COMPARISON OF GPS/GALILEO SINGLE FREQUENCY IONOSPHERIC MODELS WITH VERTICAL TEC MAPS

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ABSTRACT. The ionospheric delay is the major current source of potential range delay for single-frequency GNSS users (Kunches and Klobuchar, 2001). Single-frequency GNSS users are in most need of an ionospheric model to eliminate the ionospheric delay to a high degree of accuracy. GPS system uses the Klobuchar model for this task, which its coefficients are sent through the GPS navigation message to GPS users. Klobuchar model uses the Ionospheric Corrections Algorithm (ICA) (Klobuchar, 1987) designed to account for approximately 50% (rms) of the ionospheric range delay. NeQuick model is a model of the electron concentration profile that has been developed in the framework of the European Commission COST action 251. NeQuick model is being proposed for single-frequency operation in the European Galileo GNSS system (Radicella et al., 2003). A comparison study between the behaviour of the GPS Single-frequency ionospheric modelling (Klobuchar model) and the Galileo proposed approach for this task (NeQuick model) will be presented in this paper. The range delay correction by the two models has been assessed using the IGS-Global Ionospheric Maps for three different-latitude stations to reflect different geographic ionospheric activity states. The study was carried out over three different months that each of them reflects a different state of solar activity, which is a major indication for the ionospheric development state.

Keywords: 1. GPS 2. Galileo 3. Ionospheric modelling

1. INTRODUCTION

GNSS users face many error sources that affect the quality of GNSS operations. These errors have different sources namely; satellite dependent errors (satellite orbital error, satellite clock error and relativistic effects), receiver dependent errors (receiver clock error and antenna phase centre variations) and signal path dependent errors (ionospheric errors, tropospheric errors, cycle slips and multipath). The ionospheric error is the major source of error faced by single-frequency GNSS users however using double-frequency GNSS measurements could eliminate the ionospheric error to a high degree of accuracy. The urgent need to eliminate the ionospheric error by single-frequency GNSS users creates the necessity of different options for different GNSS systems. GPS, the American GNSS system uses the Klobuchar model (Klobuchar, 1982) to eliminate the ionospheric error to a certain degree of accuracy.

The development studies of Galileo, the future European GNSS system which assumes to offer better performance than GPS propose using NeQuick model to eliminate the ionospheric error for single-frequency operations (Radicella et al., 2003). NeQuick model is a model of the electron concentration profile that has been developed by the Aeronomy and Radiopropagation Laboratory of the Abdus Salam ICTP in Trieste, Italy and at the Institute of

Geophysics, Astrophysics and Meteorology of the University of Graz, Austria in the framework of the European Commission COST action 251. A number of studies investigated the behaviour of NeQuick model (Azpilicueta et al., 2003), (Coisson et al., 2004), (Aragon Angel et al., 2005)

This paper presents a comparison study between the behaviour of the GPS ionospheric model (Klobuchar model) and the proposed Galileo ionospheric model (NeQuick model) with respect to the IGS-Global Ionospheric Maps (GIM's) whose accuracy is (2-8 TECU) (IGS, 2006) for three stations over a period of three months. The range delay correction offered by both models was assessed using the range delay extracted using the IGS-GIM's. The study involved different ionospheric activity geographical regions (near-equatorial, medium and high latitudes) as well as different ionospheric activity states with respect to the solar activity (quiet, medium and active ionospheric activity states).

The paper started with a short description of the Klobuchar model and the NeQuick model then the study will be presented followed with discussion and finally the main conclusions will be revealed.

2. KLOBUCHAR MODEL

The Klobuchar model (Klobuchar, 1982), was designed based on the Bent model (Llewellyn and Bent, 1973). The model is built on a simple cosine representation of the ionospheric delay, with a fixed phase-zero at 14.00 hours local time and a constant night time offset of 5 nanoseconds. The period and amplitude of the ionospheric delay are represented as third degree polynomials in local time and geomagnetic latitude. The eight time-varying coefficients of the two polynomials are broadcast in the GPS navigation message. These coefficients are selected from 370 possible sets of constants by the GPS master control station and placed in the satellite upload message for downlink to the user. These coefficients are based on two parameters, day of the year and average solar 10.7-cm flux value (the solar flux density at 10.7cm wavelength) for the previous five days. One year is divided into 37 ten-day-periods. Each period is represented by ten different solar activity levels. The following solar flux numbers separate the different solar activity levels: 75, 100, 120, 140, 155, 170, 185, 200, 215 and 230 flux units. Solar activity less than 75 flux units is set to level 1 and greater than 230 flux units is set by default to level 10 (Komjathy, 1997). Based on my sample data set, the average update range of the coefficients is of 1 to 10 days.

The model assumes an ideal smooth behaviour of the ionosphere, therefore any significant fluctuations from day to day will not modelled properly. The accuracy of the model is limited to 50-60% of the total effect (Dodson, 1988). Under special circumstances, such as severe ionosphere activity at low elevations, the range error can be of order of 50 m (Newby et al., 1990).

This model has one main advantage, which is its simplicity and the low computation time but it also has many shortcomings:

- Low accuracy for computing the ionospheric delay correction (50-60%) (Dodson, 1988)
- The algorithm does not properly represent the behaviour of the ionosphere in the near-equatorial region of the world, where the highest values of the ionospheric delay are occurred (Klobuchar, 1982).
- The algorithm is very poor in high latitude regions where the ionospheric variability is high due to auroral processes.
- The model is unable to represent the behaviour of the ionosphere when the ionosphere differs by substantial amounts from its average behaviour.

3. NEQUICK MODEL

NeQuick model is based on the original profiler proposed by Di Giovanni and Radicella (1990) (DGR) and able to give the electron concentration distribution on the bottomside and topside of the ionosphere as well as the ionospheric Total Electron Content (TEC). The model has been used by the ESA EGNOS project for assessment analysis.

The basic input parameters of the model are geographic coordinates, epoch, solar activity index and values of foF2 and M(3000)F2. Different options for the input or derivation of these two parameters could be used depending on the purpose. Amongst these options are, International Telecommunication Union-Radiocommunication sector (ITU-R) coefficients (CCIR, 1967), measured values, regional grid values maps, regional or global maps based on (effective ionisation level) AZ derived from regional or global vertical TEC maps and global maps based on Az values calculated from slant TEC values measured from sets of ground stations. The last option is the proposed option for operational purposes in satellite navigation. The NeQuick model with the ITU-R ionospheric coefficients could be installed in a Galileo receiver such that the model would be driven using the Az parameter that is a function of the receiver location and satellite ray-path. The Az parameter would be determined from measured slant TEC data obtained during the previous 24 hours at monitoring stations distributed around the world. The Az parameter would be broadcasted to the user in the navigation message and updated at least once a day (Radicella et al., 2003).

The output of the model is the electron density in the ionosphere as a function of height, geographic coordinates and epoch in Universal Time or Local Time. It is worth mentioning that for Galileo application the output of the model is the integrated slant TEC along the ray-path satellite-receiver, however for this particular study the model is used to produce vertical TEC for the sake of comparison with Klobuchar model.

4. BEHAVIOUR TEST STUDY

The study's objective is to compare the behaviour of the Klobuchar and NeQuick models with respect to the IGS-GIM's under different ionospheric-activity circumstances. For this purpose, three different-latitude stations (Table (1)) have been chosen to reflect different ionospheric activity regions (near-equatorial, middle-latitude and high-latitude geographic regions). The study compared the range delay corrections offered by the two models with respect to the IGS-GIM's for (GPS-L1 frequency and Galileo-E2L1E1) (1575.42 MHz) over three different months (Table (2)) which each month of them reflects a different state of solar activity based upon Sun Spot Number (SSN) which is a major indication of ionospheric activity states (quiet, medium and active ionospheric activity states) (SIDC, 2007). The tested periods are quiet (free from disturbed ionospheric conditions) as Kp-index (WDC, 2007) shows (Table (2)), so the GNSS correction are expected to be reliable.

The input data for Klobuchar model were: GPS Time (sec. of week), signal-frequency (MHZ), Station Latitude & Longitude (radians), Elevation of Satellite above Station (radians), Azimuth of Satellite from Station (radians) and klobuchar parameters array (a0,a1,a2,a3,b0,b1,b2,b3). The input data for Nequick model were: Time (year, month, day, UT), ground station (latitude, longitude), Satellite (elevation, azimuth) and Sunspot Number (R12). The average vertical range delay at L1 of the two models and GIM's over one day were plotted in the following figures. Also the RMS values were computed using those daily averages.

Table 1: the geographical positions of the tested stations

Station ID	Latitude degree	Longitude degree	Height meters	Country
ASWAN	24.088 N	32.899 E	79.000	Egypt
IESSG	52.941 N	1.1923 W	98.495	UK
NYAL	78.930 N	11.870 E	82.000	Norway

Table 2: the dates and activity states of the tested periods

Activity state	Quiet	Medium	Active
Month	February 1998	April 1999	September 2001
Kp-index	2	3	3

4.1 NEAR-EQUATORIAL GEOGRAPHIC REGION

The study's findings for ASWAN station which represent the near-equatorial geographic region which can be characterized with the highest values of the peak-electron density with the most pronounced amplitude and phase scintillation effects, are shown in Figures 1, 2 and 3. These figures show the average daily range delay correction offered by the Klobuchar model, NeQuick model and the IGS-GIM's. The average daily range delay differences between both models and the IGS-GIM's are shown in Figures 4, 5 and 6.

Figure 1: L1 range delay correction (ASWAN station) (February, 1998)

Figure 2: L1 range delay correction (ASWAN station) (April,1999)

Figure 3: L1 range delay correction (ASWAN station)(September,2001)

Figure 4: L1 range delay difference (ASWAN station) (February,1998)

Figure 5: L1 range delay difference (ASWAN station) (April,1999)

Figure 6: L1 range delay difference (ASWAN station)(September,2001)

4.2 MIDDLE-LATITUDE GEOGRAPHIC REGION

The study's findings for IESSG station which represent the middle-latitude region which is the least variable and undisturbed region among the different ionospheric regions, are shown in Figures 7, 8 and 9. These figures show the average daily range delay correction offered by the Klobuchar model, NeQuick model and the IGS-GIM's. The average daily range delay differences between both models and the IGS-GIM's are shown in Figures 10, 11 and 12.

Figure 7: L1 range delay correction (IESSG station) (February,1998)

Figure 8: L1 range delay correction (IESSG station) (April, 1999)

Figure 9: L1 range delay correction (IESSG station) (September, 2001)

Figure 10: L1 range delay difference (IESSG station) (February,1998)

Figure 11: L1 range delay difference (IESSG station) (April,1999)

Figure 12: L1 range delay difference (IESSG station)(September,2001)

4.3 HIGH-LATITUDE GEOGRAPHIC REGION

The study's findings for NYAL station which represent the high-latitude region where the aurora activity takes place as another source of the ionosphere's ionization, are shown in Figures 13, 14 and 15. These Figures show the average daily range delay correction offered by the Klobuchar model, NeQuick model and the IGS-GIM's. The average daily range delay differences between both models and the IGS-GIM's are shown in Figures 16, 17, and 18.

Figure 13: L1 range delay correction (NYAL station) (February,1998)

Figure 14: L1 range delay correction (NYAL station) (April, 1999)

Figure 15: L1 range delay correction (NYAL station) (September, 2001)

Figure 16: L1 range delay difference (NYAL station) (February,1998)

Figure 17: L1 range delay difference (NYAL station) (April,1999)

Figure 18: L1 range delay difference (NYAL station)(September,2001)

The RMS of the L1 average daily range delay differences for the different geographical regions (stations) as well as different ionospheric activity states (tested time periods) are shown in Tables 3, 4 and 5.

Table 3: The RMS (metres) for L1 range delay difference for near-equatorial geographic region

Time	Ionospheric Activity State	Near-equatorial region ASWAN station	
		Klobuchar model	NeQuick model
February 1998	Quiet	0.843	1.095
April 1999	Medium	0.959	1.252
September 2001	Active	1.171	1.570

Table 4: The RMS (metres) for L1 range delay difference for middle-latitude geographic region

Time	Ionospheric Activity State	Middle-latitude region IESSG station	
		Klobuchar model	NeQuick model
February 1998	Quiet	1.030	0.357
April 1999	Medium	1.038	0.756
September 2001	Active	1.337	1.479

Table 5: The RMS (metres) for L1 range delay difference for high-latitude geographic region

Time	Ionospheric Activity State	High-latitude region NYAL station	
		Klobuchar model	NeQuick model
February 1998	Quiet	0.831	0.339
April 1999	Medium	0.670	0.496
September 2001	Active	0.873	0.753

5. DISCUSSION

It can be concluded from Figures 1, 2 and 3 that for near-equatorial geographic region, the Klobuchar model is offering better behaviour than the NeQuick model as it provides range corrections more closely to the IGS-GIM's corrections. NeQuick model is able to show day-to-day variations in the range delay corrections due to its dependence on daily values of average sun spot number while Klobuchar model is unable to show day-to-day variations as the ionospheric coefficients sent in the GPS navigation message is not updated on daily basis. It can be seen that the Klobuchar model-ionospheric coefficients sent in the GPS navigation message were updated four times during February 1998 (quiet ionospheric state), eight times during April 1999 (medium ionospheric state) and fourteen times during September 2001 (active ionospheric state). It can be concluded from Table 3 that for near equatorial-latitude geographic region, the behaviour of Klobuchar model is better than the NeQuick model by 23% rms for quiet ionospheric activity state. For medium ionospheric activity state, the behaviour of Klobuchar model is better than the NeQuick model by 23.4% rms. Also for the active ionospheric state, the behaviour of Klobuchar model is better than the NeQuick model by 25.4% rms.

It can be concluded from Figures 7, 8 and 9 that for middle-latitude geographic region, the NeQuick model is offering better behaviour than the Klobuchar model as it provides range corrections more closely to the IGS-GIM's corrections except for active ionospheric activity state. NeQuick model is able to show day-to-day variations in the range delay corrections while Klobuchar model is unable to show day-to-day variations due to the limitations in the GPS navigation message- ionospheric coefficients updating. It can be concluded from Table 4 that for middle-latitude geographic region, the behaviour of NeQuick model is better than the Klobuchar model by 65.3% rms for quiet ionospheric activity state. For medium ionospheric activity state, the behaviour of NeQuick model is better than the Klobuchar model by 27.1% rms. However for the active ionospheric state, the behaviour of Klobuchar model is better than the NeQuick model by 9.6% rms.

It can be concluded from Figures 13, 14 and 15 that for high-latitude geographic region, the NeQuick model is offering better behaviour than the Klobuchar model as it provides range corrections more closely to the IGS-GIM's corrections during all states of ionospheric activity. It can be concluded from Table 5 that for high-latitude geographic region, the behaviour of NeQuick model is better than the Klobuchar model by 59.2% rms for quiet ionospheric activity state. For medium ionospheric activity state, the behaviour of NeQuick model is better than the Klobuchar model by 26% rms. Also for the active ionospheric state, the behaviour of NeQuick model is better than the Klobuchar model by 13.7% rms.

Generally, NeQuick model offers better behaviour in correcting range delay comparing with Klobuchar model in middle-latitude and high-latitude geographic regions where the ionosphere is less variable and the TEC values are not at maximum values comparing with near-equatorial regions. However, NeQuick model offers poor behaviour comparing with

Klobuchar model in near-equatorial regions where the ionosphere's variability is high and the TEC values at maximum.

6. CONCLUSIONS

NeQuick model, the proposed Galileo model for single-frequency ionospheric operations offers better behaviour in correcting range delay comparing with Klobuchar model, the used GPS model for single-frequency ionospheric operations in middle-latitude and high-latitude geographic regions. However, NeQuick model offers poor behaviour comparing with Klobuchar model in near-equatorial regions where the ionosphere's variability is high and the TEC values at maximum.

NeQuick model is able to show day-to-day variations in the range delay corrections due to its dependence on daily values of average sun spot number while Klobuchar model is unable to show day-to-day variations due to the limitations in the GPS navigation message-ionospheric coefficients updating.

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