IMPACT OF HIGHER ORDER IONOSPHERIC DELAY ON PRECISE GNSS COMPUTATION

M. Hernández-Pajares (1), A. Aragón-Àngel (1), P. Defraigne (2), N. Bergeot (2), R. Prieto-Cerdeira(3), J. Sanz (1)

(1) Universitat Politècnica de Catalunya (UPC)
Mod. C3, Campus Nord UPC
Jordi Girona 1-3, 08034 Barcelona, Spain
e-mail: manuel@ma4.upc.edu
(2) Royal Observatory of Belgium (ROB)
Avenue Circulaire, 3
Brussels, Belgium
e-mail: pascale.defraigne@oma.be, web page: http://www.astro.oma.be
(3) European Space Agency (ESA)
Keplerlaan 1
Noordwijk, The Netherlans
e-mail: Roberto.Prieto.Cerdeira@esa.int, web page: http:// www.esa.int

ABSTRACT

This paper presents the results achieved within the project "Ionospheric Delay Corrections in GNSS Signals for High Precision Applications (IONO-DeCo)". The goal was to design an optimal strategy to remove high order signal delays induced by ionospheric refraction from GNSS measurements. It was motivated by the fact that the higher order ionospheric effects (I2+) are one of the main limiting factors in very precise GNSS processing when millimeter precision is required. A comprehensive study of the I2+ effects in range and in GNSS products(such as receiver position, clock and tropospheric delay, GNSS satellite position, clocks, geocenter offset) is summarized, where all the relevant effects are considered (second and third order, geometric and dSTEC bending). Both effects and mitigation errors are characterized, after showing that the combination of multifrequency L-band observations is not a useful way to cancel the second order term.

The different effects in terms of pseudo-observations have been generated with TOMION software from the actual GPS-constellation to ground-network geometry, using the International Reference Ionosphere (IRI-2012). Then they have been analysed independently with BERNESE and GIPSY-OASIS softwares (network solutions), as far as with the ATOMIUM software (user PPP solution).

The main conclusion is the confirmation that the I2 impact represents most of the overall I2+ one (more than 80%), and is the predominant source of mismodelling in GNSS network solution excepting for the tropospheric estimation (which is mostly due to both geometric and dSTEC bending influences). As a consequence I2 (and both dSTEC and geometric bending in a much smaller extent), should be corrected at both network solution (providing satellite orbits and clock products) and user level in a consistent way, by using as well an algorithm with direct estimation of STEC (with pseudorange or VTEC-map alignment estimation of the ionospheric phase ambiguity), avoiding the significant mapping function errors. In this way a nuisance residual error is found (sub-mm signature in network solution positioning).

1. GENERAL SPECIFICATIONS

A large number of scientific applications demand high precision positioning and time transfer: seismic ground deformations, sea level monitoring or land survey applications require sub-centimetre precision in precise position; monitoring of stable atomic frequency standards requires an increasing sub-nanosecond precision. Differential GNSS is presently the best tool to reach these precisions, as it removes the majority of the errors affecting the signals. However, the associated need for dense GNSS observation networks is not fulfilled for many locations (e.g. Pacific, Africa). An alternative is to use Precise Point Positioning, but this technique requires correcting signal delays at the highest level of precision.

The design of the GPS signals with two frequencies (f1 and f2) for each transmitted carrier phase was intended to minimize the effects of the ionosphere by allowing the possibility to work with signal combinations. Combining the two carrier phases in the 'ionosphere-free' linear combination, it is possible to cancel out the first term in a series expansion of the refractive index of the ionosphere. However errors remain due to the higher order terms in this series expansion. There are also systematic errors due to bending of the signals, caused by the signals passing at an angle through gradients in the refractive index. The bending also affects f1 and f2 frequencies differently so they take slightly different paths, meaning that the 'ionosphere-free' linear combination may no longer completely cancel the first refractive index term. In order to properly cancel out the second and higher order terms (I2+ terms), or at least mitigate them, it has to be taken into account that the more preeminent one, at mid and high elevation, is the second order term (I2), which is proportional to the geomagnetic field projection along the ray, and to the number density of free electrons, both terms multiplied and integrated along the transmitter-receiver ray. For the I2 terms cancellation/mitigation, two main different approaches are possible:

a) Combining independent and simultaneous measurements of the same transmitter-receiver pair at three different frequencies. It is theoretically possible to cancel out both I1 and I2 similarly as it is done typically in precise dual-frequency GNSS measurements for I1.

b) Modeling (and removing from the GNSS measurements) the I2 term, in function of accurate values of electron content and geomagnetic field. This approach is applicable to the remaining higher order terms as well.

Taking into account that the impact of second and higher order signal delays induced by ionospheric refraction constitute one of the main error sources on GNSS measurements, the goal of the project IONO-DeCo has been twofold. First, to assess a realistic evaluation of the impact of all the high order ionospheric terms in both range and geodetic domains. And, second, to identify optimal strategies to mitigate them. In this regard, the correction modelling from electron density and geomagnetic models have been the main options investigated.

The first approach related to the combination of three Galileo or GPS modernized L-band measurements signals (for cancelling the I2 term) has been disregarded after showing, theoretically and experimentally, the impossibility to discriminate between the augmented noise and I2+ effect on the observables. However, our theoretical study has shown that an ionosphere-free combination of two L-band frequencies and one C-band frequency would remove the second-order terms with no significant noise amplification; the noise combination is 1.3 times the noise of the L-band signals. Furthermore, adding a Ku-band signal rather than a C-band signal would provide a combination noise similar as the noise of the L-band signal. As current GNSS only provide L-band signals, we have only concentrated our study on the I2+ correction modelling from electron density and geomagnetic models.

2. HIGHER ORDER IONOSPHERIC TERMS: BASIC INTRODUCTION AND MODELING OPTIONS

The first order ionospheric refraction (I1) takes more than 99.9% of the total ionospheric delay. We will show that the correction of the I2 order term is necessary when requiring a precision better than one centimetre level in range for all the elevations (dSTEC and geometric bending effects should also be considered for low elevation). For precisions of more than one millimetre level, the correction of the I3 order term (and bending terms) may be also considered.

The final implemented expressions for every I2+ terms used to assess their impact at range and geodetic domains are presented below. They have been taken from previous works, involving some of the co-authors of the IONO-DeCo project (Hernández-Pajares et al (2007), IERS (2010), Petrie et al. (2010), Pireaux et al. (2010)) trying to assess their impact from different points of view..

The GNSS measurements with higher precision at a given frequency f , the carrier phase Lf, can be expressed in terms of a non-dispersive term ρ* (including the geometric distance, receiver and transmitter clock errors and tropospheric delay), its ambiguity Bf (the unknown initial pseudorange at phase locking time), the wind-up or phase rotation term φ and the first, second and third order terms in the straight line propagation approximation (If,1 , If,2 and If,3 respectively), among the geometric and STEC differential (dSTEC) bending terms (If,gb and If,dSb respectively):

$$L_f = \rho^* + B_f + (c/f)\varphi + I_{f,1} + I_{f,2} + I_{f,3} + I_{f,gb} + I_{f,dSb} \qquad (1)$$

where all the ionospheric terms, including the third order term which can be described in terms a main (If,3,M) and a small (If,3,s) term (If,3= If,3,M + If,3,s), are summarized in Table 1.

3. REPRESENTATIVE STUDY FOR ALL THE HIGHER ORDER IONOSPHERIC TERMS, AND ITS MITIGATION ERRORS, IN NOMINAL SOLAR MAXIMUM CONDITIONS

Two aspects have been considered to assess the importance of the different higher order ionospheric corrections and their approximations:

a) At range level, looking at the values of slant delays of the different high order terms.

b) At geodetic domain level, provided by the impact of such values in the different geodetic parameters estimated consistently (i.e. simultaneously) from a global GNSS network.

For that, a sub-network of 44 stations has been selected from the 232 stations of the IGS08 network (Rebischung, 2011)

Iono Term (I_f)	k	$I_f \cdot (-f^k / \alpha_f)$	Considered Approximations	α_f (S.I. units)	$I_c / I_f /(-f^k)$	$I_c(P) / I_f$
First order, $I_{f,1}$	2	$S = \int_S^R N_e dl$	-	40.309	0	- 1
2nd order, $I_{f,2}$	3	$\int_S^R B \cdot \cos\theta \cdot N_e dl$	$B_0 S$ $B_0 MV$	$1.1284 \cdot 10^{12}$	$\frac{1}{f_1 f_2 (f_1 + f_2)}$	- 2
3rd order, N^2 term, $I_{f,3,M}$	4	$\int_S^R N_e^2 dl$	$\eta N_m S$ $\eta N_m MV$	812.42	$\frac{1}{f_1^2 f_2^2}$	- 3
3rd order B term, $I_{f,3,s}$	4	$\int_S^R N_e B^2 (1 + \cos^2\theta) dl$	$B_0 S (1 + \cos^2\theta_0)$ $B_0 MV (1 + \cos^2\theta_0)$	$1.5793 \cdot 10^{22}$	$\frac{1}{f_1^2 f_2^2}$	- 3
Geometric Bending, $I_{f,gb}$	4	$\frac{S^2 e^{-\beta E}}{H_{F2} h_{m,F2}^{1/8}}$ [*]	$\frac{2.495 \cdot 10^8}{-7.5 \cdot 10^{-5}} \left[\left(1 - 0.8595 \cos^2 E\right)^{-1/2} - 1 \right] S^2$ [**] $\frac{2.495 \cdot 10^8}{-7.5 \cdot 10^{31}} \left[\left(1 - 0.8595 \cos^2 E\right)^{-1/2} - 1 \right] M^2 V^2$	$-7.5 \cdot 10^{-5}$ [*]	$\frac{1}{f_1^2 f_2^2}$	1
dSTEC Bending, $I_{f,dSb}$	4	$\int_S^R \frac{a^2}{r^2 - a^2} N_e^2 dl$	$\frac{0.1108 \cdot e^{-2.1844 E}}{40.309^2 f^2 H_{F2} \left(h_{m,F2}\right)^{0.3}} S^2$ [***]	40.309^2	$\frac{1}{f_1^2 f_2^2}$	- 1

			$\frac{0.1108 \cdot e^{-2.1844 E}}{40.309^2 f^2 H_{F2}\left(h_{m,F2}\right)^{0.3}} M^2 V^2$			

Table 1: Basic dependences of high order ionospheric terms: [1] represents the path integral of magnitude X from satellite to receiver, I_f and I_c are the corresponding terms at frequency f and first-order carrier phase ionospheric free combination and I_c(Pc) represents the terms for the ionospheric free ionospheric combination P_c; f1 and f2 are the frequencies of L1 and L2 measurements; N_e is the electron density and N_m is its corresponding maximum; B the geomagnetic field modulus; θ is the angle between the GNSS signal propagation direction and the geomagnetic field; r is geocentric distance and a=r cosE is the GNSS ray impact parameter; M is the mapping function and V is the vertical total electron content; E is the elevation; [2] and hm,F2 are the F2 scale height and electron density peak height. In [*] and [**] the following NON-SI units are considered: the STEC is expressed in $TECU = 10^{16} m^{-3}$ and the elevation in degrees, with $\beta = 2.13$. In [***] NON-SI units are taken as well: where the elevation is in radians, HF2 and hmF2 are in km, *f* is in Hz and STEC is in electrons m^{-2}. And the shape parameter is η=0.66.

(NOTE: [1] represents $\int_S^R X dl$ and [2] represents $H_{F2} = \frac{V}{\sqrt{2\pi e}\, N_m}$)

Term	Position North (mm)	Position East (mm)	Position Up (mm)	Rec. clocks (ps)	Clock. Frequency (1e-16)	Zpd (mm)
I2	-1.2 to 1.3	-2.2 to 1.5	-2.0 to 3.0	-12 to 22	0 to 13	-1.3 to 0.5
I2 corr. (VTEC)	-	-	-	-	-	-
I2 corr. (STEC)	-	-	-	-	-	-
I3	-	-	-	-	-	-
I3 corr. (VTEC)	-	-	-	-	-	-
I3 corr. (STEC)	-	-	-	-	-	-
Geo-bend.	-	-	-	-	0 to 12	-
Geo-bend. corr. (VTEC)	-	-	-	-	-	-
dSTEC-bend.	-	-	-	-18 to 5	0 to 17	0 to 1.5
dSTEC-bend. Corr.	-	-	-	-	-	-
All	-1.5 to 1.5	-2 to 2	-2.5 to 2.5	-20 to 14	0 to 23	-0.6 to 1.5
All corrected	-1.0 to 1.0	-2 to 2	-3 to 2 5	-16 to 5	0 to 12	-0.3 to 0.8

Table 2: Some key numbers summarizing the residual impact of I2+ terms and their corrections for an end-user making use of Precise Point Positioning.

to test the impact of the I2 and I2+ terms on range and different geodetic and GNSS parameter estimations. Figure 1 shows the global distribution of this sub-network of stations.

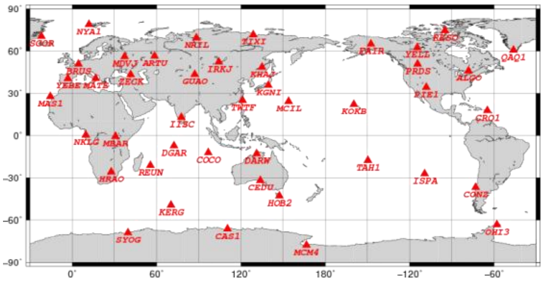

Figure 1: Selection of 44 stations from the IGS tracking network for the test plan.

In a first step, higher order ionospheric delays and corrections in range domain has been computed with new TOMION version. In a second step, simulated RINEX observation files have been created for all the stations of the network, with and without modeling the I2+ delays and adding them to the simulated code and phase data. Simulations have been done with the Bernese 5.0 software, using IGS final products for satellite clock and orbits. The tropospheric delay has been modeled based on a standard atmosphere. In order to better approximate reality, some normal distributed random error with specified sigmas for code and phase data has been additionally considered, with an elevation-dependent factor.

An analysis of these synthetic RINEX files with and without the higher order ionospheric delay has then been performed with Bernese 5.0 software to determine the satellite orbit and clocks, the geocenter motion, and the Earth rotation parameters, to estimate the impact of the I2+ delays and their modeling on the geodetic parameters. A parallel computation has been done with the GIPSY-OASIS software for validation.

In order to estimate the impact of the I2+ modeling on Precise Point Positioning (PPP) applications, we used the ATOMIUM software developed by ROB. The PPP solutions (positioning, troposphere and receiver clock solution) have been computed using first the simulated observations without I2+ delays, and the satellite clocks and orbits obtained from these data with the Bernese software. Second, the PPP solutions have been computed with the simulated observations containing the I2+ delays, and the satellite clocks and orbits obtained from these data with the Bernese. The differences between the position, troposphere and clock solutions obtained from the two runs have provided a quantification of the impact of the I2+ modeling on these GNSS applications.

4. ANALYSIS OF SIMULATION RESULTS: PERFORMANCE SUMMARY

A summary of the range of values achieved for every I2+ term, modeling error and corresponding geodetic impact (i.e. global non-fiducial network solution), in the Solar Maximum quiet conditions (the maximum TEC value ever observed, but without any storm going on), is provided in Table 3. The values above 1 mm are indicated in red, and the more remarkable, greater than 1 cm, are enhanced in bold font. The impact of the I2+ terms for a PPP user is summarized in Table 2. As the I2+ errors have been absorbed by the clocks, there have no impact on the PPP user. In this Table 2, only the non-negligible residual effects have been reported.

From this study, we can conclude that:

(1) The major impact of the I2+ perturbations comes from the I2 term. It has the highest magnitude at low elevation where it can reach 2 cm on the range. The I2 impact on the ranges induces a geocenter artificial displacement of 4 mm, more than 1 cm error on the satellite orbits, and up to 30 ps on the satellite clocks. When these products are used for PPP application, a ~1 mm change on the position is still visible with a clock bias limited to 20 ps and a maximum frequency change of 1.3e-15. The tropospheric zenith delay is not affected by the I2 term, thanks to the very high elevation-dependence of the tropospheric delay, while I2 has only a factor 4 between high and low elevation values.

(2) The second term, by order of magnitude, is the dSTEC bending, i.e. the impact on the dual-frequency ionosphere-free combination L3 due to the difference in STEC of the signals on the different frequencies caused by their different bending (and hence path). This term is very large at low elevation (up to 1.4 cm on the range), but decreases down to zero at the zenith. Its impact on the geodetic parameters as well as on the end PPP products is not negligible. It reaches the level of 7 mm on the satellite orbits, and 1.5 ps on the satellite clocks. For the PPP user, the residual effects due to the dSTEC bending reach 18 ps for the receiver clocks, 1.7e-15 for the clock frequency (at 4 h) and 1.5 mm for the tropospheric delay. It must be noted that for the troposphere delay, the dSTEC bending has a larger impact than the I2 term.

(3) The geometric bending has a lower impact than the dSTEC bending, but in the opposite sense. Correcting for this term without a correction of the dSTEC bending should not be recommended as it would reinforce the effect of the dSTEC bending, as this latter is partly mitigated by the effect of geometric bending on the range.

(4) When correcting the I2+ terms with simplified and practically feasible modeling, the I2+ errors are much mitigated at the level of about 90%. From our results, we also recommend the correction using the observed STEC, deduced from the geometry-free combination,

which is by far better than when using an external VTEC product for a given height, combined with a mapping function.

5. CONCLUSIONS

Concerning the possibility to work with three frequencies taken into account the fore coming FOC of Galileo, there are strong observational evidences, which confirm the theoretical expectations, that L-band three-frequency first and second order ionospheric-free combination appears as not useful for high precise GNSS applications due to the huge increase of thermal noise (+20 times), and augmented multipath/unmodelled antenna phase center errors. In this context, the modelling approach is the one considered feasible and useful for I2+ correction / mitigation. A deep analysis of I2+ value and mitigation error impact on GNSS precise network and user solutions under high solar maximum conditions have been performed with actual geometry and realistic simulated values. In particular:

- The range I2+ terms in Lc and Pc have been calculated for up to 44 worldwide IGS receivers and simulated values corresponding to Solar Max. Conditions with IRI, for electron densities, and IGRF11 for magnetic field.
- The GNSS precise network solution has been computed with BERNESE and GIPSY-OASIS2 (GOA) in a non-fiducial approach (with Helmert alignment of coordinates), and adding the different I2+ terms and modeling errors to the GOA modeled Lc and Pc observations.
- Finally, the corresponding impact is assessed, for each given I2+ term and modeling error, by subtracting the estimated solution from the nominal solution with the modeled GOA/BERNESE obs. (i.e. ~0 for the a priori estimates…).

The particular analysis of I2, the I2+ term predominantly studied in the literature confirms the consistency of these results with the I2+ distribution in range and geodetic domains

These results led to some final recommendations regarding to the most remarkable model errors:

(1) Correcting I2 with the integral approximation expression using direct STEC observations (ionospheric dual-frequency GNSS phase measurements after estimating the ambiguities) reduces the residual error versus the integral approximation expression and deprojected VTEC:

- The range error is reduced by half;
- The error in receiver coordinates is reduced more than 50% (0.4 mm), similarly to satellite and receiver clocks (less than 1 mm);
- The estimated troposphere is improved more than 50% (error much less than 0.1 mm) and,
- The Z-translation derived from the satellite orbits is also reduced by half (up to -0.5 mm).

(2) It is also confirmed that in case it is not possible to correct both bending effects (geometric and dSTEC ones), it is better not correcting any of them than just one.

(3) The I2 impact represents most of the overall I2+ . It is approximately more than 80% identical, and is the predominant source of mismodelling in GNSS network solution excepting for the tropospheric estimation (which is mostly due to both geometric and dSTEC bending influence).

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Term	Range val. @ ele = 10º (mm)	Range val. @ ele=90º (mm)	Z-Sat.Coor. GIPSY (mm)	Z-Sat.Coor. BERNESE (mm)	Sat. clocks GIPSY (ps)	Sat. clocks BERNESE (ps)	Rec. pos. GIPSY (mm)	Rec. pos. BERNESE (mm)	Rec.clocks GIPSY (ps)	Rec. clocks BERNESE (ps)	Zpd GIPSY (mm)	Zpd BERNESE (mm)
I2	**-12 to 20**	**-3 to 5**	**-2 to 11**	**-5 to 14**	**-22 to 28**	**-25 to 32**	-1.8 to 2	-1.5 to 1.5	-12 to 15	**-12 to 22**	-0.3 to 0.5	-0.8 to 1.3
I2 corr. (VTEC)	**-5 to 2**	-0.5 to 0.4										
I2 corr. (STEC)	-1.6 to 0.4	-0.3 to 0.3	-1 to 1	**-16 to 8**	-3 to 2	-15 to 15[*]	-0.3 to 0.2	-2 to 2	-3 to 2	**-7 to 19**	-0.1 to 0.1	-0.8 to 0.7[*]
I3	0 to 1.2	0 to 0.4	-1 to 0.5	-4 to 4	-1 to 1	-1 to 5	-0.2 to 0.2	-0.5 to 1	-2 to 0.1	-6 to 9	0 to 0.1	-0.3 to 0.5
I3 corr. (VTEC)	-0.3 to 0.2	-0.1 to 0	-0.1 to 0.1	-4 to 4	-0.1 to 0.1	-0.5 to 2	-0.1 to 0.2	-0.5 to 0.2	-0.1 to 0.1	-2 to 2	0.0	-0.2 to 0.2
I3 corr. (STEC)	-0.1 to 0.0	-0.1 to 0										
Geo-bend.	**-6 to 0**	0.0	0.1 to 3	**-3 to 5**	**-3 to 6**	**-5 to 7**	-0.5 to 0.5	-1 to 1.5	-1 to 4	-4 to 11	-0.6 to 0	-1.6 to 0.6
Geo-bend. corr. (VTEC)	-1.5 to 3	0.0	-2 to 0.5	**-5 to 2**	-2 to 3	-1 to 3	-0.2 to 0.2	-0.5 to 0.5	-2 to 0.0	-6 to 6	0 to 0.4	-0.3 to 0.5
dSTEC-bend.	**0 to 14**	0	**-7 to 0**	**-5 to 6**	-15 to 12	-10 to 9	-1 to 1	-1.5 to 1.2	-11 to 4	-13 to 7	-0.2 to 1.4	-0.3 to 1.7
dSTEC-bend. Corr.	-1 to 2	-0.1 to 0	-2 to 0	-4 to 4	-3 to 2	-3 to 4	-0.4 to 0.4	-1 to 0.7	-2 to 0.1	-4 to 5	-0.1 to 0.3	-0.6 to 0.7
All			**-5 to 8**	**-12 to 12**	**-31 to 32**	**-28 to 40**	-1.6 to 2.6	-1.5 to 2.5	-14 to 14	**-15 to 21**	-0.2 to 1.1	-0.8 to 1.4
All corrected			-4 to 1	-4 to 4	-7 to 5	-12 to 6	-0.4 to 0.3	-1 to 1	-4 to 1	-8 to 5	-0.1 to 0.7	-0.4 to 1.0

Table 3: Some key number summarizing the impact of I2+ terms and its corrections: columns 2 and 3 in range domain (full range of values for 10º and 90º of elevation respectively), and effect on estimated parameters with GIPSY and BERNESE in global network processing with the actual geometry of Figure 1 (range defined by bias -/+ standard deviation; from 4th column). The Solar Maximum conditions are recreated with the International Reference Ionosphere 2012, for the maximum values of the two main driven parameters since 1958 (Rz12 = 201.3 and IG12=165.6). Notes: [*] = removing PRN27; color code: blue, 5mm > |X| >= 1 mm, red, |X| >= 5 m.