The EGNOS Integrity Concept: Evaluation of the Ionospheric Corrections

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BIOGRAPHY

Adrian Waegli graduated with the M.Sc. degree in Geomatics Engineering at the Swiss Federal Institute of Technology Lausanne in 2003. His diploma thesis focused on the integrity concept of EGNOS with special emphasis on the ionospheric corrections.

ABSTRACT

Within the validation work of EGNOS for civil aviation, it is interesting to analyze the transmitted corrections individually. In this paper, the ionospheric model of EGNOS is compared to the one determined by an independent organization (*CODE*).

The continuous monitoring of the ionosphere is envisaged in order to analyze the ionospheric corrections in real-time. Two methods based on dual-frequency GPS measurements are described. The first approach computes the ionospheric delays after calibration of the receiver *DCB* (Differential Code Bias) using phase-smoothed code measurements. The second method is based on spherical harmonic expansions.

1 INTRODUCTION

EGNOS (European Geostationary Navigation Overlay Service) will be the European space based augmentation system. It will improve the performance of the two military satellite systems, GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System), and will make them available for critical civil security applications. EGNOS will broadcast pseudorange corrections and integrity messages from geostationary satellites. This allows the user to compute the integrity level of its position, and then to decide whether it satisfies the security requirement of its application.

EGNOS demonstrations and tests have been performed using the ESTB (EGNOS System Test Bed). It is interesting to evaluate the broadcast pseudorange corrections individually. As the ionosphere is the main source of errors in GPS, the ionospheric corrections were analyzed first. The goal of this research is to develop tools for the computation of ionospheric delays independent of EGNOS. Two methods were investigated:

- the ionospheric corrections broadcasted by ESTB can be evaluated by comparing them to the ionospheric delays interpolated from ionospheric grid masks published by the Center for Orbit Determination in Europe (*CODE*).

- an independent and permanent analysis of the ionospheric corrections is possible with dual-frequency GPS measurements.

2 INTEGRITY CONCEPT OF EGNOS

EGNOS aims to achieve the performance required for critical civil security applications (e.g. civil aviation, maritime applications). Therefore, it transmits pseudorange corrections and their precision. So, the precision and integrity of GPS and GLONASS can be improved and makes them available for applications with severe security requirements ([Oosterlinck and Gauthier, 2001]).

The ESTB correction messages provide information about:

- the errors related to the atmosphere: ionospheric and tropospheric corrections.
- the slowly varying error sources of GPS satellites: position and the satellite clock errors (slow corrections).
- the fast changing errors due to the (turned off) selective availability *SA* (fast corrections).

Only the receiver's errors and the errors related to the surroundings persist (e.g. multipath, receiver clock error). The corrected pseudoranges allow to compute an improved ("augmented") navigation solution.

The precision of the corrections is indicated by a standard deviation. The precision of each pseudorange and of the position are derived by error propagation.

The integrity verification is based on the standard deviation of the position and the application. For instance, the civil aviation derives the protection level. This is a confidence interval which is computed by multiplying the standard deviation of the position by a coefficient depending on the phase of flight. Then, those protection levels are compared to the alert limit (defined by the phase of flight) to determine whether the integrity of the position is guaranteed (Figure 1). Maritime and land applications proceed similarly.

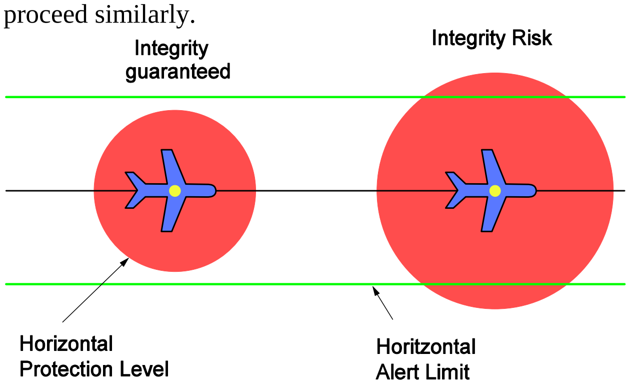

Figure 1 : Protection level vs. alert limit

3 COMPUTATION OF THE IONOSPHERIC CORRECTIONS

The ionospheric corrections and their precision are calculated in several steps ([Eurocontrol, 2002], Figure 4):

The ESTB messages broadcast an interpolation grid to the user. It is assumed that all electrons are concentrated in an infinitely small layer at an altitude of 350km in the ionosphere ("single layer model"). The ionospheric corrections are broadcasted at the specified Ionospheric Grid Points (*IGP*) as vertical delay estimates with a certain accuracy. The density of the *IGP* is dictated by a possible large variation of the ionospheric delay during high solar density (especially at lower latitudes, Figure 2).

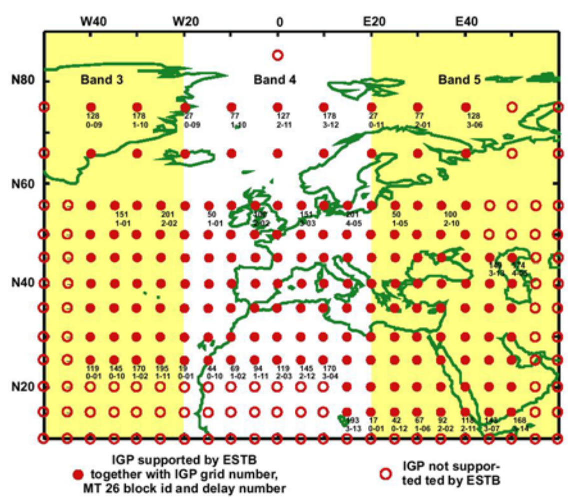

Figure 2 : *IGP* density over the European Civil Aviation Conference ([Eurocontrol, 2002])

Since the user might not get all the ESTB transmissions (masking,random bit errors), a model of degradation is applied to the correction information transmitted. Therefore, after reception of the EGNOS messages, the standard deviation of the vertical ionospheric corrections at the *IGP* increases with time.

Then, the user computes the Ionospheric Pierce Point *IPP* (which is the intersection of the line "user-satellite" with the single layer) using the satellite ephemeris transmitted by GPS (Figure 3).

Knowing the coordinates of the *IPP*, its vertical ionospheric delay is linearly interpolated using 3 or 4 *IGP*. The standard deviation of the *IPP* is calculated using the same interpolation scheme.

Once the vertical delay is known, it is multiplied by an obliquity factor to determine the slant ionospheric delay and the slant residual ionospheric error.

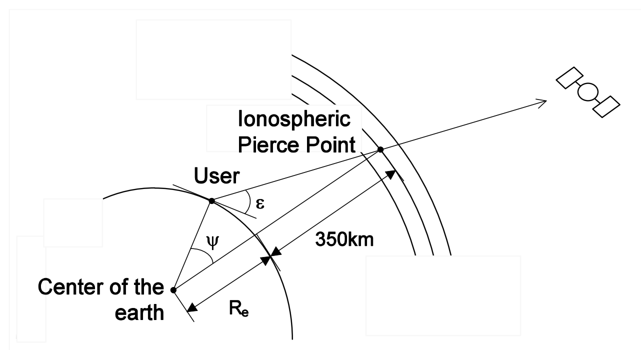

Figure 3 : Computation of the Ionospheric Pierce Point *IPP*

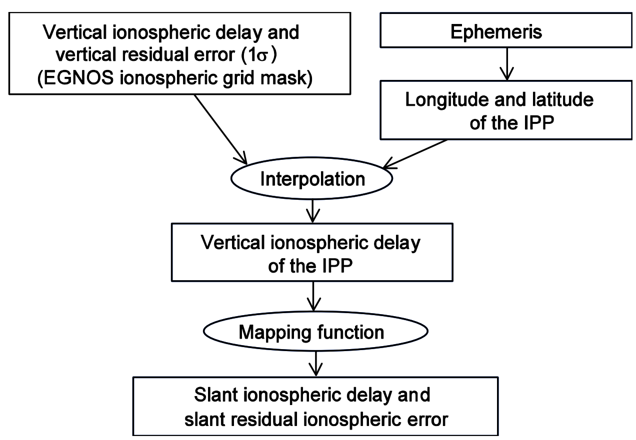

Figure 4 : Computation of the slant ionospheric delay and the slant residual ionospheric error

4 ESTB VS. CODE

The ESTB ionospheric corrections can be analyzed using reference values calculated by independent organizations. *CODE* (Center for Orbit Determination in Europe) is a part of the International GPS Service (*IGS*). *CODE* computes precise ephemeris data and ionospheric grid masks. Those masks are available in an interval of 2 hours and are on a grid of 5° in latitude and 2.5° in longitude. The accuracy of the vertical delay at the grid points is approximately 2cm.

The position of the sun and the maximum ionospheric delays are highly correlated. The regions with the maximum electron content are moving around the geomagnetic axis of the earth. In a first approximation, a movement around the earth rotation axis was assumed. Thus, the ionospheric delay I_1 for L1 at time t can be interpolated from two successive ionospheric grid masks (T_i and T_{i+1}):

$$I_1(\lambda,\phi)_t = \frac{t-T_i}{T_{i+1}-T_i}\left(I_1(\lambda,\phi)_{T_{i+1}} - I_1(\lambda,\phi)_{T_i}\right) + I_1(\lambda,\phi)_{T_i} \qquad \text{Eq. 1}$$

A comparison of the ESTB ionospheric corrections and the *CODE* ionospheric delays of 6 entire satellite passes (120'000 epochs) has shown that:

– differences larger than 2m only occur for very low satellite elevations (<10°, Figure 5).
– the mean difference between both solutions (50cm) is comparable to the user ionospheric range error broadcast by the ESTB (40cm).

Note that no integrity failure was registered during the analyzed period.

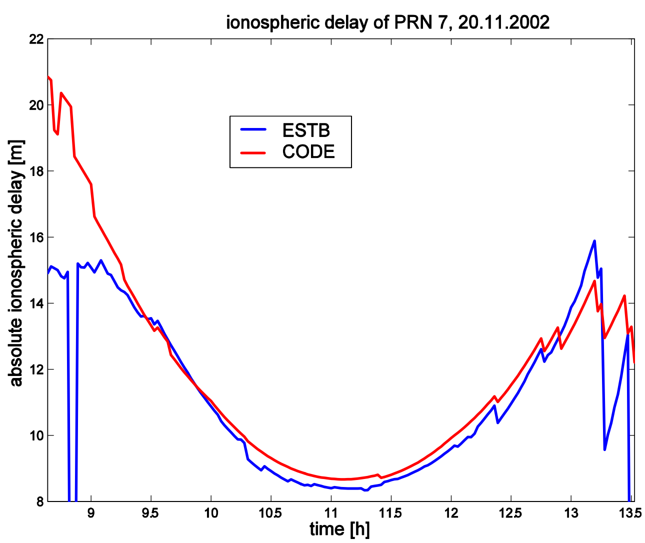

Figure 5 : Comparison of the *CODE* and ESTB ionospheric delay for PRN 7 on 20.11.2002 at EPFL (6.5°E, 46.5°N)

5 IONOSPHERIC DELAY FROM GPS MEASUREMENTS

Dual frequency measurements can be used to determine the slant ionospheric delay. The difference between L1 and L2 is called the "geometry free" linear combination L4. For code and carrier phase measurements, we have:

$$P4 - v_{P4} = \frac{f_2^2 - f_1^2}{f_1^2}\cdot I_1 + c\cdot(\Delta b^s + \Delta b_r) \qquad \text{Eq. 2}$$
$$L4 - v_{L4} = -\frac{f_2^2 - f_1^2}{f_1^2}\cdot I_1 + \lambda\cdot B_1 - \lambda\cdot B_2$$

P4	pseudorange measurement (P4=P1-P2)
L4	carrier phase measurement (L4=L1-L2)
v_i	residual error
f	frequency of L1 and L2
λ_i	wavelength of L1 and L2
I_1	ionospheric delay of L1
Δb^s, Δb_r	Differential Code Biases (*DCB*)
B_i	constant bias, expressed in cycles, principally including the initial carrier phase ambiguity

Systems of Eq. 2 are singular; therefore, it is necessary to simplify. Two methods were taken into consideration:

– after calibration of the receiver *DCB* and knowing the satellite *DCB* (broadcasted by GPS or determined by *CODE*), the slant ionospheric delay can be computed using code measurements.
– the number of unknowns of the ionospheric term I_1 can be reduced using mathematical models describing the vertical ionospheric delay.

5.1 CALIBRATION OF THE RECEIVER DCB

5.1.1 DESCRIPTION OF THE RECEIVER DCB

The receive chain within a GNSS receiver causes different delays to signals with different frequencies. The receive chain amplifies and filters the GPS signal before conversion to digital samples. The delay is a combination of four distinct sources ([Cartmell, 2000]):

– phase delay (t_{phase}): measure of the change in phase experienced by a single frequency sinusoid passing through the receive chain.
– group delay (t_{group}): delay experienced by a modulation of a signal that passes through an analogue component. It is caused by each of the frequencies that compose the modulation experiencing a different change in phase.
– propagation delay ($t_{propagation}$): time taken by a signal to propagate through the receive chain. It is difficult to separate it from t_{phase} and t_{group}, and depends on the

design and the physical dimensions of the receive chain.

– the asymmetry of the correlation function (code measurements) depends on the amplitude and the phase response of the receive chain and causes a delay $t_{asymmetry}$.

Pseudorange measurements include the propagation and group delay as well as the delay related to the asymmetry of the correlation function:

$$t_{code} = t_{group} + t_{propagation} + t_{asymmetry} \qquad \text{Eq. 3}$$

Each pseudorange measurement (C/A, P1, P2) experiences a different delay, because t_{group} and $t_{asymmetry}$ depend on the bandwidth of the signal and because dual-frequency receivers often use different receive chains for L1 and L2 (which results in different $t_{propagation}$).

Carrier phase measurements include the propagation and the phase delay:

$$t_{carrier-phase} = t_{phase} + t_{propagation} \qquad \text{Eq. 4}$$

As for code measurements, the delays for L1 and L2 are different because different receive chains are used for L1 and L2.

5.1.2 CALIBRATION OF THE RECEIVER DCB OF A NOVATEL OEM4

The receiver *DCB* is different for each receiver type. Its value heavily depends on the temperature and may change after hardware upgrades ([Hansen, 1998]).

The receiver *DCB* (Δb_r) were calibrated using phase-smoothed code measurements, P4 ([Schaer, 1999]). The ionospheric delay was calculated using *CODE* ionospheric grid masks. The satellite *DCB* (Δb_s) estimated by *CODE* were used. A *DCB* value was computed for each satellite:

$$\Delta b_r = \tilde{P}4 - (1 - \frac{f_1^2}{f_2^2}) \cdot I_1 - \Delta b^s \qquad \text{Eq. 5}$$

Figure 6 shows that the receiver *DCB* oscillate around a constant mean value for most of the satellites. Some others are progressively diverging or converging. A first investigation shows that the problem doesn't seem to be related neither to errors in the ionospheric grid mask from *CODE*, nor to the elevation of the satellite. Different receiver types in vicinity showed a similar behavior. The problem was observed for at least 7 satellites.

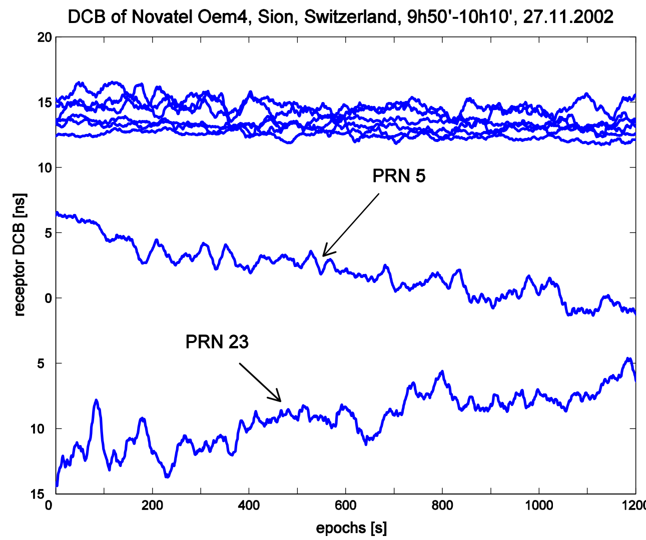

Figure 6 : Determination of the receiver *DCB* with phase-smoothed code measurements

Normally, the *DCB* are estimated as being the mean value of the measurements of all satellites. The calibrated mean *DCB* were applied to dual-frequency phase-smoothed code measurements of regular satellite signals (Figure 7). The resulting ionospheric delay is relatively noisy but can be smoothed over a longer interval in time. Applying the mean *DCB* to measurements with the mentioned anomaly, erroneous ionospheric delay results.

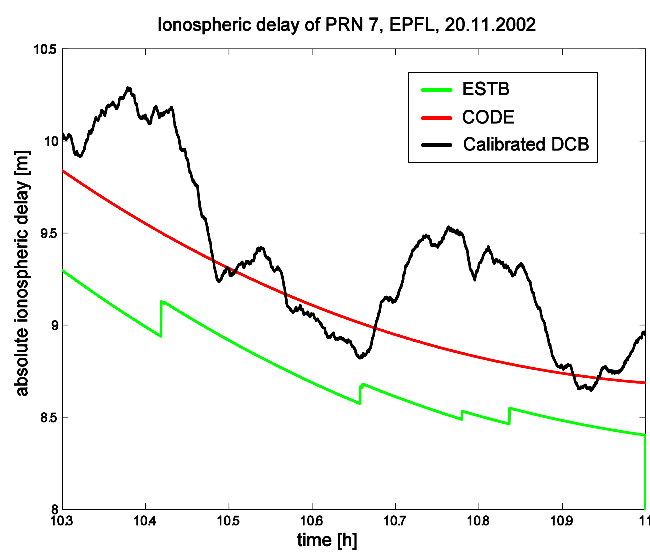

Figure 7 : Comparison of the ionospheric delay computed using the calibrated receiver *DCB* with the ESTB ionospheric corrections and the *CODE* ionospheric delays.

5.1.3 LOCAL IONOSPHERIC MODELS

The vertical ionospheric delay can be described with mathematical models, as:

- two-dimensional Taylor series expansions, [Wild, 1994].
- spherical harmonic expansions, [Schaer, 1999].

This approach can be used for code and carrier phase observables.

The former parameterization represents locally the ionospheric delay and is used to model ionospheric turbulences. It is applicable to a fraction of a day during which the parameters are considered constant. The vertical ionospheric delay $I_{1,v}$ is expressed as a function of the geocentric latitude β and the "sun-fixed" longitude s ([Wild et al., 1995]).

$$I_{1,v} = \sum_{n=0}^{n_{max}} \sum_{m=0}^{m_{max}} C_n^m \cdot (\beta - \beta_0)^n \cdot (s - s_0)^m \qquad \text{Eq. 6}$$

n_{max}, m_{max}	maximum degree and order
C_n^m	unknown coefficients
β_0, s_0	coordinates of the origin of the development

The spherical harmonic expansions are used for global ionospheric models (e.g. *CODE*) but can be used as well for local ionospheric models. For the later, a set of parameters represents the ionospheric delay for a duration of 24h.

The vertical ionospheric delay $I_{1,v}$ is again expressed as a function of the geographical latitude β and the "sun-fixed" longitude s:

$$I_{1,v} = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_n^m(\sin(\beta)) \cdot (C_n^m \cos(ms) + S_n^m \cdot \sin(ms)) \qquad \text{Eq. 7}$$

$\tilde{P}_n^m(\sin(\beta))$	normalized Legendre functions
C_n^m, S_n^m	unknown coefficients
n_{max}, m_{max}	maximum degree and order ($m_{max} \leq n_{max}$)

Spherical harmonic expansions of degree and order 3 were applied in this work (Figure 8). First results present numerical instabilities. Thus, the model has to be tested in order to reach a stable solution.

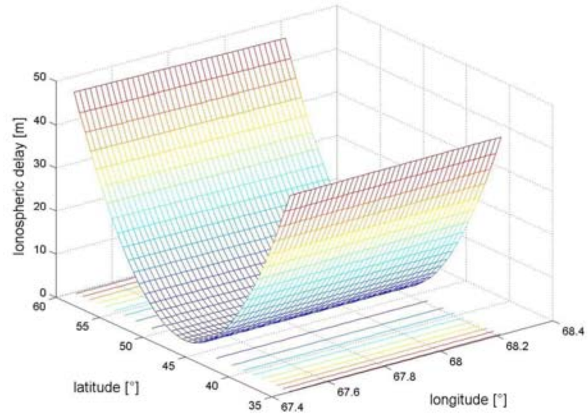

Figure 8 : Local ionospheric model computed with spherical harmonic expansions (n=m=3).

6 CONCLUSION

The ESTB ionospheric corrections were compared to ionospheric delays interpolated from *CODE* ionospheric grid masks. A first analysis showed that the mean difference between both delays is comparable to the slant residual ionospheric error of the ESTB.

An independent and permanent analysis of the ionospheric corrections is possible with dual-frequency GPS measurements. This approach requires the determination of ionospheric models and the estimation of receiver *DCB* or cycle ambiguities.

The receiver *DCB* can be calibrated by means of ionospheric grid masks and satellite *DCB* from *CODE*. Then, the ionospheric delays may be computed with dual-frequency GPS measurements.

The mathematical approach is very promising. Further investigations will be necessary to develop the algorithms which allow to compute the ionospheric delays in real-time. The monitoring of the individual EGNOS corrections will be of great importance in the validation procedure of EGNOS for civil critical security applications. Once validated, the monitoring could improve the security of those applications.

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