Vermessung & Geoinformation 2/2007, P. 80 – 89, 6 Figs.

Global models of the ionosphere obtained by integration of GNSS and satellite altimetry data

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Abstract

The high free-electron and ion density in the ionosphere disturbs both the group and phase velocity of the signals of all space geodetic techniques, operating in the microwave band. In first approximation this delay is proportional to the so-called Slant Total Electron Content (STEC) along the ray path and can be corrected only if the measurements are carried out at two distinct frequencies. On the other hand, this effect allows information to be gained about the parameters of the ionosphere in terms of Total Electron Content (TEC) values. The classical input data for the development of Global Ionosphere Maps (GIM) of the total electron content is obtained from dual-frequency Global Navigation Satellite System (GNSS) observations. However, the GNSS stations are inhomogeneously distributed, with large gaps particularly over the sea surface, which lowers the precision of the GIM over these areas. On their part, dual-frequency satellite altimetry missions such as Jason-1 provide information about the ionosphere precisely above the sea surface. Due to the limited spread of the measurements and some open questions related to their systematic errors, the ionospheric data from satellite altimetry is used only for cross-validation of the GNSS GIM so far. It can be anticipated however, that some specifics of the ionosphere parameters derived by satellite altimetry will partly balance the inhomogeneity of the GNSS data. In this study we create two-hourly GIM from GNSS data and additionally introduce satellite altimetry observations, which help to compensate the insufficient GNSS coverage of the oceans. Furthermore, this method allows the independent estimation of systematic instrumental errors, affecting the two types of measurements. Thus, besides the daily values of the Differential Code Biases (DCB) for all GNSS satellites and receivers, also a constant daily bias for the Jason-1 satellite is estimated and investigated.

Kurzfassung

Durch die hohe Dichte von freien Ionen und Elektronen in der Ionosphäre werden die Beobachtungen aller geodätischen Weltraumverfahren, die im Mikrowellenbereich operieren, verzögert. Die Laufzeitverzögerung der Beobachtungsstrahlen ist in erster Näherung proportional zum so genannten Gesamtelektronengehalt entlang des Strahlenwegs (Slant Total Electron Content, STEC). Dieser Effekt kann nur dann korrigiert werden, wenn die Messungen auf zwei verschiedenen Frequenzen erfolgen. Auf diese Weise lässt sich aber auch Information über die Ionosphärenparameter in Form von TEC-Werten gewinnen. Die klassischen Eingabedaten für die Entwicklung globaler Karten der Ionosphäre (Global Ionosphere Maps, GIM) sind Zweifrequenzbeobachtungen des Globalen Satellitennavigationssystems (Global Navigation Satellite System, GNSS). Die GNSS-Stationen sind jedoch nicht homogen auf der Erde verteilt, wobei vor allem die Meeresoberfläche schlecht abgedeckt ist. Andererseits liefern die Zweifrequenz-Messungen von Satellitenaltimetrie Missionen wie Jason-1 Information für die Ionosphärenparameter genau über den Ozeanen. Aufgrund der begrenzten Verteilung dieser Messungen, sowie einiger offenen Fragen bezüglich der systematischen Fehler, werden die Altimetrie Daten derzeit nur zur Validierung der GNSS GIM genutzt. Man kann jedoch annehmen, dass gewisse Besonderheiten der Ionosphärenparameter, die von Satellitenaltimetrie-Messungen erhalten werden, die Inkonsistenzen der GNSS Beobachtungen ausgleichen können. In dieser Studie werden für die Erzeugung globaler Ionosphärenkarten in zweistündigen Intervallen neben GNSS auch Messungen aus Satellitenaltimetrie herangezogen, deren Verteilung die mangelhafte GNSS-Abdeckung der Meeresoberfläche auszugleichen hilft. Außerdem erlaubt diese Methode die unabhängige Schätzung von systematischen, technik-spezifischen Fehlern. Deshalb wird neben den täglichen Werten der instrumentellen Einflüsse (Differential Code Biases, DCB) aller GNSS Satelliten und Empfänger auch ein konstanter täglicher Jason-1 Messfehler geschätzt und untersucht.

1. The ionosphere and its impact on space geodetic techniques

The Earth's ionosphere is defined as that part of the upper atmosphere where the density of free electrons and ions is high enough to influence the propagation of electromagnetic radio frequency waves [9]. The boundaries of this area are roughly set between 50 and 1000 km above the Earth's surface. The ionisation process is primarily driven by the Sun's activity and varies strongly with time, as well as with geographical location. The diurnal maximum of free electrons and ions occurs around local noon; as for the spatial variations, the low latitude and equatorial regions are characterized by stronger ionization than the high latitudes.

When electromagnetic waves travel through the ionosphere, the integration between the electromagnetic field and the free electrons influences both the speed and the propagation direction of the signals. This effect is known as ionospheric refraction [10] and has to be considered in the determination of the propagation velocity of the signals of all space geodetic techniques operating with electromagnetic waves (Fig. 1).

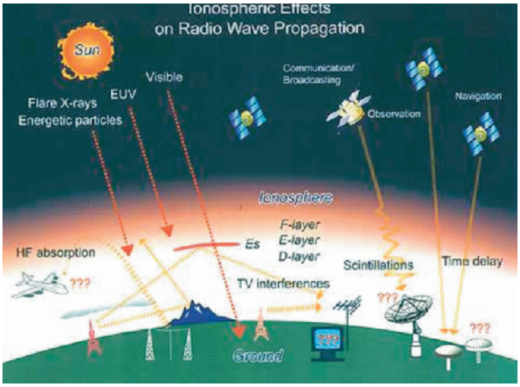

Figure 1: Ionospheric effects on radio wave propagation (http://www2.nict.go.jp/)

The ionospheric refraction disturbs the group and phase velocity of the signals by the same amount but with different sign. The effect of the refraction can be determined in terms of STEC (Slant Total Electron Content), which is the integral of the electron density along the signal path *S* - see equations (1) and (2). This quantity represents the total amount of free electrons in a cylinder with a cross section of 1m^2 and the slant signal path as axis. STEC is measured in Total Electron Content Units (TECU), with 1 TECU equivalent to 10^{16} electrons/m^2. Equations (1) and (2) express the effect in meters of the ionised medium on phase and group signal propagation:

$$I_{phase} = \int_S \left[\left(1 - \frac{40.28 N_e}{f^2}\right) - 1\right] dS = -\frac{40.28}{f^2}\int_S N_e\, dS = = -\frac{40.28 \cdot 10^{16}}{f^2} STEC, \qquad (1)$$

$$I_{group} = \int_S \left[\left(1 + \frac{40.28 N_e}{f^2}\right) - 1\right] dS = \frac{40.28}{f^2}\int_S N_e\, dS = = \frac{40.28 \cdot 10^{16}}{f^2} STEC, \qquad (2)$$

f ... carrier frequency in Hz,
N_e ... free electron density in the medium,
S ... slant signal path.

The measurements of nearly all space geodetic techniques operating with electromagnetic waves are carried out at two different radio frequencies, which allows the ionospheric influence to be eliminated by linear combinations of the observations. On the other hand, in this way information about the ionosphere parameters can be obtained. If the behaviour of the ionosphere is known, the ionospheric refraction can be computed via equations (1) and (2) and used to correct single-frequency measurements.

1.1. Probing the ionosphere through GNSS

The Global Navigation Satellite System (GNSS), presently consisting on GPS (Global Positioning System) and GLONASS (GLObal NAvigation Satellites System), provides information about the ionospheric refraction, enabling high resolution ionosphere imaging in longitude, latitude, and time (e.g. [2], [17], and references therein). Both observables of the system – carrier phase and code measurements – are affected by the ionosphere. According to equations (1) and (2), this effect depends on the signal frequency f and on the STEC between the satellite and the receiver. Thus, forming the so-called geometry-free linear combination by subtracting simultaneous observations at the two different frequencies L1 and L2, and in this way removing all frequency-independent effects (such as clock errors, troposphere delay etc.), leads to an observable, which contains only the ionospheric refraction and the inter-frequency hardware biases Δbk and Δb_i (usually in ns), associated with the satellite k and the receiver i. In this work carrier phase smoothed code observations are used and the ionospheric observable reads as:

$$\Phi^k_{i,4} = \Phi^k_{i,1} - \Phi^k_{i,2} = -\xi_4 \alpha I^k_i + c(\Delta b^k - \Delta b_i), \qquad (3)$$

$\Phi^k_{i,1}$, $\Phi^k_{1,2}$ ... carrier phase observations at the two frequencies, corrected by the carrier phase ambiguities,

I^k_i ... the ionospheric refraction between the satellite and the receiver related to L1 (in meters),

$\xi_4 = 1 - f_1^2/f_2^2$ ... factor for relating the ionospheric refraction on L4 to L1,

α ... constant used to convert meters into TECU.

The ionospheric parameters derived from the geometry-free linear combination are affected by inter-frequency hardware biases (e.g. [15]), also called Differential Code Biases (DCB); when modelling the ionosphere it is necessary to estimate them as additional unknowns.

In 1998 a special Ionosphere Working Group of the International GNSS Service (IGS) was initiated for developing global ionospheric TEC maps ([8] and [12]). Up to now, four Analysis Centres (AC) - Centre for Orbit Determination in Europe (CODE) [13] and [17], European Space Agency (ESA) [7], Jet Propulsion Laboratory (JPL) [15], and Universidad Politécnica de Cataluña (UPC) [11], deliver daily global maps of vertical TEC and DCB values in the IONospheric EXchange (IONEX) format [16] by using different estimation methods. Since the end of 2005 a combined IGS solution is also available.

1.2. Ionosphere parameters provided by satellite altimetry

Satellite altimetry missions with double-frequency radar altimeter on-board, such as TOPEX/ Poseidon (T/P) and Jason-1 provide information about the ionosphere in the form of Vertical Total Electron Content (VTEC). The T/P mission was launched in August 1992 for observing the ocean circulation and was operational till October 2005. Jason-1, launched in December 2001, is the follow-on to T/P and has inherited its main features – orbit, instruments, measurement accuracy, etc. The orbit altitude of the two missions is 1336 km. The primary sensor of both T/P and Jason-1 is the NASA Radar Altimeter operating at 13.6 GHz (Ku-band) and 5.3 GHz (C-band), simultaneously. The two widely separated frequencies allow TEC to be detected directly from the nadir altimetry sampling data along the satellite track [14].

1.3. TEC derived from GNSS and satellite altimetry - key issues

The TEC estimates from GNSS and from satellite altimetry measurements have often been compared in order to asses the precision of the two techniques (e.g. [3], and references therein). Generally, the agreement between GNSS and altimetry derived TEC is good, but there are still some contradictions, which need further investigation. One important topic is the better understanding of the frequency-dependent systematic errors in the altimetry measurements, which would bias both the sea-level height and the TEC estimates [4]. The TEC values obtained by satellite altimetry are expected to be lower than the ones coming from GNSS because opposite to GNSS, the altimetry satellites do not sample the topside ionosphere due to their lower orbit altitude. However, several studies have shown that T/P and Jason-1 systematically overestimate the vertical TEC by about 3–4 TECU compared to the values delivered by GNSS (i.e. [1] and [3]). On the other hand, most of the ionosphere models from GNSS data are based on the Single Layer Model (SLM, described in section 2.), which does not account well for the ionospheric contribution above the altitude of the altimetry missions [3]. Furthermore, it has to be pointed out that when using SLM the STEC values derived from GNSS measurements have to be converted into vertical TEC (VTEC), while the altimetry missions deliver directly the vertical values. The mapping function (see equation (4)) used for this convertion is a potential error source for the GNSS TEC estimates. Finally, for comparing with altimetry TEC, the values derived from GNSS have to be interpolated for regions far from the observing stations – that is above the oceans, i.e. such comparisons are performed in the worst scenario for GNSS.

The differences between GNSS and altimetry derived TEC as well as the systematic errors of the Jason-1 satellite are treated in more detail in subsection 3.2.

2. Development of 3D global ionosphere maps

The global maps created in this study represent the ionosphere in longitude, latitude and time and are based on the Single Layer Model (SLM). SLM assumes that all free electrons are concentrated in an infinitesimally thin layer above the Earth's surface. The height H of this thin shell is usually set at the height, where the highest electron density is expected, which is between 300 and 450 km. A signal transmitted from the satellite to the receiver crosses the ionospheric shell in the so-called ionospheric pierce point. The zenith angle at that point is z' and the signal arrives at the ground station with zenith distance z. The relation between the measured slant TEC along the ray path and the vertical value at the pierce point is given by a mapping function (4). In this study the Modified Single Layer Model (MSLM) was adopted (as in [5], and [6]) and the mapping function for the transformation between STEC and VTEC reads as:

$$F(z) = \frac{STEC}{VTEC} = \frac{1}{\cos z'} = \frac{1}{\sqrt{1-\left(\frac{R_e}{R_e+H}\sin(\alpha z)\right)^2}}, \qquad (4)$$

with $\alpha = 0.9782$, $H = 506.7$ km and R_e – the Earth radius.

The GNSS-derived STEC values are extracted from the geometry-free linear combination applied on dual-frequency carrier-phase smoothed code observations, as shown in equation (3). Data from around 190 stations of the International GNSS Service (IGS) is used with sampling rate of 30 seconds. In the case of satellite altimetry, the ionospheric refraction extracted from the double-frequency measurements of Jason-1 is adopted and converted into VTEC by a factor depending on the operational frequency of the altimeter. A spherical harmonic extension up to degree and order 15 is chosen for the global representation of VTEC, as a function of geomagnetic latitude and sun-fixed longitude [17]:

$$E_V(\beta,s) = \sum_{n=0}^{n_{max}} \sum_{m=0}^{n} \tilde{P}_{nm}(\sin\beta)(a_{nm}\cos(ms)+b_{nm}\sin(ms)), \tag{5}$$

E_V ... Vertical Total Electron Content,

β ... geomagnetic latitude of the ionospheric pierce point,

$s = \lambda_G + UT - \pi$ ... sun-fixed longitude of the ionospheric pierce point,

λ_G ... geographical longitude,

$\tilde{P}_{nm} = N_{nm}P_{nm}$ ... normalized Legendre function from degree n and order m,

a_{nm}, b_{nm} ... unknown coefficients of the spherical extension.

A software based on Matlab was developed for computation of 12 two-hourly global VTEC maps per day, the corresponding RMS (Root Mean Square) maps, and daily values of the DCB for all GNSS satellites and receivers. The VTEC and RMS values are estimated for grid points in an interval of ±5° in longitude and ±2.5° in latitude. The final outputs are in the IONEX [16] format.

For the combination of GNSS and altimetry data a least-squares adjustment (Gauss-Markov model) is applied on each set of observations and then the normal equations are combined by adding the relevant matrices. At this stage of our work, we adopt equal weights ($p_{GNSS} = 1$) for all GNSS observations in both the GNSS-only and the combined solution. As for the relative weighting of the altimetry data, different strategies are possible. On the one hand, due to the much higher number of GNSS measurements compared to satellite altimetry, the Jason-1 data should be over weighted, in order to increase its impact on the combined GIM. For the combined GIM presented in section 3.2 we adopt the a priori standard deviation $\sigma_0 = 0.25$ TECU ($p_{ALT} = 4$) for the altimetry measurements, which was determined experimentally. In the case of overweighting the Jason-1 data, however, it becomes crucial to assess the bias between GNSS and altimetry TEC, discussed in section 1.3. On the other hand, if we take into account the higher noise of the altimetry measurements compared to the carrier-phase smoothed code observations from GNSS, a lower weight should be applied on the Jason-1 derived observations than on the ones from GNSS. It has to be pointed out, that the relative weighting acts like a scaling factor for the contribution of the altimetry data in the combined GIM. It is a very complex issue, depending on the different spatial and temporal distribution of the observations and on their specific systematic errors. Therefore, the relative weighting of the two types of measurements needs to be optimised and is a matter of further investigation. Nevertheless, the spatial distribution of the altimetry observations (see Fig. 2) partly balances the gaps over the oceans between the GNSS stations, which is the main motivation behind adding altimetry data to the GNSS ionosphere model.

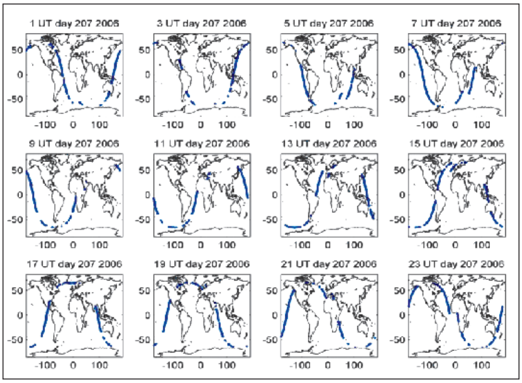

Figure 2: Jason-1 footprints in two-hourly snapshots, day 207 2006

3. Results

The ionosphere models computed within this work are referred to as IGG (Institute of Geodesy and Geophysics) GNSS-only or IGG COMB (GNSS combined with altimetry data) Global Ionosphere Maps. The presented GIM refer to the 26th of July in 2006 (DOY 207). For validation of the obtained results, all IGG VTEC maps are routinely compared with the GIM provided by the IGS Analysis Centre CODE (Center for Orbit Determination in Europe, [5]). The bias and standard deviation of the difference CODE minus IGG are shown in the figure capture of the IGG VTEC maps (Fig.3a). It has to be mentioned, that the reference epochs of the IGG GIM (01, 03, 05, …, 23 UT) were set up at a very early stage of our work without taking into account the IGS conventions, and they do not overlap with the ones adopted in the IGS GIM (00, 02, 04, …, 24 UT).

Therefore, an interpolation in time is performed when computing the differences between the CODE and IGG maps, which can worsen the results of the comparison. The alignment of the IGG GIM reference epochs to the IGS convention is in progress.

3.1. IGG GNSS-only solution

The two-hourly IGG GNSS-only VTEC and RMS maps in two hours intervals for day 207 in 2006 are shown in figures 3a and 3b. The ionosphere maximum, which appears around local noon as travelling along with the Sun, is clearly visible in the VTEC maps (Fig. 3a). As anticipated, the precision of the GIM (Fig. 3b) is lower in areas where no GNSS sites are located, which is mainly above the sea surface.

In parallel to VTEC, the differential code biases for all GNSS satellites and ground stations are computed daily as constant values, with a zero-mean condition imposed on the satellite DCB. The results for day 207 in 2006 are shown in figures 4a and 4b. The estimated (IGG) values agree very well with the monthly DCB provided by the IGS Analysis Center CODE [5], especially for the GPS satellites and receivers. The lager differences in some of the DCB of the GLONASS system are subject of further investigation.

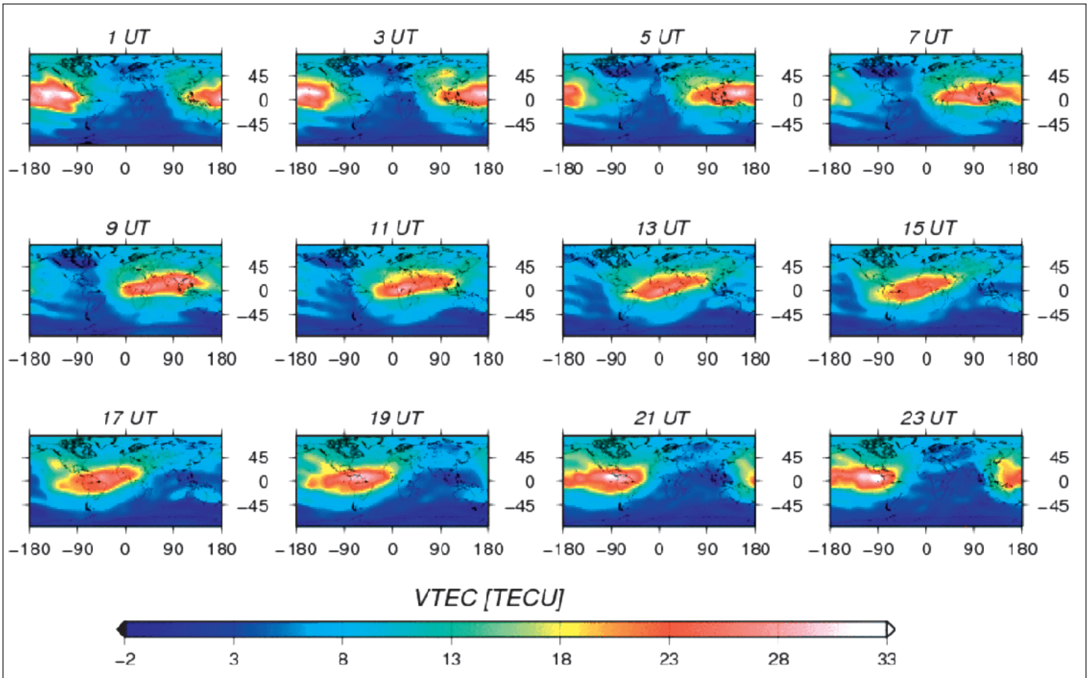

Figure 3a: *VTEC, IGG GNSS-only, DOY 207 2006; bias$^{code-igg}$ = −0.10 TECIU, std$^{code-igg}$ = 0.97 TECU*

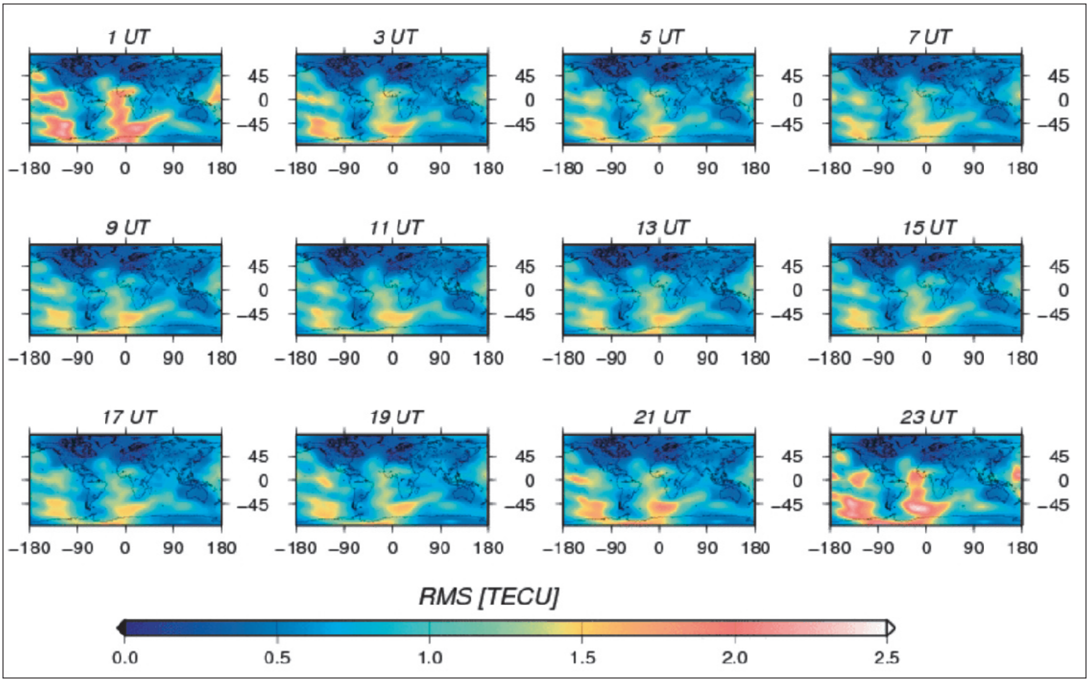

Figure 3b: RMS, IGG GNSS-only, DOY 207 2006

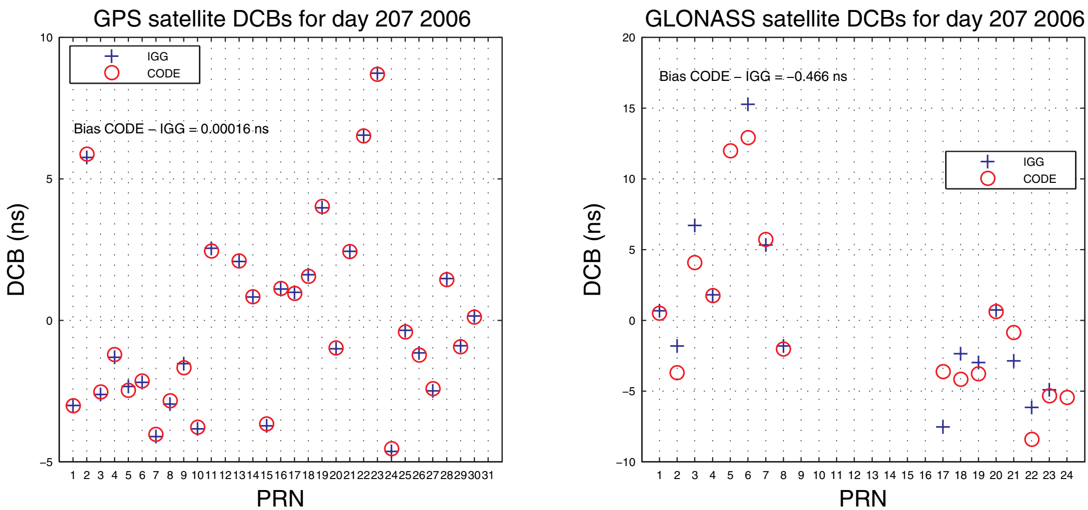

Figure 4a: Estimated GPS and GLONASS satellite DCB, IGG vs. CODE, day 207 2006

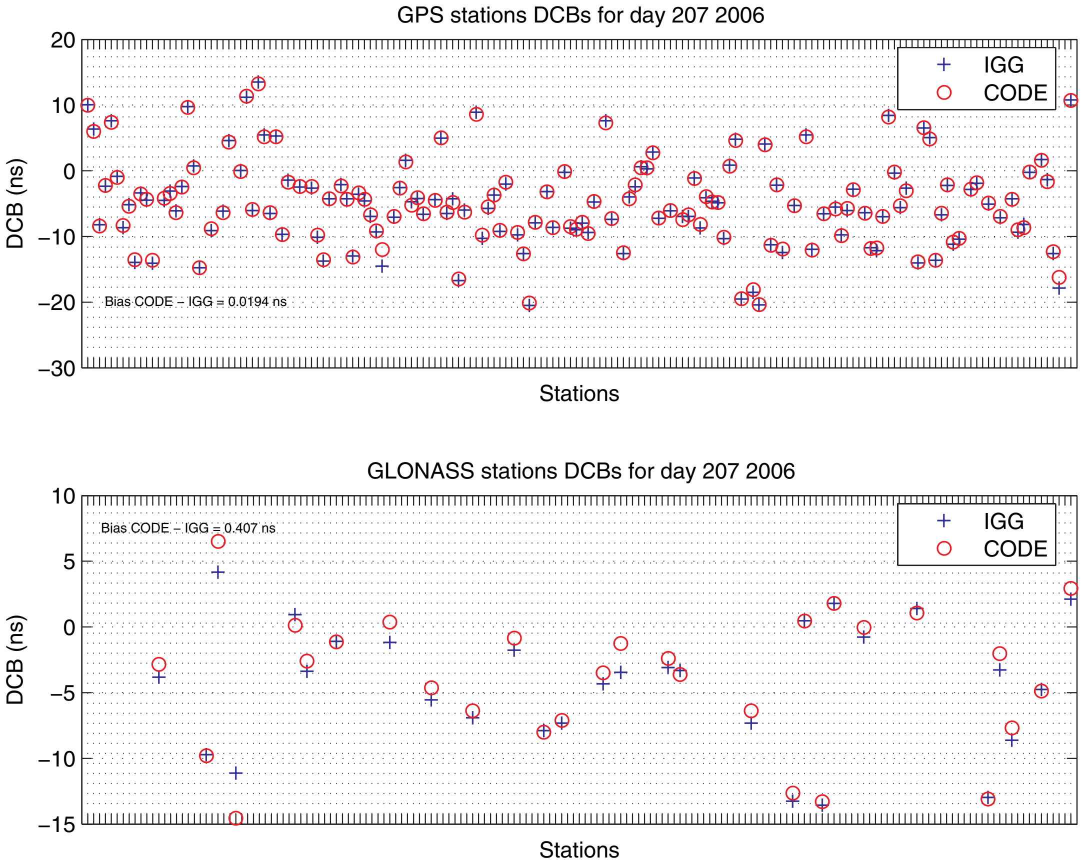

Figure 4b: Estimated GPS and GLONASS receiver DCB, IGG vs. CODE, day 207 2006

3.2. IGG COMB solution

The impact of altimetry data integration on the estimated GIM is evident over the areas coinciding with the footprints of Jason-1, shown in Fig.2. In the case of overweighting the altimetry data, the combination with Jason-1 measurements causes a decrease of the RMS up to 2 TECU and a general trend for increase of the VTEC values along the Jason-1 track (Fig.5). However, the bias between GNSS and altimetry TEC is a very important issue especially if a higher weight is applied to the altimetry data than to the GNSS measurements.

As mentioned in 1.3, several studies show that despite of the lower orbit altitude of the altimetry satellites, the vertical TEC delivered by these missions is higher than the values obtained from GNSS. Due to this contradiction it can be assumed, that the altimetry measurements are biased by an instrumental offset, similar to the GNSS DCB. The combination of ionosphere data from GNSS and altimetry, realised by stacking of the normal equations, allows the independent estimation of technique-specific time delays additionally to the combined ionospheric parameters. Thus, we developed combined ionosphere models for several subsequent days in 2006 with additional estimation of one constant Jason-1 bias per day, referred to as JB (Table 1). Since the Jason-1 bias is computed as a single unknown, it includes the effect of the plasmaspheric component (VTEC above ~1300 km height above the Earth's surface), additionally to the actual JASON instrumental offset.

DOY	*201*	*202*	*203*	*204*	*205*	*206*	*207*	*208*	*209*	*210*	*211*	*212*	*213*	*214*
JB	3.52	3.60	3.30	3.28	3.42	3.68	3.30	3.19	3.73	3.76	3.71	3.09	3.74	3.55

Table 1: Estimated daily Jason-1 bias in TECU

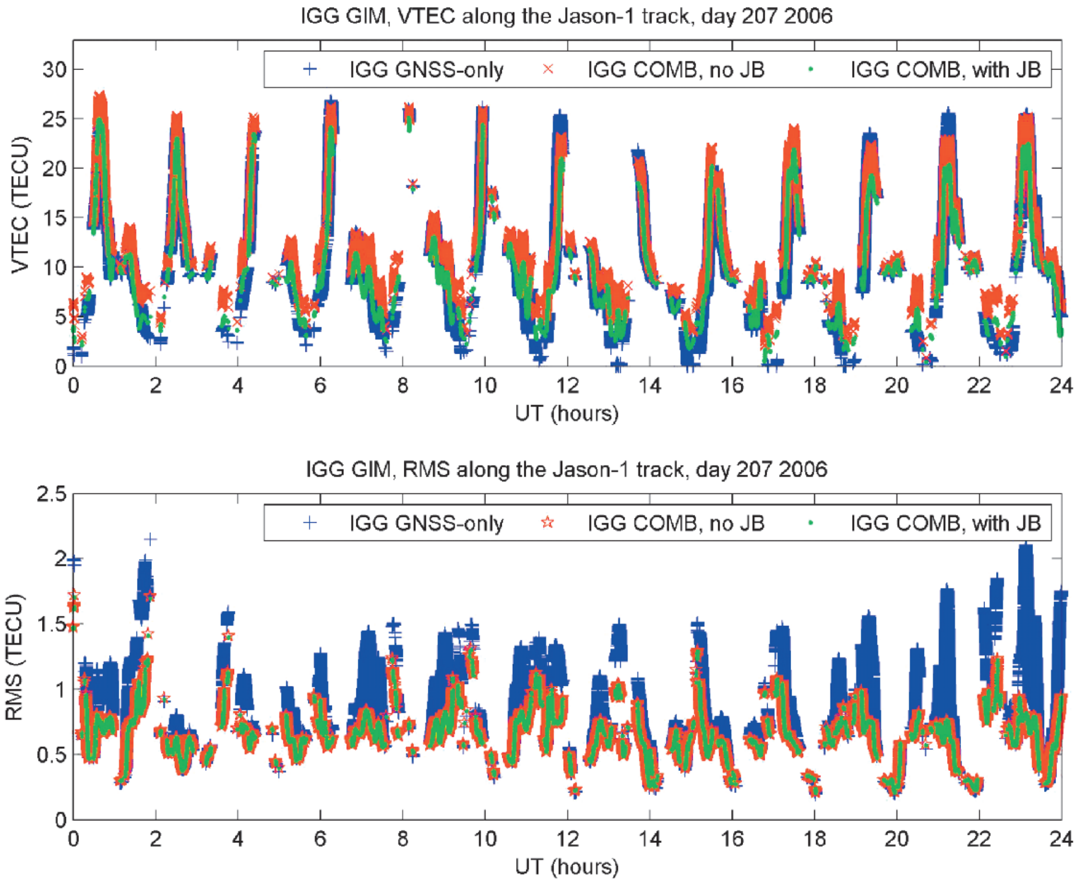

Figure 5: *VTEC and RMS interpolated along the Jason-1 track from the different IGG GIM, DOY 207 2006*

In order to demonstrate the differences between the GNSS-only and the combined IGG GIM, the VTEC and RMS values along the Jason-1 track were interpolated from the different IGG global maps for day 207 in 2006 – IGG GNSS-only GIM, IGG COMB GIM without estimation of Jason-1 bias, and IGG COMB GIM with Jason-1 bias estimated as a constant – and plotted as a function of time (Fig.5). Regarding the TEC values (Fig.5, upper plot), the IGG COMB without estimation of Jason-1 bias (IGG COMB, no JB) seems to generally overestimate the VTEC compared to the GNSS-only solution. The introduction of JB compensates this effect and acts as a negative offset as to the IGG COMB solution without JB, because the amount of TECU determined as Jason-1 bias (3.3 TECU for that day) does not contribute to the VTEC obtained from the altimetry data anymore. Nevertheless, there are also differences between the IGG GNSS-only and COMB with JB GIM. In the domain of low ionosphere activity (TEC below 10 TECU), which is mostly at mid and high latitudes, a general trend for increase of the VTEC values along the Jason-1 track is visible. This effect can be interpreted as the positive contribution of the altimetry data in areas, where nearly no GNSS observations are available. However, there is also a decrease of VTEC in the combined model, coinciding with the ionospheric maximum as it travels with the Sun along the geomagnetic equator. This decrease can be related to the insufficient performance of the altimetry measurements in low latitudes, caused by the contribution of the topside ionosphere. As already mentioned, the altimetry measurements do not account for the topside ionosphere and therefore, despite of the discussed TEC overestimation, the integration of altimetry data in the GNSS GIM leads to a decrease of the obtained TEC over the area where the plasmaspheric contribution reaches its maximum (see also Fig.6). As for the precision of the global maps, the lower plot in Fig.5 clearly shows the decrease of the RMS along the Jason-1 track caused by the combination. As it could be expected, the introduction of the Jason-1 bias has nearly no impact on the RMS of the combined GIM.

In order to investigate the obtained results and examine the self-consistency of our approach, we applied the same procedure, which is used for routine validation of the rapid and final global ionosphere maps produced by the IGS Analysis Centres (AC) [12]. In this validation procedure raw VTEC delivered by Jason-1 along its track is compared with the corresponding values interpolated from the global maps from GNSS data. The comparison was performed for 15 consecutive days in 2006 including the IGG GNSS-only and the IGG COMB GIM with estimated Jason-1 bias, as well as the official combined IGS GIM. Fig. 6 shows the mean bias for the regarded days of the final IGS solution and the two different IGG GIM compared to Jason-1. The comparison is performed in time (upper plot) and in latitude (lower plot). The difference between the raw Jason-1 VTEC and both the IGG and IGS GNSS-only GIM has a mean of about 3 TECU, with the IGS GIM performing slightly better than the IGG GNSS-only GIM. The magnitude of this difference generally corresponds to the estimated Jason-1 biases, shown in Table 1. As expected, with mean differences of –0.19 TECU in time and –0.09 TECU in latitude, the IGG COMB GIM with estimated JB coincides better with the Jason-1 raw data (after removing the computed offset), than the IGG and IGS GNSS-only solutions.

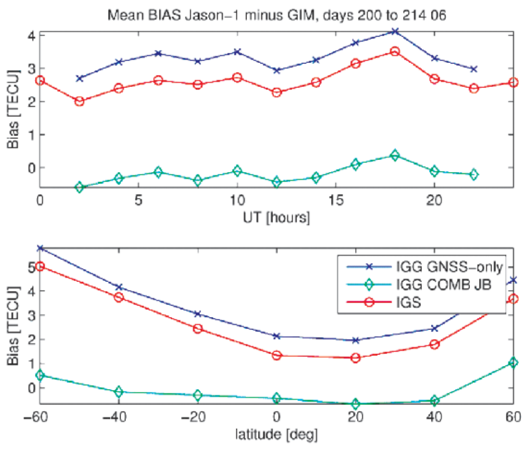

Figure 6: ΔVTEC, Jason-1 minus IGG and IGS GIM, DOY 207 2006

The plasmaspheric component is evident in the lower plot of Fig.6 as a decrease of the difference between Jason-1 and the GNSS-only solutions along the JASON orbital track at lower latitudes, where the topside ionosphere – not sampled from Jason-1 – reaches its maximum. As a next step of our study, the estimated constant Jason-1 bias will be replaced by a proper function of the latitude, which should account for the topside ionosphere. Such approach will improve the combined solution and, on the other hand, it could be used as a tool for rough estimation of the plasmaspheric component.

4. Conclusions and outlook

The combined GIM from GNSS and altimetry data have the potential to contribute to the accuracy of the global ionosphere maps especially over the seas, where none or only a few GNSS stations are located (worst case for GNSS). Still, the combined GIM must be optimised with main focus on the technique-specific error sources and the relative weighting of the individual results from the different techniques. Furthermore, the implementation of an appropriate function for modelling the Jason-1 offset could provide information about the topside ionosphere and improve the performance of the combined GIM. As a next step, a modified coordinate system can be adopted for improving the representation of the ionosphere and in this way enhancing the agreement between GNSS and altimetry derived TEC [1]. In order to achieve a global coverage and higher accuracy and reliability of the ionosphere models, the combination method can be adopted also for ionospheric data from other space geodetic techniques, such as VLBI and DORIS. For an objective validation of the results, they will be applied on single-frequency measurements, and then compared to the corresponding results from dual-frequency, in which the ionospheric effect is corrected.

Acknowledgements

Project P19564-N10 is funded by the Austrian Science Fund (FWF). Thanks to the International GNSS Service (IGS) and to ADSCentral, GFZ Potsdam, for the free supply with GNSS and altimetry data. We are also grateful for the free availability of the Generic Mapping Tools (GMT) and the GPS Toolkit (GPStk) software.

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