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Systematic differences between VTEC obtained by different space-geodetic techniques during CONT08

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Abstract The ionosphere is a dispersive medium for microwaves and most space-geodetic techniques using two or more signal frequencies can be applied to extract information on ionospheric parameters, including terrestrial as well as satellite-based GNSS, DORIS, altimetry, and VLBI. Because of their different sensitivity regarding ionization, their different spatial and temporal data distribution, and their different signal paths, a joint analysis of all observation types seems reasonable and promises the best results for ionosphere modeling. However, it has turned out that there exist offsets between ionospheric observations of the diverse techniques mainly caused by calibration uncertainties or model errors. Direct comparisons of the information from different data types are difficult because of the inhomogeneous measurement epochs and locations. In the approach presented here, all measurements are combined into one ionosphere model of Vertical Total Electron Content (VTEC). A Variance Component Estimation (VCE) is applied to take into account the different accuracy levels of the observations. In order to consider systematic offsets, a constant bias term is allowed for each observation group. The investigations have been performed for the time interval of the CONT08 campaign (two weeks in August 2008) in a region around the Hawaiian Islands. Almost all analyzed observation techniques show good data sensitivity and are suitable for VTEC modeling in case the systematic offsets which can reach up to 5 TECU are taken into account. Only the Envisat DORIS data cannot provide reliable results.

Keywords Ionosphere · Variance Component Estimation · Inter-technique biases

1 Introduction

Ionospheric information such as the Vertical Total Electron Content (VTEC) can be extracted from the measurements of most space-geodetic techniques. As the sensitivity of the different data sets is not uniform because of their different frequencies, their different measurement principles, and their different data distribution, a combination of all techniques not only improves the reliability and redundancy but also the accuracy of the determination of VTEC. However, it is known for several years, see e.g. Brunini et al. (2005), that there exist systematic differences between the results of the individual techniques, whose reasons are still not all completely understood. The CONT08 campaign (2008-08-12 to 2008-08-26, respectively DOY (Day of Year) 225 to 239) offers the possibility to compare two weeks of continuously measured data not only from permanent network of GNSS and DORIS as well as from altimetry observations, but also from VLBI which is normally not available continuously.

A region of 40° by 40° around the Hawaiian Islands has been chosen as area of investigation. Kauai is the only place where a VLBI station (KOKEE, Kokee Park) is completely surrounded by open sea. In addition, five GNSS permanent reference stations of the IGS network are located at this archipelago, as well as a DORIS beacon. Besides, altimetry measurements over the ocean can be used just like space-based GNSS observations from Formosat-3/COSMIC or other Low Earth Orbiters (LEO). Fig. 1 shows the reference stations together with the measurement distribution on one day (2008-08-24) of the two week campaign. One can easily identify the typical distribution characteristics: terrestrial GPS is available around the stations with displacements depending on the elevation angle, altimetry data along the satellites ground tracks, and COSMIC data almost

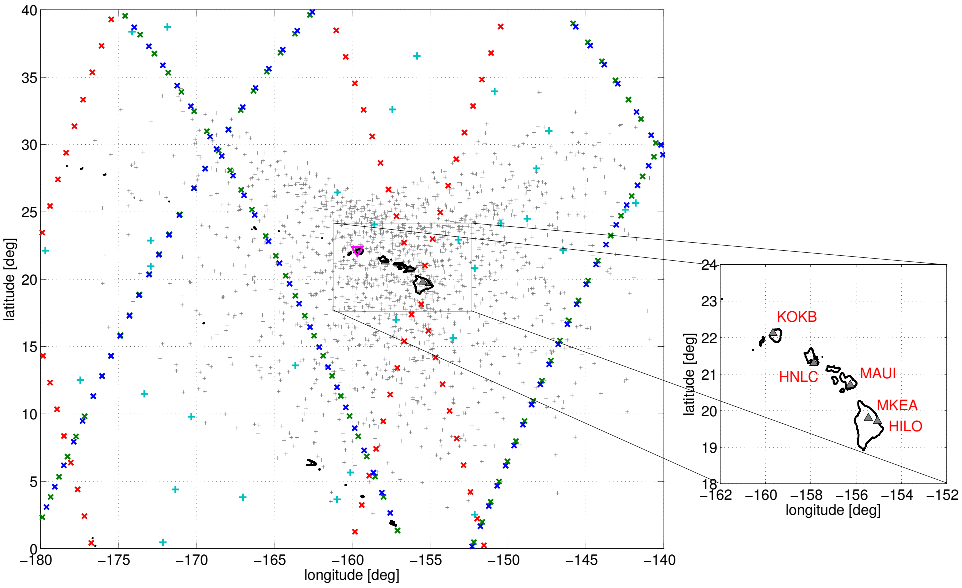

Fig. 1 Map of the area under investigation with data distribution over 24 hours (2008-08-24). GPS observations marked in gray (one triangle for each station and plus signs for ionospheric pierce points), VLBI in magenta, COSMIC in cyan, DORIS on board of Envisat in red, and Jason-1/2 in blue/green.

homogeneous over land and ocean but sparse. VLBI VTEC is only available directly above the telescope due to necessary pre-processing steps (see section 2.4).

A direct comparison of the different observation types is difficult as all measurements vary in time as well as in location requiring an interpolation in time and space. To avoid this, the approach pursued here combines all measurements in one ionosphere VTEC model and retrieves information on the sensitivity of the different data sets as well as on systematic offsets between them from the internal model consistency.

The focus of this paper is not on the ionosphere model itself – which has been presented in Dettmering et al. (2011) – but on the suitability of different space-geodetic observation techniques to contribute to the estimation of VTEC.

The outline of the paper is the following: In a first part (section 2) the different data sets are introduced including the preprocessing which is necessary to derive the VTEC observations. The next section covers the model approach and the data combination strategy (section 3) followed by the results of sensitivity analysis (section 4) and inter-technique bias estimation (section 5). Since the main topic of the paper is not on the VTEC results they are not shown here. The paper concludes with a summary and an outlook on further investigations.

2 Data Preprocessing

As input for the investigations VTEC data up to a height of 2000 km have been used after deducting the plasmaspheric electron density. The data are extracted separately for each observation technique from the original measurements. As the raw data sets differ significantly in amount, format, and contents, effort and complexity of preprocessing is technique-specific. Sometimes external data and/or model assumptions are unavoidable. Nevertheless, the preprocessing is done as consistent as possible using e.g. the same reduction procedure (Iijima et al. 1999) to convert the VTEC from the various orbit heights to 2000 km.

2.1 Terrestrial GNSS

Data from five IGS (International GNSS Service, (Dow et al. 2009)) permanent stations are used. From the original daily RINEX files with measurements sampled every 30 seconds, all GPS data with elevations larger than 5 degrees are extracted to process code leveled phase observations (Wilson and Mannucci 1994) and convert them to Slant Total Electron Content (STEC) along the signal path (Dettmering 2003). Daily Differential Code Biases (DCB) for satellites and receivers are also taken from IGS. For mapping STEC to the vertical the modified single layer mapping function (MSLM) of the Center for Orbit Determination in Europe, CODE (Hugentobler et al. 2002) is applied. Finally, the sampling interval is changed to 30 minutes (by using only every 60th observation) to adapt the data amount to the other techniques and to reduce the data correlations as these are not included in the stochastic model of the parameter estimation (see section 3). The data of each reference station are introduced as an independent observation group.

2.2 Radio Occultation on Low Earth Orbiter (LEO)

Nowadays, there are several LEO missions equipped with GPS receivers which not only receive signals from above the LEO (positive elevations) but also from GPS satellites rising or setting behind the Earth. One of these missions that is used here is Formosat-3/COSMIC (Fong et al. 2009). It consists of six satellites globally producing about 2000 occultations per day. It is due to this amount of data that this mission is chosen, as single satellites such as CHAMP can only provide less than 5 measurements per day in the small area under investigation.

The VTEC below the satellites is directly provided by UCAR (University Corporation for Atmospheric Research) through its CDAAC product "ionPrf" (UCAR 2010). No further processing is necessary because the DCBs are already included. As location for the profile, the position of maximal electron density is used. The measured TEC above the satellites is not considered. Extrapolation from orbit height (approximately 800 km) to 2000 km is done by IRI relations in order to be consistent with the other observation techniques. The observations from all COSMIC satellites are treated as one observation group.

2.3 Altimetry and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite)

Satellite radar altimeters directly measure in nadir direction. Therefore, the VTEC can easily be extracted from the data using observations at two frequencies. The principle is the same as for terrestrial GNSS data, yet no mapping is needed, no DCBs are applied and the preprocessing is based on different frequencies. In August 2008, two suitable altimeters provide data: Jason-1 and Jason-2. Both satellites follow the same ground track with a time separation of only about one minute as they have been still in calibration/validation phase during CONT08. 1Hz profiles were taken from AVISO GDR (Geophysical Data Records), smoothed by a median filter with filter length of 20 seconds (i.e. approximately 120 km on ground, as recommended by AVISO (2008)) and thinned to a time spacing of 30 seconds. Unfortunately, due to a safe-hold event Jason-1 only provides data in the second week of CONT08.

Envisat cannot contribute with dual-frequency ionospheric information as the S-Band is unavailable since January 2008. As an alternative, Envisat 1Hz DORIS ionosphere data are used. These data are directly taken from the AVISO GDR files (ESA 2007). Despite the fact that no detailed information on the preprocessing is available the data are nevertheless used in the investigation. As the Envisat DORIS ionospheric correction is a standard product any information on its usefulness and accuracy may be interesting for users. A data reduction to 30 seconds is done without further smoothing.

Each altimeter mission is handled as an independent observation group.

2.4 Very Long Baseline Interferometry (VLBI)

The original VLBI measurements are single-difference group delays of a signal from an extra-galactic compact radio source arriving at two or more VLBI telescopes at about the same epoch. These single difference observations are carried out around the two center frequencies at X-band (f_x) and at S-band. The ionospheric delay τ_{ion} is caused by dispersive effects through the atmosphere after other dispersive effects, such as dispersive instrumental delays, have been calibrated for. The values are given in the VLBI observation file provided by the International VLBI Service for Geodesy and Astrometry (IVS) (Schlüter and Behrend 2007) along with a number of other quantities necessary for geodetic and astrometric analysis. Following Hobiger et al. (2006) it can be described by

$$\tau_{ion} = \frac{1.34 \cdot 10^{-7}}{{f_x}^2} \mathit{\Delta} N_s + \mathit{\Delta} \tau_{offset}. \tag{1}$$

The variable $\mathit{\Delta}\tau_{offset} = \tau_{offset2} - \tau_{offset1}$ is the unknown ionospheric offset and $\mathit{\Delta}N_s = [mf(\varepsilon_2)VTEC'_2 - mf(\varepsilon_1)VTEC'_1]$ denotes the unknown difference of the path integral over the electron density along the line of sight at the two observation sites 1 and 2. The ionospheric mapping function mf depends on the elevation angle ε of the observation and is given by IERS (2010). $VTEC'$ denotes the unknown VTEC at the ionospheric pierce point. Due to the differential measurement concept, the observation equation (1) relates four unknown parameters (two offsets and two VTEC values) to each observation. It is evident that a redundant estimation of the parameters can only be achieved by gathering some observations together. Following Hobiger et al. (2006), the $VTEC'$ at the specific ionospheric pierce point is modeled as a function of $VTEC$, the vertical total electron content above the telescope:

$$VTEC'(t) = \left(1 + (\varphi' - \varphi)\begin{bmatrix} G_s \\ G_n \end{bmatrix}\right) VTEC(t + (\lambda' - \lambda)/15). \tag{2}$$

This model accounts for the longitudinal and latitudinal differences between the observation site and the specific ionospheric pierce point: The latitudinal difference is modeled by two coefficients, a north and a south gradient (G_n and G_s, depending on the site specific azimuthal angle), which are solved in the estimation process together with $VTEC$. In contrast, the longitudinal difference is not geometrically related to the observation site but temporally assuming that the ionosphere remains constant during the (short) duration Earth takes to rotate the angle of longitudinal difference, i.e. the epoch of the ionospheric delay observation is shifted forward or backward in time until the longitudes of the specific pierce point and the observation site would coincide. Within equation (2) φ, λ, and t denote latitude, longitude, and time. For a modern standard IVS session, such as IVS-R1 or IVS-R4, VTEC values are parameterized with a half-hourly resolution, applying least-square estimation in a Gauss-Markov model, while the ionospheric offset and the gradients are defined constant over the duration of the observing session of about 24 hours. The singularity caused by the unknown ionospheric offsets is compensated by setting the sum over the offsets to zero (Sekido et al. 2003).
Based on this approach VTEC values above VLBI station KOKEE are estimated with a sampling interval of 30 minutes and used as another observation group.

2.5 Background Model IRI 2007

In addition to the data obtained by these five observation techniques a model ionosphere is used as background model for the VTEC computation (only differences to this model are estimated) and as prior information to overcome rank deficiencies caused by insufficient data distribution, see Dettmering et al. (2011). Due to its independence of all observation groups the International Reference Ionosphere IRI 2007 (Bilitza and Reinisch 2008) has been chosen as background model. All observations are reduced by the corresponding IRI values before being introduced in the process of parameter estimation.

3 Model Approach

The observations described in the previous section are combined in one joint VTEC model. The approach consists of the given initial part (IRI 2007) $VTEC_0$ and an additional unknown part $\varDelta VTEC$ represented by a series expansion in terms of three one-dimensional endpoint-interpolating B-spline functions $\varPhi_k^J(x)$ with $x \in \{\varphi, \lambda, t\}$ whose corresponding coefficients d_{k_1,k_2,k_3} are calculated by parameter estimation (Schmidt 2007; Schmidt et al. 2008)

$$\varDelta VTEC(\varphi, \lambda, t) = \sum_{k_1=0}^{K_1-1} \sum_{k_2=0}^{K_2-1} \sum_{k_3=0}^{K_3-1} d_{k_1,k_2,k_3} \varPhi_{k_1}^{J_1}(\varphi) \varPhi_{k_2}^{J_2}(\lambda) \varPhi_{k_3}^{J_3}(t). \tag{3}$$

Each 1-D base function system consists of $K = 2^J + 2$ single B-spline functions $\varPhi_k^J(x)$. B-spline levels J_3=5 for the time t and J_1=J_2=3 for latitude φ and longitude λ are used to compute 29 single 24-hour models (15 days, 12 hour overlapping time between the single models) each with 3400 unknown coefficients corresponding to a temporal resolution of approximately 40 minutes and spatial resolution of about 4 degrees.
Special attention must be given to the data combination. This is no big challenge for the functional part of the model as all observations are VTEC values computed during a preprocessing so that only one type of observation equation is necessary. To account for possible systematic differences between the various techniques one constant offset per model (i.e. per 24 hours) is introduced for each observation group which is estimated together with the VTEC B-spline coefficients. In addition, it is important to consider the different accuracy levels of the input data in the stochastic model. As starting point all observations were assumed to be of the same accuracy without any correlations (weight matrix is set to identity matrix). Since this equal weighting of all observations is not realistic a Variance Component Estimation (VCE) is implemented to account for the different accuracy levels of the input data types. Instead of one single a-posteriori variance σ_0^2, individual variance factors σ_i^2 for each observation group $i \in \{1...p\}$ are estimated (cf. Eq. (4)). Theoretically, the groups can be defined by observation techniques, by missions or stations. In the following $p = 11$ groups are used (including the background model) as described in Sect. 2. The weight matrices P_i of all groups are assumed to be known (identity matrix, i.e. no correlations are introduced). This is of course a simplification of the real situation which could lead to slighly underestimated formal errors. The use of realistic full noise variance-covariance matrices for all observation groups will be a

goal in futher investigations.

$$\Sigma = \begin{pmatrix} \sigma_1^2 P_1^{-1} & 0 & \cdots & 0 \\ 0 & \sigma_2^2 P_2^{-1} & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & & \sigma_p^2 P_p^{-1} \end{pmatrix} \tag{4}$$

For estimating the variance factors in an efficient way a fast Monte-Carlo implementation of the iterative maximum-likelihood Variance Component Estimation (MCVCE) has been applied after Koch and Kusche (2002). More details on the model approach can be found in Dettmering et al. (2011).

4 Sensitivity of observation techniques

The sensitivity of the measurements for probing the ionosphere depends mainly on the used frequencies and their separation together with the correctness of assumptions and models necessary for data preprocessing (e.g. single layer model and mapping function for GNSS observations). As the accuracy and reliability of these models are normally not known, the accuracy levels of the data from different observation techniques have to be determined empirically. This is done by the VCE (see previous section). The estimated variance components (VC) are shown in Fig. 2. It can be seen that the VCs for altimetry (Jason-1/2 as well as DORIS on board Envisat) are similar to each other. The mean values for the whole period do not differ significantly from each other. Nevertheless, the DORIS values show much higher day-to-day variations. COSMIC and VLBI reach higher VCs but still much smaller than the background model (IRI 2007). Smallest VCs can be seen for the GPS stations. For most days they are around 0.5 and very smooth. All outliers can be explained by the data quality, e.g. hnlc is the only station without P-Code information on L1 frequency (instead C/A-code must be used) on DOY 227, 228, 234, and 236-239 and the IGS DCB for station hilo is not reliable at DOY 236.

The estimated VCs are factors without dimension and must be interpreted together with the full weight matrix of the model. In order to state on the accuracy of the single measurements the diagonal of the covariance matrix of the adjusted observations is analyzed and the mean standard deviations per observation group for each 24h-model are plotted in Fig. 3. The graphs show that GPS observations can reach an average accuracy of about 0.2 to 0.4 TECU, VLBI about 0.4 TECU, all altimetry data (including DORIS on Envisat) around 0.5 TECU, and COSMIC only 1.4 TECU. The DORIS and COSMIC accuracies are characterized by strong temporal variations whose reasons are not yet explained.

5 Inter-Technique Biases

The existence of offsets between ionospheric VTEC of different space-geodetic observation techniques is well-known for many years (Brunini et al. 2005). Probably, the biases are caused by more than one effect. It is obvious that model errors as well as unconsidered hardware delays and calibration uncertainties contribute to the total offset. Hardware delays in GPS receivers and satellites and in VLBI telescopes have an impact as well as errors in sea state bias models of altimetry or mapping errors using a simple single layer model for converting STEC to VTEC. It is not evident that all these effects are time constant, they could also show drifts or dependencies on absolute electron density or other quantities.

The model approach allows the estimation of one constant offset per observation group to absorb all these error sources by one single parameter. As already discussed, the groups may be defined by technique (GPS, altimetry, VLBI,...) or by mission/station. In the investigations presented here each GPS station and each altimeter mission is handled as an independent observation group. For GPS this was not obligatory because receiver DCBs had already been introduced within the preprocessing. Nevertheless, it allows for a different weighting of the stations which is reasonable because of the different input measurement types (P-Code/CA-Code) as discussed in the previous section. In addition, it allows for detecting possible errors in IGS DCBs.

The estimated offsets represent the systematic biases of all measurements of a group with respect to the background model (IRI 2007) averaged over the whole time span (24 hours per model) and the whole area. The GPS values are shown in Fig. 4 for each day within the CONT08 time period. All five stations show a similar temporal behavior. Only one outlier can be seen: for hilo around DOY 236. On this day the given IGS DCB is not reliable as it differs significantly from the DCBs before and after. Thus, in general there exists only one offset for all stations which shows a distinct time dependency. The time series is clearly correlated (correlation coefficient 0.72) with the absolute ionospheric activity given by the IGS global ionospheric maps (GIM) (Hernández-Pajares et al. 2009) for this region. Moreover, IRI 2007 is not based on local and/or actual measurements and is known for errors depending on ionospheric activity. Thus, the GPS-IRI differences probably also depend on absolute VTEC and the estimated mean bias between GPS and IRI 2007 of -1.5 TECU is only valid for the CONT08 time period. Further investigations are necessary, preferably in times with high solar activity.

For a combination of different space-geodetic ionospheric

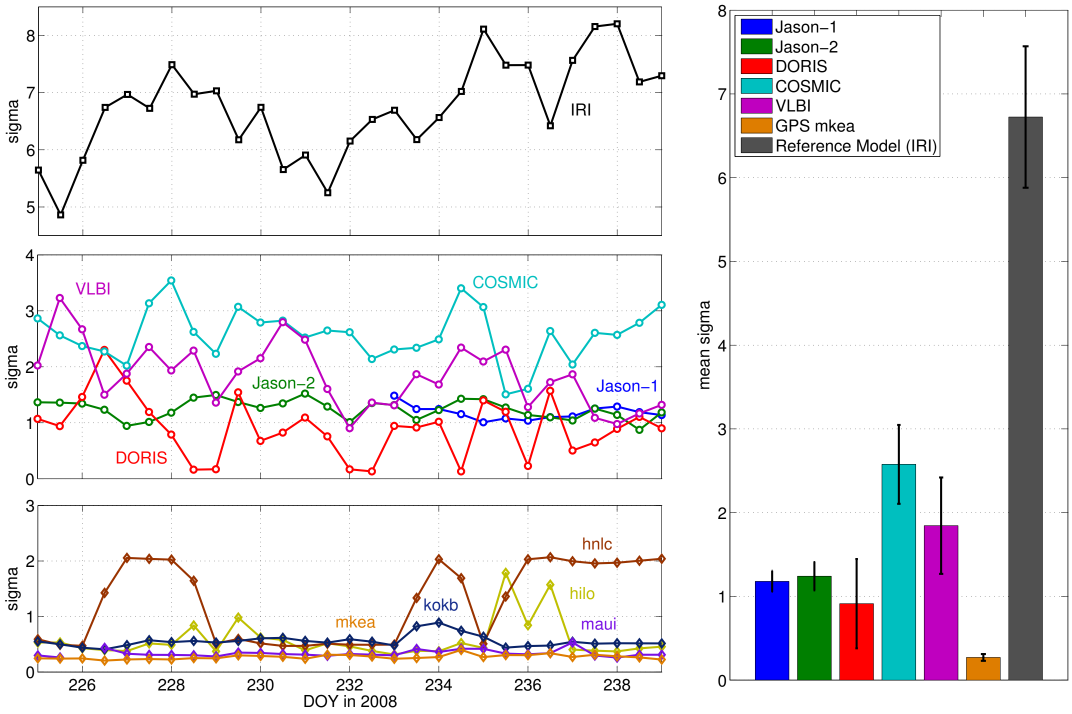

Fig. 2 Estimated VCE results (standard deviation factors σ_i) of all observation techniques. Left side: 15 days time series of CONT08 separately for background model (top), GPS (bottom) and other techniques (mid). Right side: mean standard deviation factors for the whole period. All values have no units as these are only factors and must be interpreted together with the weight matrix.

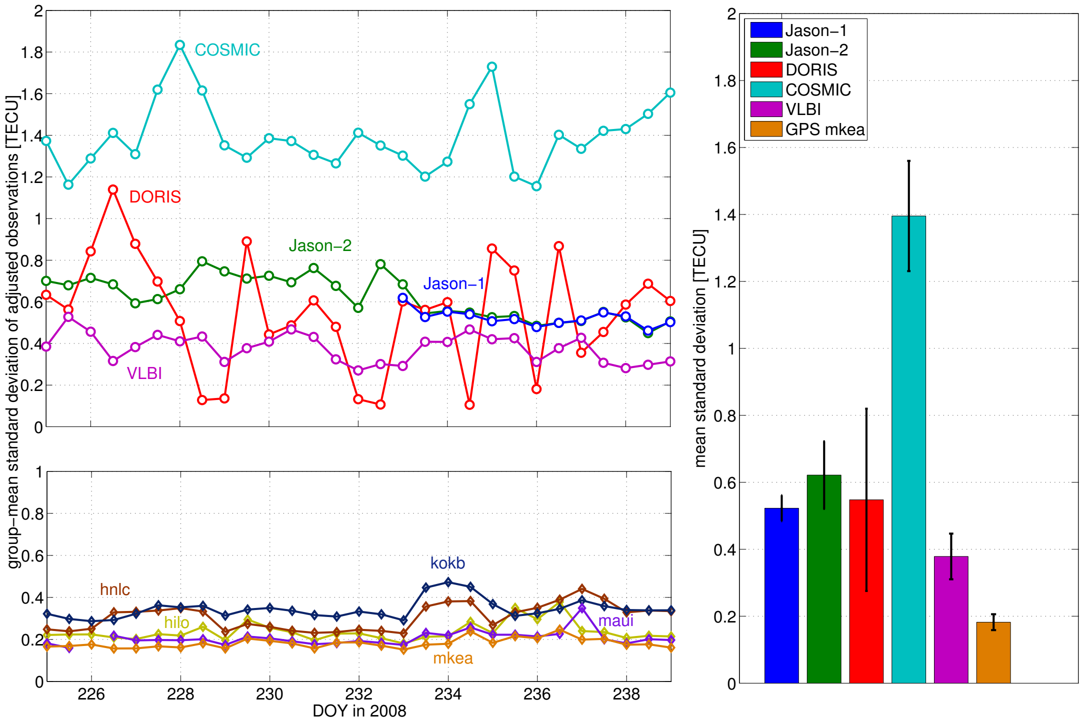

Fig. 3 Accuracy of the adjusted observations. For each 24-hour-model the average of standard deviations of all observations per group are plotted on the left side. On the right side the mean values for the whole CONT08 campaign are shown.

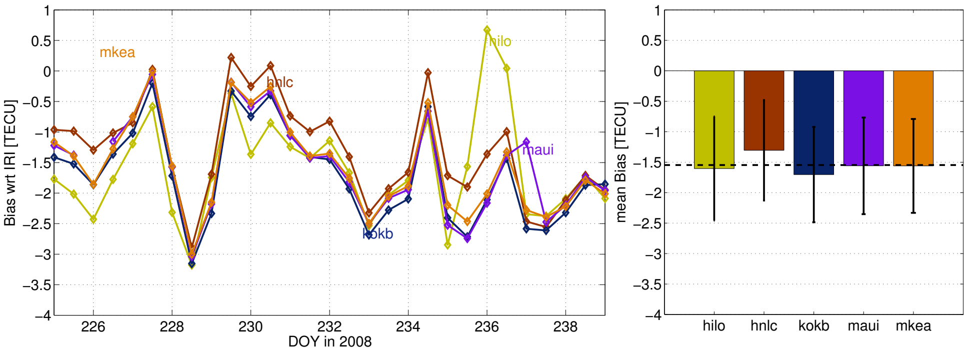

Fig. 4 Biases of GPS observations per station with respect to IRI 2007 (GPS-IRI). Time series (left) and mean values (right) for the CONT08 time period.

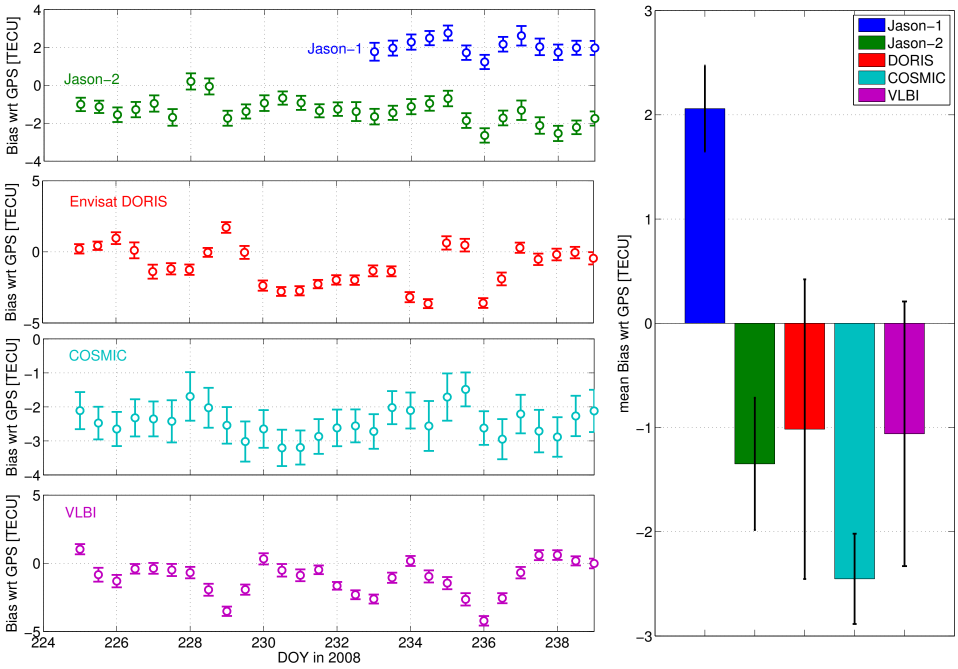

Fig. 5 Biases of space-geodetic observation techniques with respect to GPS. Time series (left) and mean values (right) for the CONT08 time period.

observations the inter-technique biases have to be known. They can be easily computed from the differences of the estimated offsets to IRI and are shown in Fig. 5. Both altimeter missions show significant offsets with respect to GPS of 2.1 TECU (Jason-1) and -1.3 TECU (Jason-2), respectively, each with time scatter of about 0.5 TECU. The temporal variations are very similar to each other (correlation coefficient of 0.85) as the satellites follow the same ground track with a separation of only 1 minute. The offset between Jason-1 and Jason-2 can be computed to 3.8 ± 0.3 TECU (DOY233-239) or 3.4 ± 0.8 TECU (CONT08). The DORIS measurements on board of Envisat as well as the VLBI measurements do not show significant offsets with respect to GPS when taking the whole CONT08 time period into consideration. The DORIS offset can be computed to -1.0 ± 1.4 TECU, VLBI results in -1.0 ± 1.3 TECU. Both time series show strong temporal variations, which may contain a systematic oscillation with a frequency of about 4 days in case of VLBI. Actually, no explanation for this behavior is available. The ionospheric offsets $\Delta\tau_{offset}$ estimated within the VLBI preprocessing remain constant at about -0.8 ns during the whole period. A longer time series would be necessary to verify and study the oscillation. Regarding DORIS it is important to know that all results strongly depend on input data, such as data spacing (of DORIS itself or of one of the other techniques) or GPS elevation mask. Thus, the DORIS result is not reliable despite the relatively small formal errors per 24 hour. The COSMIC bias relative to GPS reaches -2.4 ± 0.4 TECU with only small temporal variations. This technique is the only one where each single 24h-bias represents the temporal mean bias for the whole CONT08 time period taking the formal errors into account.

All computed results are only valid in the area under consideration and during the CONT08 time period. The result may differ for other regions and times, mainly depending on the ionospheric conditions and solar activities. Thus, special care should be taken when transferring the results to other regions or times. This is especially true in case of VLBI, since these data represent somehow the site-specific offset for VLBI station Kokee and may differ at other VLBI stations.

A comprehensive validation of the presented inter-technique offsets is difficult as no reference values are available. However, some investigations have been published comparing two or three space-geodetic methods for probing the ionosphere. Nevertheless, it is important to consider that most of these results refer to other observation periods and areas and – as mentioned before – a transfer is not always possible without limitations.

Independent calibration and validation efforts between Jason-1 and Jason-2 carried out by the altimeter community reveal an offset in dual-frequency ionospheric corrections of -8.5 mm which is caused by a relative Ku-band and C-band range difference (CLS 2010). Converted to VTEC, this corresponds to about 3.9 TECU at 13.6 GHz. This independent value is confirming the result computed here.

Todorova et al. (2007) found the offset between Jason-1 and GPS to be between 3 and 4 TECU for a time period of 14 days in 2006. As no height reduction is done in their work the result include the VTEC difference between Jason-1 orbit height of about 1300 km and GPS orbit height of about 20000 km in addition to instrumental effects. This can explain the difference of 1 to 2 TECU with regards to the results presented here.

Comparisons of dual-frequency ionospheric corrections of Jason-1 with different GPS GIM show time variable effects regarding a time span of about 230 cycles (about 6 years). At the beginning of the Jason-1 lifetime in 2002 the cycle mean differences to JPL GIM vary around zero, those to CODE GIM around -3 TECU. In 2008 this has changed to 2.5 TECU (JPL) and -0.5 TECU (CODE), respectively. Both GIM have been reduced to altimeter orbit height by the equations given in Iijima et al. (1999). Here, two items can be stated: (1) the differences between the individual IGS GIMs are in the order of 3 TECU, and (2) the differences between dual-frequency measurements and GIM depend on the absolute ionospheric activity which is reduced significantly from 2002 to 2008. The difference of 2.5 TECU in 2008 between Jason-1 and JPL GIM agrees with the result obtained here.

DORIS ionospheric corrections on board of TOPEX-Poseidon show a global mean difference to the dual-frequency altimeter estimates of about 1 cm, see e.g. ESA (2007). DGFI investigations of Envisat (GDR-B data set) show differences between DORIS and dual-frequency measurements of about -2 mm and between DORIS and GIM of about -4.5 mm (2 TECU at 13.6 GHz). This could not be confirmed by the results within this actual study. As already indicated by the strong variations with time and the sensitivity regarding model parameter changes the estimated DORIS bias is not reliable.

Previous comparisons of COSMIC VTEC with other space-geodetic techniques are not known.

For the validation of VLBI offset external investigations including station Kokee are needed. In Hobiger et al. (2004) as well as in Hobiger et al. (2006) some comparisons between VLBI and GPS were done. However, both papers do not give numbers for the offset of Kokee station. Only a global offset of -2.8 TECU (respectively -3.0 TECU) is given. This is not representative for a single station. Nevertheless, values for Hartrao, Westford and Wettzell of about 9, -4, and -2 TECU confirm the order of magnitude of the bias values.

In general, the comparisons confirm the results presented in the previous sections – even they can not be seen as full validation. However, since the mathematical approach consists of only two parts, namely a VTEC representation and a bias modeling, a validation of the estimated VTEC model would also provide validation of the bias model. As the focus of the paper is not on the VTEC estimation a comparison to other VTEC models is beyond the scope of this work and the reader may refer to previous papers of the authors (Schmidt et al. 2008; Dettmering et al. 2011) which include VTEC validations.

6 Summary and Outlook

This paper investigates the ability of different space-geodetic techniques for probing the ionosphere and for the estimation of VTEC, exemplified during the VLBI CONT08 campaign in the region around the Hawaiian Islands. Only one of the techniques in the study, the DORIS information collected on board of Envisat, shows insufficient results in such a manner that the results depend strongly on the model parameters and the input data without indicating this in the formal errors. All other data (GPS, altimetry, COSMIC, and VLBI) are reliable and could be used for ionospheric modeling

Table 1 Ionospheric characteristics of different observation techniques, errors computed from variations of 29 single solutions. All values only valid for CONT08 time period and Hawaiian region.

	mean bias w.r.t. GPS [TECU]	mean accuracy single observation [TECU]
Jason-1	+2.1 ± 0.4	0.5 ± 0.0
Jason-2	−1.3 ± 0.6	0.6 ± 0.1
DORIS Envisat	−1.0 ± 1.4	0.5 ± 0.3
COSMIC	−2.4 ± 0.4	1.4 ± 0.2
VLBI	−1.1 ± 1.3	0.4 ± 0.1
GPS	—	0.3 ± 0.1

when taking into account the systematic biases existing between each other which reach up to 5 TECU during the fortnight under investigation. GPS offers the most precise and useful data, followed by VLBI, altimetry and COSMIC. The mean values for the estimated biases and accuracies are summarized in Table 1. A combination of all techniques is recommended to make use of the different temporal and spatial distributions of the data sets. While GPS and VLBI are ground based and only available in continental areas and altimetry is linked to the oceans, COSMIC is the only technique independent from the land-water distribution. Moreover, all signals offer different geometry when passing the ionosphere. This effect becomes important in case of the estimation of 4-dimensional models of the electron density distribution.

The IRI 2007 which is used as background model within the study gets considerable higher variance components than any of the geodetic techniques. The offset of GPS with respect to IRI has been computed to -1.5 ± 0.7 TECU and shows a correlation with the absolute VTEC. This shows that IRI 2007 is lacking local near real-time information and could be improved by the assimilation of geodetic measurements.

The DORIS results presented here were not satisfying. However, the system itself seems to be well suited for ionospheric modeling: it consist of two relatively low frequencies not too close to each other and a global and dense coverage of terrestrial beacon stations. Further efforts would be advantageous to use the original DORIS data instead of the corrections processed for the altimeter satellites.

It is important to keep in mind that all presented results are only valid for the area under investigation as well as for this specific time period. CONT08 offers the possibility to compare observations made by different space-geodetic techniques during a period of about two weeks on a continuous basis. However, 2008 is a year with low solar activity. To get a more representative result a longer time span or even another fortnight during sunspot maximum would be essential.

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