospheric delay estimation must be kept in memory, for each satellite in view. In case of loss of frequency, this value is then used to initialize the states of the Kalman filter. Each state is thus initialized as described in the following:

I_0 is initialized thanks to the following formula:

$$I_0 = \frac{\sum_{k=1}^{Nb\_sat} \frac{I_k}{Ob_k}}{Nb\_sat}$$

Where:

- Nb_sat is the number of satellites in view. The ionospheric delay can then be deduced by summing zenithal delay and spatial gradients that are evaluated in [Lestarquit, 1997].
- Ob_k is the obliquity factor corresponding to the k[th] satellite in view
- I_k is the slant ionospheric delay estimation coming from the k[th] satellite in view

Ambiguity for each satellite in view is derived from the difference between dual frequency and single frequency code minus carrier estimations. The mean of this difference over the first measurements is used as initial value for each satellite in view.

The obliquity factor, which is the ratio between slant and zenithal electronic content, depends upon the transmitting satellite elevation. It is a function of elevation of each considered satellite in view [RTCA, 2001]:

$$Ob = \left[1 - \left(\frac{R_e}{R_e + h}\cos(E)\right)^2\right]^{-\frac{1}{2}}$$

Where: R_e is the Earth equatorial radius, h the altitude and E the elevation angle.

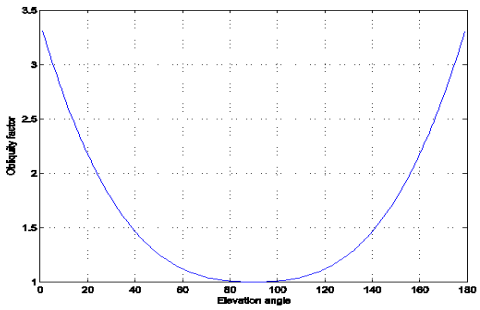

Figure 2: obliquity factor as a function of elevation

Here, for a zenith position of a space vehicle, the obliquity factor equals 1, its values are 3 for GPS mask angle (5 degrees) and 2.7 for Galileo mask angle (10 degrees).

The Kalman filter provides real time estimation of the ionospheric delay thanks to measurements from all satellites in view and of ambiguities for these satellites for the same frequency. The relationship between observation vector Y and state vector X at the instant t is:

$$Y_l = H_l X_l + V_l$$

Where:

- Y_t is the observation vector, composed of the difference between code and carrier phase measurements for all satellites in view. Note that the obliquity factor is multiplied by two in the algorithm for the construction of the matrix H so as to obtain two times the ionospheric code delay: for each satellite.
- V_t is the observation noise
- H_t is the observation matrix

$$H_t = \begin{pmatrix} Ob_1^{'} & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ Ob_{Nb\_sat}^{'} & 0 & \cdots & 1 \end{pmatrix}$$

The state transition formula is:

$$X_{t+1} = F_t X_t + W_t$$

F is taken equal to the identity.

An extensive study of the error covariance values impact has already been performed as mentioned in [Lestarquit, 1997], in this study, the same values are used and recalled in the following.

W is a noise process, it is here to model random fluctuations in linear prediction model imperfections. The covariance matrix of W is Q:

$$Q = \begin{pmatrix} \left(\frac{5\Delta t}{3600}\right)^2 & 0 & \cdots & 0 \\ 0 & 10^{-4} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 10^{-4} \end{pmatrix}$$

Q_{11} is in m².

The covariance matrix of the measurement noise V is:

$$R = 3.5^2 * \begin{pmatrix} \left(\frac{Ob_1}{\Delta t}\right)^2 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \left(\frac{Ob_n}{\Delta t}\right)^2 \end{pmatrix}$$

Where Δt is the measurement interval, 3.5 is a multiplicative empirical term used in [Lestarquit, 1997]. The measurement rate is one second. When the receiver loses track of one satellite signal, its corresponding state in the state vector of the Kalman filter is suppressed, its ambiguity is not kept in memory. When a new satellite signal appears, the state vector is redefined taking into account the corresponding ambiguity, that is to say, the ambiguity is added in the state vector and the Kalman filter is reinitialized, the initial state and covariance are redefined taking into account the new number of satellites, the previously defined matrix .

As proposed, the code minus carrier calculation is based on raw measurements and thus, the remaining noise and multipath components still affect the measurements. It is consequently of interest to discuss the sensibility of the filter to multipath. During calculation of raw code minus carrier, multipath effects on both code and carrier phase measurements are accumulated as these effects are not the same on code and on carrier phase. However, as this study focuses on APV phases of flight, the multipath are not strong and their impact on the filter are not expected to be significant.

In presence of high dynamics, cycle slip probability increases as calculated in [Ouzeau, 2006]. Dynamics parameters such as the receiver acceleration and jerk could be estimated by the filter. But, the more the number of estimated parameters, the more difficult the filter setting. As a consequence, a trade-off between the filter robustness against perturbations and the accuracy of the filter estimations must be made. In this study, dynamics parameters are not estimated.

4. CIVIL AVIATION REQUIREMENTS AND ALGORITHM PERFORMANCES

In this study, the proposed algorithm accuracy is studied. Indeed, the main goal of Kalman filtering code minus carrier measurements is to provide an accurate estimation of ionospheric delay while using only one GNSS frequency. One must provide an estimation that minimizes the residual ionospheric delay in order not to add a large bias on pseudoranges.

The focus here is made on APV phases of flight as it is the first approach phase of flight after NPA that requires vertical guidance and that has restrictive requirements in terms of accuracy.

The zenith delay I_0 in the Kalman states, is initialized by using a weighted mean of all satellites measurements to take into account the elevation of each satellite in view.

Another point that must be addressed is the time of convergence of the filter. This time of convergence can be observed on ambiguities estimations as those ones are not expected to vary and consequently, a convergence test can be made to evaluate the filter estimations availability after a loss of frequency. Indeed, the ambiguities estimations are not noisy as the ionospheric delay.

The last point to mention is the algorithm complexity. Indeed, in a nominal dual frequency case, the estimation of ionospheric delay is provided by simple combination of two frequency pseudoranges to obtain ionospheric-free measurements. This estimation provides sufficient performances in terms of accuracy. In case of single frequency mode, this estimation is made by using code minus carrier divergence technique. Cycle slips are monitored though algorithms proposed in [Ouzeau, 2006]. The Kalman filter is used on the one hand to estimate ambiguities from all satellites in view (that can also allow to monitor cycle slips), and on the other hand, to provide an estimation of mean ionospheric delay from all satellites measurements. The complexity of the algorithm is consequently higher than the complexity of nominal dual frequency estimations. The complexity of the algorithm is dependent upon the number of satellites in view, indeed, the number of states increases with the number of satellites in view. In addition, the number of states depends upon the fact both GPS and Galileo satellites measurements are taken into account or if one filter is used for each standalone constellation. Even if this technique is not used all along aircraft flights, because of the complexity, this algorithm can be implemented within receivers to continue APV phase of flights while the receiver only uses one frequency during degraded mode of operation. A discussion can be made about the utility of such an algorithm because of the low probability of falling into single frequency mode and a trade-off must be made between the complexity (number of measurements estimated) and the utility of the algorithm. This discussion is not in the scope of this study as the probability of losing one frequency is difficult to assess.

The proposed algorithm is tested over actual aircraft measurements, using dual frequency measurements from a few laps of an aircraft flying around the Blagnac Airport.

5. MEASUREMENTS CAMPAIGN

Code and carrier phase measurements were collected during a flight around Toulouse-Blagnac airport (France), which path is drawn in the following Figure 3 and Figure 4.

Figure 3: aircraft path, data collected from Airbus campaign, zoom on the Blagnac Airport (Toulouse, France), ©Airbus, all rights reserved.

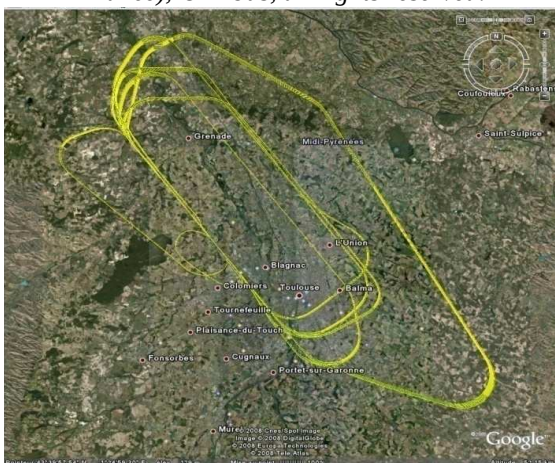

Figure 4: aircraft path, data collected from Airbus campaign around Blagnac Airport (Toulouse, France), ©Airbus, all rights reserved.

Dual frequency measurements were collected during those flights around Blagnac airport (France), on both GPS L1 C/A and L2. The objectives of processing such measurements are multiple. First, it is convenient to test the algorithm on real measurements during aircraft flight to experience aircraft approaches with actual conditions. Indeed, aircraft dynamics and multipaths allow testing the filter robustness against those types of interferences during APV and even during other phases of flight. Secondly, even if the goal is to estimate single frequency ionospheric delay, a dual frequency basis is necessary to compare the performances of the estimation algorithm. As a consequence, dual frequency measurements are needed. Nevertheless, those measurements are L1/L2. The dual frequency measurements in nominal modes will be L1/L5 for GPS and E1/E5a or E1/E5b for Galileo. Since L5 is

still not available, this study will unfortunately be based on those dual frequency measurements. Pegasus software (Eurocontrol) is used to process the collected data before using the algorithm presented under Matlab environment.

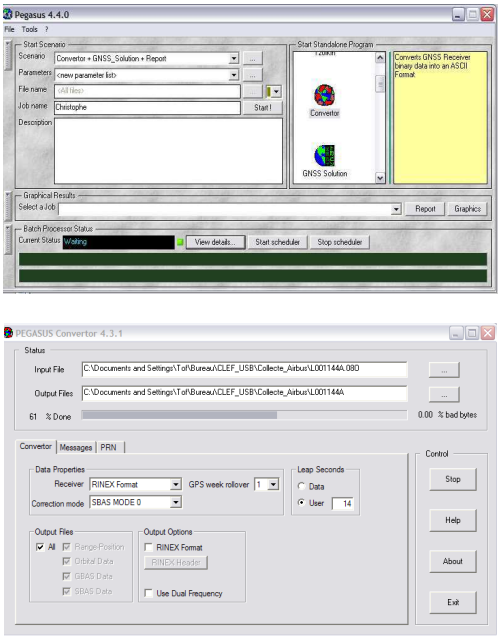

Figure 5: Eurocontrol Pegasus Software

Dual and single frequency ionospheric delays are calculated for all satellites in view during the measurement campaign. The scenario presented here is the loss of GPS L2 leading to single GPS L1 C/A frequency mode.

The Airbus collect was made during 2h20, the measurements available are provided each 0.2 second. In the following, the presented figures are all as a function of the number of samples, 5 samples are available each second. The total number of time samples is 42000.

Note that the number of satellites in view varies along time as it is presented in next paragraph.

The minimum number of satellites in view equals 7 for short periods of time identified in figure 6. This graph allows identifying the onset or the loss of satellites from the receiver point of view.

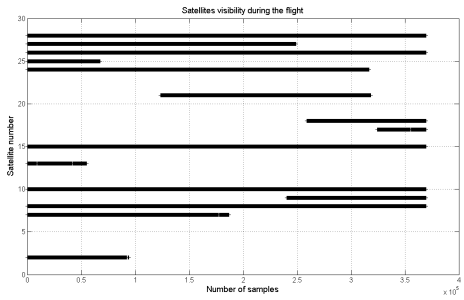

Figure 6: satellites in view as a function of time samples

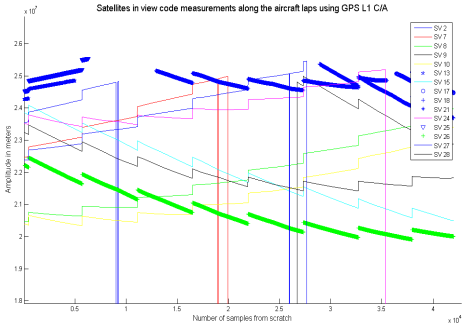

Figure 7: GPS L1 C/A code measurements during recording for all satellites in view

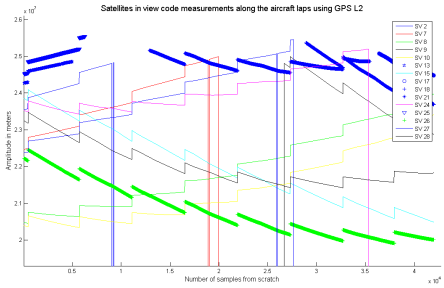

Figure 8: GPS L2 code measurements during recording for all satellites in view

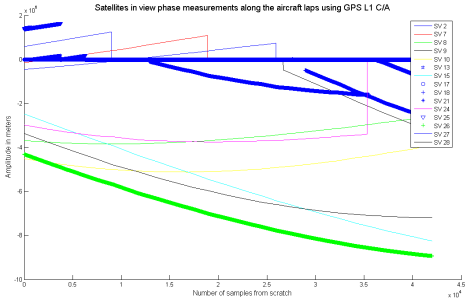

Figure 9: GPS L1 C/A carrier phase measurements during recording for all satellites in view

The abrupt changes that appear in code and phase measurements show clock shifts (regular ruptures) or losses of satellites (it is correlated with the number of available satellites and can be observed for both frequencies and on code and carrier phase measurements). When a satellite is lost, its corresponding state is not kept in memory. When a new satellite appears, its corresponding state is initialized.

6. TEST RESULTS

To know precisely the performance of the estimation algorithm, it is necessary to identify the instants of loss or recovery of satellites, the time of start and end of flight.

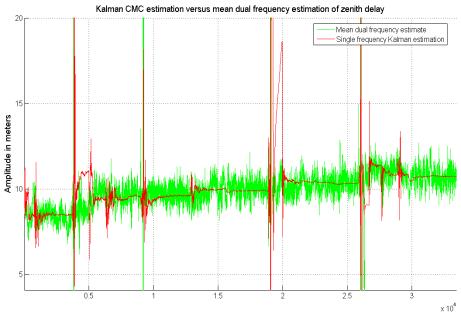

Figure 10: Ionospheric code delay at the zenith of the aircraft through Kalman filtering (in red) versus mean dual frequency estimation (in green).

In figure 10, the mean dual frequency estimation of zenith ionospheric code delay for all satellites in view is plotted in green. The red curve represents the Kalman estimation as described in the previous section. This estimation concerns the zenith ionospheric code delay for all satellites in view and is initiated with dual frequency measurements. Each jump in the estimation corresponds to a cycle slip observed. Indeed, derivatives of the carrier phase measurements show we are dealing with cycle slips as it is shown in figure 11. Cycle slips may have been detected thanks to Doppler-predicted phase measurements as proposed in [Ouzeau, 2006], but Doppler values were not available in the data set used.

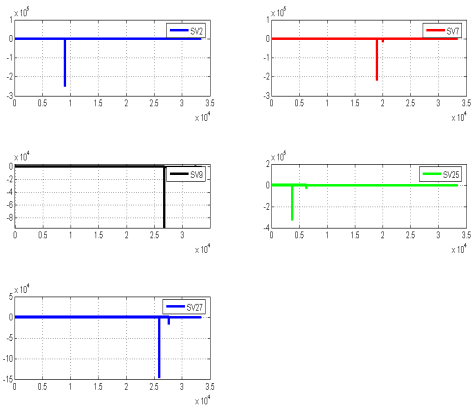

Figure 11: first order derivatives of carrier phase measurements on the identified cycle-slip biased measurements

The problem of cycle slip detection is not addressed here, a discussion about the impact of this phenomenon and cycle slip detection algorithm are proposed in [Ouzeau, 2006].

The accuracy of the filter is evaluated by comparing the mean and the standard deviations (STD) of dual and single frequency estimations at the zenith of the receiver, over all the available measurements. Those moments are calculated over the measurements not affected by cycle slips. Recall that those moments concern the accuracy of the vertical ionospheric code delay estimated for a satellite located at the zenith of the aircraft. Slant ionospheric code delay can be estimated by multiplying those values by the obliquity of the corresponding satellite in view, taking into account its elevation. Thus, to obtain the same statistics for a satellite near the horizon, at the limit of the mask angles defined in [Eurocae, 2007], it is necessary to multiply the obtained mean and STD values by the corresponding obliquity values. As the elevation mask angles correspond to 5 degrees for GPS satellites and 10 degrees for Galileo satellites, the weighting obliquity value is 3 for a GPS satellite and 2.7 for a Galileo satellite near the horizon. Those values are provided in the following table as a function of the number of samples tested.

	N_{sample}	Zenith		Mask	
		Mean	STD	Mean	STD
Dual freq	$2.4\ 10^3$	9.59 m	2.11 m	GPS: 28.77m Galileo: 25.89m	GPS: 6.33m Galileo: 5.7m
Sing freq	$2.4\ 10^3$	9.72 m	0.31 m	GPS: 29.16m Galileo: 26.24m	GPS: 0.93m Galileo: 0.84m

Table 2: Mean and STD of dual and single frequency estimations of mean ionospheric code delay at the zenith of the aircraft.

As it can be seen on figure 10, there is a time of convergence that must be taken into account and compared to time to alert for the corresponding phase of flight. This time of convergence can be evaluated by looking at the convergence of the estimated ambiguities as those ones do not vary when no cycle slip occurs.

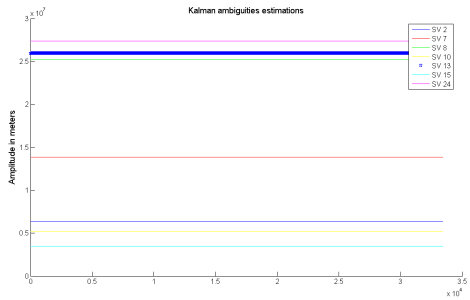

Figure 12: Ambiguities estimation through Kalman filtering.

Figure 12 shows the estimation of the ambiguities for the satellites in view all along the

collect. It can be seen that those ambiguities do not vary with large amplitudes. Nevertheless, in case of cycle slip, with a zoom over the impacted ambiguities, some irregularities can be observed. Each time a cycle slip occurs, the corresponding ambiguities estimations present peaks. The filter estimations then converge after this type of irregularity. The higher the cycle slip amplitude, the higher the irregularity in the ambiguity estimation. The time of convergence of the filter for the corresponding impacted state depends upon this cycle slip amplitude. As the measurements are collected onboard a flying aircraft, due to its high dynamics, the probability of cycle slip occurrence increases as it is described in [Ouzeau, 2006].

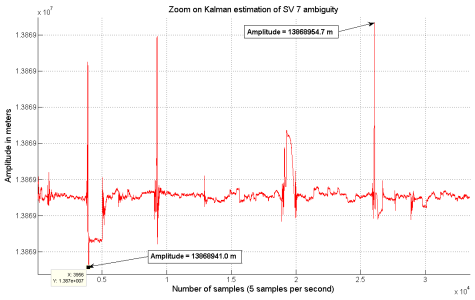

Figure 13: Kalman filter estimation of ambiguity for satellite 7

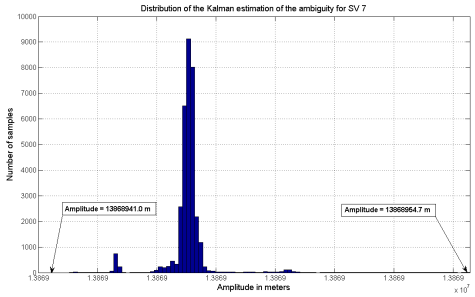

Figure 14: Distribution of Kalman filter estimation of ambiguity for satellite 7

7. CONCLUSION

The performance of ionospheric code delay estimation has been estimated in single frequency mode for civil aviation application.
Three parameters must be taken into account: the mean and the standard deviation of the ionospheric code delay estimation and the Kalman filter time of convergence. It appears from this processing of the 2h20 data set that the estimation provided by the Kalman filter can allow keeping the accuracy of dual frequency estimations after a loss of frequency, when no cycle slip occurs, because the accuracy of the estimated ionospheric delay is better than the accuracy of the dual frequency ionospheric delay estimation.

Thus, if cycle slips are detected, integrity is maintained as mentioned in [Ouzeau, 2006]. But in this study, only a few cycle slips were experienced. Further investigations can estimate the mean time of convergence of the filter over a large number of cycle slips, with varying amplitudes and the obtained time of convergence will have to be evaluated as a function of the cycle slip amplitudes during intensive studies. But this implies a very large number of samples and a very large time of simulation. The obtained time of convergence statistics must be then compared to TTA.

The architecture of a complete algorithm including ionospheric code delay estimation and cycle slip detection must be built for single frequency mode.

ACKNOWLEDGMENTS

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