STUDY OF THE OBLIQUITY FACTOR ERROR IN SLANT TO VERTICAL AND VERTICAL TO SLANT IONOSPHERIC DELAY CONVERSION

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ABSTRACT

Ionosphere is at present time the main source of error to a satellite navigation system that operates at single frequency. To provide information about this error the ionosphere is modeled by assuming it as a thin shell. NeQuick 3D ionospheric electron density model has been used to perform a complete analysis of the errors that can be introduced with this assumption. GPS derived slant TEC data have been used to check the outcome obtained with the simulations. The results show that the conversion factor error depends on: satellite elevation angle, satellite azimuth, ground station latitude, solar activity and season.

INTRODUCTION

The satellite-based navigation systems that are now available (GPS and GLONASS) have provided sufficient positioning capability to users. However, their efficient use has been a driving force to increase accuracy, availability, reliability, and integrity requirements particularly to provide global aircraft guidance throughout flight including precision approach by using augmented single frequency operation.
As a result, satellite augmentation systems have been planned on a regional but compatible and coordinated scale. ESA, the European Union and Eurocontrol, are developing EGNOS, the European Geo-stationary Navigation Overlay Service that will cover the European Civil Aviation Conference (ECAC) region. The United States Federal Aviation Administration leads the development of the Wide Area Augmentation System (WAAS) that cover the United States and Canada and the Japanese Civil Aviation Bureau is implementing the MTSAT Satellite-Based Augmentation System (MSAS), which will cover the Flight Instrumental Region of Japan. These regional Systems integrate global Satellite-Based Augmentation Systems (SBAS). The GPS (and GLONASS for EGNOS) operation will be augmented by a Geo-stationary ranging service which will provide the users with additional pseudo-range measurements, a Ground Control Integrity Monitoring (GCIM) service that will improve the integrity of the Navigation Service to the users, and a wide area differential (WAD) service which will improve the position accuracy by broadcasting corrections to users.

Ionosphere introduces a group delay in satellite signal and is at present time the main source of error to a satellite navigation system that operate at single frequency. As the SBAS user navigation system does not take advantage of dual frequency measurements that in practical terms eliminate the ionospheric delay, the user needs additional information to remove such delay. The augmented operation will feed the navigation system with ionospheric information in the form of vertical delays (Grid Ionospheric Vertical Delay (GIVD)) at defined grid points (Ionospheric Grid Points (IGP)) so that the user receiver can calculate ionospheric corrections. In addition a realistic upper bound of the error associated to this estimation is given (Grid Ionospheric Vertical Error (GIVE)). To provide this information the ionosphere is modeled by assuming it as a thin shell located at 350 km above the reference geode that define the Ionospheric Pierce Points surface. The calculation of the GIVDs is done by converting slant delay measurements into vertical values at the Ionospheric Pierce Points (IPP) by means of an Obliquity Factor (OF) that, following the thin shell approximation, is a simple function of the satellite elevation angle only. An interpolation algorithm applied to vertical values at IPP allows determining the vertical delay at the IGPs.

The presence of obliquity factor errors introduced in the estimation of vertical ionospheric delays from slant measurements due to the thin shell approximation has been reported in the open literature only in a qualitative way. In particular the possible dependence of this errors on different parameters has not been described with a systematic approach. Under the ESA-EGNOS Ionospheric Expert Team activities the authors have used the NeQuick 3D ionospheric electron density model [1] to perform a complete analysis of the errors that can be introduced if a thin shell approximation is assumed for the ionosphere.

CONVERSION ERROR EVALUATION

The error introduced by the obliquity factor in the determination of GIVE bound values to be applied to the updated GIVD is defined through the following equations:

$$\mathrm{sTEC} = \int_{\mathrm{Receiver}}^{\mathrm{Satellite}} \mathrm{Ne(s)ds}$$

$$\mathrm{vTEC}_{\mathrm{PP}} = \int_{\mathrm{0km}}^{\mathrm{20000km}} \mathrm{Ne}(\phi_{\mathrm{PP}}, \lambda_{\mathrm{PP}}, \mathrm{h})\mathrm{dh}$$

$$\mathrm{Converted\ vTEC}_{\mathrm{pp}} = \mathrm{sTEC} \cdot \cos(\chi)$$

$$\mathrm{Error} = \mathrm{Converted\ vTEC}_{\mathrm{pp}} - \mathrm{vTEC}_{\mathrm{pp}}$$

Where: ϕ_{PP} is the geodetic latitude of the pierce point, λ_{PP} is the geodetic longitude of the pierce point, and χ is the satellite zenith angle at the pierce point.

MODEL SIMULATIONS

The first analysis has been done by using NeQuick model to simulate “average” ionosphere electron density N_e without storm or TID conditions. Pierce points height has been assumed at 350 km and only spherical reference frames were used.

Analysis and Results [2]

Errors were calculated for each ray-path determined by 31 RIMS and the positions assumed by 24 GPS satellites, every 10 minutes, along their orbits during 24 hours. The calculations were done for a representative day in Jan., Apr., Jul. for moderate solar activity (Solar Flux =130 f.u.) and for a representative day in Jan., Apr., Jul. for high solar activity (Solar Flux =200 f.u.).
To better understand error behavior with respect to satellite elevation angle, satellite azimuth and ground station latitude, two approaches were considered: *ground station approach* and *pierce point approach*. In the first approach NeQuick was used to simulate stec from a ground receiver and a second point having 20000 km height, elevation from 0 to 85 deg, step 5 deg (measured with respect to ground station) and azimuth from 0 to 355 deg, step 5 deg (measured with respect to ground station). Figure 1 show as an example the error dependence on satellite elevation and azimuth, with respect to ground station latitude for North latitudes 25°, 35°, 45° and 55° respectively, for 15°East and 20 UT:

For the *pierce point approach*, calculations were done using pierce points with different latitudes and longitudes.

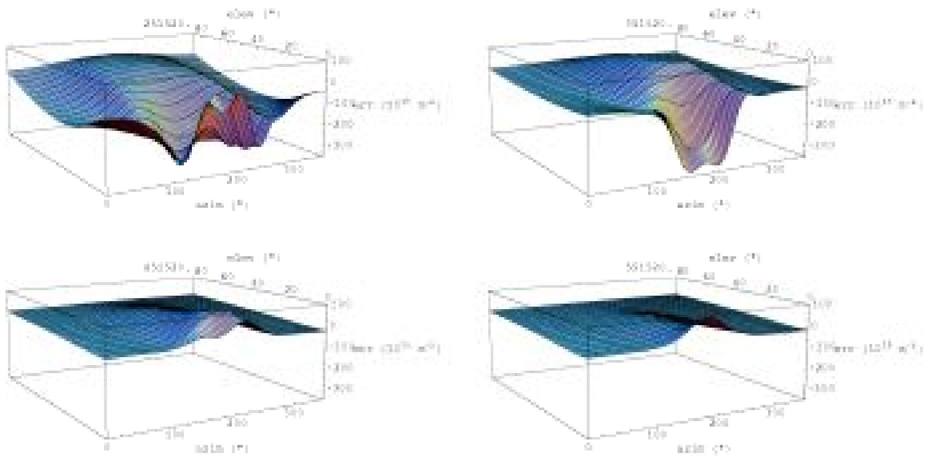

Fig.1: Error dependence on satellite elevation and azimuth, with respect to ground station latitude for North latitudes 25°, 35°, 45° and 55° respectively, for 15°East and 20 UT:

The results obtained from the analysis done by using the NeQuick model simulations indicate that the conversion factor error depends on: satellite elevation angle (increasing elevation => decreasing |error|), satellite azimuth (by sectors with a complicated structure), ground station latitude (increasing latitude => decreasing |error|), solar activity (increasing solar activity => increasing |error|) and season (following seasonal TEC trends).
It can be shown that two ray-paths with the “same” Pierce Point can be found and often the two Converted Vertical $sTEC_{pp}$ are different. In this case, all the ray-paths having the same Pierce Point determine different Converted Vertical $sTEC_{pp}$. Even if a Vertical TEC_{pp} is correct, the back conversion could lead to an error in Slant TEC. This suggests that, in general, conversion errors do not compensate.

Results Obtained From Experimental Data

To check the results obtained with the model simulation GPS derived experimental slant TEC data provided by L. Ciraolo of IROE, Florence (Italy) was used. The slant TEC data were obtained using GPS satellite tracked by 14 ground stations in Europe. In general TEC were given every 30 seconds for all the time of interest. It is important to notice that, since the method to estimate errors is based on the concept of coinciding pierce points, it is difficult to make meaningful statistics due to the reduced number of such coinciding points. At a fixed epoch it is possible to find pairs of satellite paths that determine “coinciding” pierce points were (if pp1 and pp2 are the two pierce points of a given path ground satellite) “coinciding” means:

|lat pp1 – lat pp2| < 0.2 deg and |long pp1/cos(lat pp1) – long pp2/cos(lat pp1)| < 0.2 deg

In such a case, ptec1 should be equal to ptec2. If ptec1 is different from ptec2 it can be said that at least one of the two ptec is affected by an error that, in absolute value, is at least |ptec2 – ptec1| / 2. In particular ptec1=ptec2 does not mean that there is no error as it is found in cases with three coinciding Pierce Points. As an example of the results obtained nthe number of cases for which |ptec2 - ptec1| > 5 TECu and, among them, how many correspond to situations for which one satellite has an elevation mask of 85 deg are indicated in Table 1.

TABLE 1

Day	|ptec2 - ptec1| > 5 TECu	|ptec2 - ptec1| > 5 TECu and elvation of one satellite > 85 deg
10 Jul 2000	280	11 (|ptec2-ptec1| aver = 6.7 TECu)
11 Jul 2000	312	0
12 Jul 2000	117	0
24 Jul 2000	118	0
25 Jul 2000	231	10 (|ptec2-ptec1| aver = 6.5 TECu)
26 Jul 2000	145	0

The results obtained with experimental data tend to confirm the trend found with systematic simulations done using NeQuick model.

CONCLUSIONS

Error behavior with respect to satellite elevation angle and azimuth is determined by spatial electron density gradients. In particular is possible to appreciate the superimposition of the Equatorial Anomaly and solar terminator effects.

The results obtained suggests a way to “build-up” an error function, that applied to Vertical TEC, could allows to “bound” the error on Slant TEC after “back conversion”.

Appropriate model simulations could indicate the influence of Earth curvature, latitudinal and longitudinal gradients on conversion error as a function of location and satellite elevation and azimuth. Checks of the results obtained with the simulations can be done using experimental GPS derived sTEC as indicated by the preliminary results indicated.

REFERENCES

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