Multi-technique comparison of troposphere zenith delays and gradients during CONT08

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Preprint

Abstract. CONT08 was a 15 days campaign of continuous VLBI (Very Long Baseline Interferometry) sessions during the second half of August 2008 carried out by the International VLBI Service for Geodesy and Astrometry (IVS). In this study, VLBI estimates of troposphere zenith total delays (ZTDs) and gradients during CONT08 were compared with those derived from observations with the Global Positioning System (GPS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and water vapor radiometers (WVRs) co-located with the VLBI radio telescopes. Similar geophysical models were used for the analysis of the space geodetic data, whereas the parameterization for the least-squares adjustment of the space geodetic techniques was optimized for each technique.. In addition to space geodetic techniques and WVRs, ZTDs and gradients from numerical weather models (NWMs) were used from the European Centre for Medium-Range Weather Forecasts (ECMWF) (all sites), the Japan Meteorological Agency (JMA) and Cloud Resolving Storm Simulator (CReSS) (Tsukuba), and the High Resolution Limited Area Model (HIRLAM) (European sites). Biases, standard deviations, and correlation coefficients were computed between the troposphere estimates of the various techniques for all eleven CONT08 co-located sites. ZTDs from space geodetic techniques generally agree at the sub-centimetre level during CONT08, and – as expected – the best agreement is found for intra-technique comparisons: between the Vienna VLBI Software and the combined IVS solutions as well as between the Center for Orbit Determination in Bern (CODE) solution and an IGS Kalman filter series; both intra-technique comparisons with standard deviations of about 3 to 6 mm. The best inter space geodetic technique agreement of ZTDs during CONT08 is found between the combined IVS and the IGS solutions with a mean standard deviation of about 6 mm over all sites, whereas the agreement with numerical weather models is between 6 and 20 mm. The standard deviations are generally larger at low latitude sites because of higher humidity, and the latter is also the reason why the standard deviations are larger at northern hemisphere stations during CONT08 in comparison to CONT02 which was observed in October 2002. The assessment of the troposphere gradients from the different techniques is not as clear because of different time intervals, different estimation properties, or different observables. However, the best inter-technique agreement is found between the IVS combined gradients and a GPS solutions with standard deviations between 0.2 mm and 0.7 mm.

Keywords: space geodetic techniques, numerical weather models, troposphere zenith delays, horizontal troposphere gradients

Preprint

1 Introduction

Modelling the propagation of the electromagnetic microwave signals through the electrically neutral part of the atmosphere (in this paper referred to as troposphere) is of common interest for the space geodetic techniques, e.g., Very Long Baseline Interferometry (VLBI), Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS), or Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS). The troposphere causes an excess delay as well as the bending of the microwave signals along the path through the troposphere; the (slant) delay (ΔL) along the slant path (s) between the station and the top of the troposphere (H_{trop}) can be expressed as the integral over the sum of hydrostatic and wet refractivity ($N_{h,w}$):

$$\Delta L = 10^{-6} \int_0^{H_{trop}} [N_h(s) + N_w(s)]\, ds \,. \tag{1}$$

Equation (1) can be decomposed into hydrostatic, wet, and gradient delays (Davis et al., 1993) as follows:

$$\Delta L(\alpha,\varepsilon) = ZHD\, m_h(\varepsilon) + ZWD\, m_w(\varepsilon) + m_{h,w}(\varepsilon)\cot(\varepsilon)[\, G_n \cos(\alpha) + G_e \sin(\alpha)] \tag{2}$$

where ε is the elevation angle from local horizon, α the azimuth (angle from geodetic north), and ZHD the zenith hydrostatic delay, which can be computed from the total pressure and the station coordinates (Saastamoinen, 1972). ZWD is the zenith wet delay, $m_h(\varepsilon)$ and $m_w(\varepsilon)$ are the hydrostatic and wet mapping functions (e.g., Marini, 1972; Niell, 1996; Böhm et al., 2006a), G_n and G_e are north and east troposphere gradients (MacMillan, 1995; Bar-Sever et al., 1998), respectively. The hydrostatic mapping function is accounting for the bending effect.

Troposphere delays are an important error source for space geodetic measurements. Uncertainties in the troposphere delay models propagate into all geodetic estimates, and in particular into the height component of the station positions (Herring, 1986; Davis et al., 1991) due to the high correlations between zenith delays and station heights. The influence of different mapping functions and cut-off elevation angles on geodetic parameters like station heights and baseline lengths has been investigated in several studies, e.g., Davis et al. (1985), Böhm and Schuh (2004), Böhm et al. (2006a, 2006b), Teke et al. (2007), Tesmer et al. (2007), or Steigenberger et al. (2007). Troposphere gradients describe the azimuthally asymmetric delays (Davis et al., 1993). In the analysis of VLBI and GPS observations, they are usually estimated since this improves the accuracy of geodetic estimates. Different studies have been carried out to develop and evaluate troposphere gradient models (e.g., Chen and Herring, 1997). According to MacMillan (1995), VLBI baseline length

Preprint

repeatabilities can be improved by up to 8 mm if gradients are estimated, thus gradients are very important for the realization of terrestrial reference frames (TRFs) (Böhm and Schuh, 2007) and celestial reference frames (CRFs) (MacMillan and Ma, 1997).

Various comparisons of troposphere parameters derived from space geodetic techniques and numerical weather models (NWMs) have been performed in order to assess the level of agreement. Behrend et al. (2000, 2002) compared the ZWDs derived from the non-hydrostatic numerical weather prediction (NWP) model (MM5) (Cucurull and Vandenberghe, 1999) and a hydrostatic NWP model (HIRLAM) (Cucurull et al., 2000) with the observational results of VLBI, GPS, and a water vapor radiometer (WVR), and they found good agreement for the European geodetic VLBI network during six observing sessions in 1999 in terms of biases, standard deviations, and correlations. Snajdrova et al. (2006) compared zenith total delays (ZTDs) from GPS, VLBI, DORIS, WVR (hydrostatic delays were added), and ECMWF during CONT02 (a 15 days continuous VLBI campaign in 2002) for co-located sites with VLBI antennas, and the agreement between ZTDs from GPS and VLBI was rather good (see Table 7); DORIS was fairly compatible with GPS and VLBI, but the agreement for WVR and ECMWF with ZTDs estimated from space-geodetic techniques was rather low. To get detailed information on comparisons of troposphere parameters, readers are referred to, e.g. MacMillan and Ma (1994), Chen and Herring (1997), Emardson et al. (1998), Haas et al. (1999), Behrend et al. (2000, 2002), Cucurull et al. (2000), Gradinarsky et al. (2000), Niell et al. (2001), or Schuh and Böhm (2003).

In our study, the troposphere zenith total delays from VLBI, GPS, DORIS, and WVRs are also compared with those determined by ray-tracing through the profiles of various NWMs. A detailed description of all datasets can be found in Section 2. In Section 3 we compare the ZTDs and gradients in terms of biases, standard deviations, and correlations, and we provide some conclusions in Section 4.

2 CONT08 co-located sites, techniques and solutions

This section provides a general overview of the co-located sites during CONT08, the data types available, and it focuses on the details inherent to each technique. CONT08 was a special campaign of the International VLBI Service for Geodesy and Astrometry (IVS, Schlüter and Behrend, 2007), and it was a follow-on to similar campaigns (CONT94, CONT95, CONT96, CONT02, and CONT05). The aim of this campaign was to derive the highest quality geodetic results that VLBI currently can provide. It was a 15 days continuous VLBI observation campaign, carried out from 12 to 26 of August 2008 with eleven sites on five continents (Figure 1). Unlike previous CONT

Preprint

campaigns, the CONT08 sessions were observed from 0 UT to 24 UT, and observational gaps between the single sessions (30 min gaps in the case of CONT05) were avoided by performing the daily station interrupts at well-coordinated, sequential times for all stations in order not to introduce gaps in the estimated time series, e.g. of Earth orientation parameters (Schuh and Behrend, 2009).

Figure 1 IVS CONT08 stations.

For all eleven sites of CONT08, troposphere zenith delays and gradients are available from VLBI and GPS, and for three sites (Ny-Ålesund in Norway, Hartebeesthoek in The Republic of South Africa, and Kokee Park on Hawaii, U.S.A.) also troposphere estimates from DORIS are provided. Profiles through NWMs were used to compute zenith total delays and to estimate gradients. These NWMs are a global model from the European Centre for Medium-Range Weather Forecasts (ECMWF), a regional model by the Japan Meteorological Agency (JMA) for East Asia, a regional model from the Cloud Resolving Storm Simulator (CReSS) covering Japan, and HIRLAM, which is also a regional model for Europe. ZWDs from the measurements of WVRs are available at three sites during CONT08: Onsala in Sweden, Wettzell in Germany, and Tsukuba in Japan. When comparing ZTDs of different techniques, ZHDs computed from surface pressure values were added to the ZWDs of the WVRs and HIRLAM. In Table 1 the acronyms of GPS antennas, DORIS beacons, and WVR names at VLBI co-location sites are listed.

Table 1 Geodetic instruments co-located at the VLBI sites during the CONT08 campaign.

Table 2 shows the ITRF2005 (Altamimi et al., 2007) ellipsoidal heights of the reference points of VLBI, GPS, DORIS, and WVRs, as well as the GPS antenna reference point (ARP) eccentricity in the radial direction (the radial distance from the geodetic marker to the phase center of the GPS antenna). GPS ARP eccentricities in radial direction are added to the heights of the GPS reference points when calculating the troposphere ties (see Section 3.2). The approximate horizontal distances between co-located sites are listed in Table 2 to give an idea on how similar the troposphere above the geodetic instruments can be assumed.

Table 2 ITRF2005 ellipsoidal heights and approximate horizontal distances of the co-located VLBI, GPS, and DORIS antennas, and WVRs involved in CONT08.

At the end of this introduction it should be emphasized that all comparisons and validation tests carried out in this study provide important information with respect to the planned combination and integration of various observing techniques. In fact, such a multitude of different methods to

Preprint

simultaneously determine troposphere parameters from space geodetic techniques and other sources have never been available for comparison before. Thus, the data taken during the CONT08 campaign will greatly contribute to studies in the framework of the Global Geodetic Observing System (GGOS) (Rummel et al., 2005) of the International Association of Geodesy (IAG).

2.1 Space geodetic solutions

2.1.1 VLBI-Vienna VLBI Software (VLBI-VieVS)

For the analysis of the VLBI observations carried out during CONT08, the Vienna VLBI Software (VieVS, Böhm et al., 2010) was used. Neither any cut-off elevation angle nor any down weighting of low elevation observations was applied (in CONT08 no VLBI observation was taken below 5° elevation). The zenith hydrostatic delays were determined from local surface pressure measurements (Saastamoinen 1972; Davis et al., 1985), whereas the zenith wet delays were estimated in the least-squares adjustment as piece-wise linear offsets at 30 minutes time intervals. In both cases – hydrostatic and wet – the Vienna Mapping Functions 1 (VMF1, Böhm et al., 2006a) were used. No-net-translation (NNT) and no-net-rotation (NNR) condition equations were introduced on the ITRF2005 (Altamimi et al., 2007) coordinates, except for the antenna Zelenchukskaya which is not available in ITRF2005. Source coordinates were fixed to ICRF2 (Fey et al., 2009), and atmospheric loading (Petrov and Boy 2004) as well as tidal ocean loading based on the ocean model FES2004 (Lyard et al., 2006) were introduced a priori. Nutation offsets were estimated once per day in addition to the IAU2000A model plus IERS 05 C04 values (Gambis 2004; Bizouard and Gambis 2009), and polar motion as well as the Earth's phase of rotation (UT1-UTC) were estimated once per day in addition to the IERS 05 C04 values and the ocean tidal terms as recommended by the IERS Conventions 2003 (McCarthy and Petit 2004). The estimation interval was 30 minutes for the ZWDs and 120 minutes for troposphere gradients. Loose constraints for ZWDs (10 mm after 30 minutes) and troposphere gradients (0.17 mm after 120 minutes) were introduced.

2.1.2 VLBI-International VLBI Service for Geodesy and Astrometry (VLBI-IVS)

Like previous IVS troposphere products (Heinkelmann et al., 2007), the combination of troposphere parameters during the 15 days CONT08 campaign is based on final ZTD and gradient time series by individual groups (and not carried out at the normal equation level). The VLBI-IVS series is a weighted linear combination of the estimates provided by ten IVS Analysis Centers (see Heinkelmann et al., this issue). It is important to note here that the solution with the Vienna VLBI Software (Section 2.1.1) was also part of the IVS combination which was carried out at Deutsches

Preprint

Geodätisches Forschungsinstitut. However, we want to keep both solutions in order to assess the difference between an individual and the combined solution compared to other techniques. Also, it has to be mentioned that the parameterization and the models are not homogeneous for all submissions that were used in the combination. After manual outlier exclusion, the weights for each IVS Analysis Center and parameter (zenith delays, horizontal gradients) were obtained by variance component estimation using the iterative algorithm of Förstner (1979) as outlined in Koch (1997). The details of the submissions, combination procedure and a quality assessment are presented by Heinkelmann et al. (this issue).

2.1.3 DORIS- Institut Géographique National (DORIS-IGN)

For the DORIS data analysis, the GIPSY-OASIS software package developed at JPL and modified at IGN (Willis et al., 2010b) was used. Instead of the results from the regular IGN solution (ignwd08) submitted to the International DORIS Service (IDS) (Willis et al., 2010c), a specific study was performed by using the VMF1 and also daily estimates (for test purposes in this specific study) of horizontal troposphere gradients, following some initial tests of consistency towards GPS (Willis et al., 2010a). A cut-off elevation angle of 10° was used, as Jason-2 DORIS data were not considered yet in this investigation and as the older DORIS satellites do not provide a large amount of data below this elevation angle. Consequently, during CONT08, only 4 DORIS satellites were used (Envisat, SPOT-2, SPOT-4 and SPOT-5), all having a sun-synchronous and almost polar orbit. DORIS data were processed in daily batches using a filter approach. Zenith troposphere parameters were estimated at the start of passes, and only if the previous reset was not within 20 minutes (see Bock et al., 2010, for a more detailed discussion). This solution is as close as possible to the IERS Conventions 2003 (McCarthy and Petit, 2004), and it also includes the most recent improvement in DORIS data analysis, in particular in terms of solar radiation pressure modelling (Gobinddass et al., 2009a, 2009b) as well as in terms of atmospheric drag parameterization (Gobinddass et al., 2010). Station coordinates were fixed to their ign09d02 values. This frame is based on the ignwd08 time series, it provides coordinates and velocities for all stations, and it is aligned to ITRF2005 (Willis et al., 2010b). Discontinuities in station coordinates were also properly handled using information contained in DPOD2005 (Willis et al., 2009).

2.1.4 GPS-International GNSS Service (GPS-IGS)

This ZTD product of the IGS (Byun and Bar-Sever, 2009) was estimated by using the precise point positioning (PPP) technique as defined in Zumberge et al. (1997). The Earth orientation parameters, orbits, and clocks were fixed to the IGS final combined products. The analyses were carried out with the software GIPSY-OASIS for 24 hour data intervals (Webb and Zumberge, 1993). A cut-off

Preprint

elevation angle of 7° was introduced, and the Niell mapping functions (hydrostatic and wet) (NMF; Niell, 1996) were used. A priori hydrostatic and wet delays were applied based on station altitude (2.3 m at sea level, and 0.1 m, respectively). The estimated parameters were receiver clocks (modelled as white noise), station positions (constant), zenith wet delays (random walk with variance of 3 cm/h, loose) every 5 minutes, atmospheric gradients (random walk with variance of 0.3 cm/h, loose), and phase biases (white noise). The formal errors of the new ZTD product are about 1.5 to 5 mm. However, they are biased by systematic errors in the combined GPS orbits and clocks, as concluded by Byun and Bar-Sever (2009).

2.1.5 GPS-Center for Orbit Determination in Europe (GPS-CODE)

The Center for Orbit Determination in Europe (CODE, Dach et al., 2009) is a cooperation of the Astronomical Institute of the University of Bern (AIUB), the Swiss Federal Office of Topography (swisstopo), the German Federal Agency for Cartography and Geodesy (BKG), and the Institut für Astronomische und Physikalische Geodäsie of the Technische Universität München (IAPG/TUM). CODE is one of the global IGS Analysis Centers. The solution used in this paper originated from the CODE contribution to the first IGS reprocessing campaign (Steigenberger et al., 2010). It is based on a global network of 244 GPS tracking stations processed with the current development version 5.1 of the Bernese GPS Software (Dach et al., 2007), and the following models were used: gridded VMF1 and ECMWF a priori delays, non-tidal atmospheric loading model of Petrov and Boy (2004) applied on the observation level, and S1/S2 atmospheric tidal model of Ray and Ponte (2003).

Daily normal equations were combined for the whole CONT08 time period to get one consistent solution for station coordinates, Earth rotation parameters, troposphere zenith delays and gradients. One set of station coordinates was estimated with an NNT condition of a subset of IGS05 stations w.r.t. the IGS05 reference frame. Troposphere zenith delays and gradients were represented by continuous piece-wise linear functions with a parameter spacing of 2 and 24 hours, respectively. An elevation cut-off angle of 3° and an elevation-dependent weighting ($w = \sin^2 \varepsilon$) were applied.

2.2 Water Vapor Radiometer (WVR)

A Water Vapor Radiometer (WVR) infers the wet troposphere delay from measurements of the power of the thermal radiation from the atmosphere at microwave frequencies. Typically two frequencies are used; one more sensitive to water vapor (typically a frequency close to the 22.2 GHz water vapor line) and one more sensitive to liquid water (usually around 30 GHz). By combining these measurements, the respective contributions from water vapor and liquid water to

Preprint

the observed powers can be determined. The water vapor part can then be used to estimate the wet troposphere delay (Elgered, 1993).

During CONT08 three WVRs were operated at VLBI sites: the Astrid radiometer at Onsala (Elgered and Jarlemark, 1998), as well as the Radiometrix radiometers at Wettzell and Tsukuba. The radiometers at Onsala and Wettzell were operated in sky mapping mode, thus providing measurements of the slant wet delays in several different directions. These were used in a least-squares fit in order to estimate the ZWDs and the gradients, using an approach similar to what is presented by Davis et al. (1993). In the least-squares fit, the ZWDs and the gradients were modelled as piece-wise linear functions. The estimation intervals were 30 min for the ZWDs and 2 hours for the gradients, i.e. the same as for VLBI-VieVS. The Tsukuba radiometer only measured in the zenith direction, thus only ZWD estimates from this radiometer were available.

One problem with WVRs is, that they do not provide reliable results when it is raining. Consequently, all data from rainy periods have been removed (identified by the liquid water content being larger than 0.7 mm). However, it should be noted that since the removal of rain observations was done a posteriori, the remaining observations could still be somewhat affected by rain since all observations were used for e.g. the tip-curve calibrations. Another problem is, that they cannot measure at low elevation angles (<20°) in order to avoid picking up radiation from the ground. Thus, the gradients estimated from the WVRs will be very sensitive to noise, since the effect of gradients is mostly seen for low elevation angles.

Preprint

2.3 Numerical Weather Models (NWMs)

2.3.1 European Centre for Medium-Range Weather Forecasts (ECMWF)

Operational pressure level data with a 6 hour time resolution were used at 21 levels from 1000 hPa up to 1 hPa (extended up to 136 km with a normal temperature field) with information about the geopotential, temperature, and specific humidity. In particular, four vertical profiles with a horizontal resolution of 0.25° around each station were retrieved and simply the closest profile was used for the determination of the zenith delay. The description of the algorithm for the numerical integration can be found in Böhm (2004; Appendix). For the calculation of north and east gradients, horizontal refractivity gradients were derived between the four profiles and again used for numerical integration (Böhm and Schuh, 2007).

2.3.2 High Resolution Limited-Area Model (HIRLAM)

The High Resolution Limited-Area Model (HIRLAM) is a numerical weather model for short-range forecasting, that is used by several European national meteorological services (Undén et al., 2002). It is a limited area forecasting model that uses ECMWF as boundary conditions. Different spatial resolution is available, horizontally 22 km, 11 km or 5 km, and vertically between 16 and 60 levels. The temporal resolution is 6 hours in analysis mode, and predictions are available, e.g. with 3 and 6 hours resolution.

HIRLAM files with 22 km horizontal resolution and 40 vertical levels and combined analysis and forecast data were used to achieve a temporal resolution of 3 hours. This was done by correcting the 3 hour forecast data by corrections based on a comparison of the 6 hour forecast data with the corresponding analysis data. So-called hybrid-level data of humidity and temperature together with surface pressure and geopotential data were extracted for the four nearest grid points around each station for each 6 hour epoch during CONT08. Based on these data vertical profiles of pressure, temperature and humidity were constructed for each station and finally vertical integration was used to calculate zenith wet delays.

Preprint

2.3.3 Japan Meteorological Agency-Kashima Ray-Tracing Tools (JMA-KARAT)

At the National Institute of Information and Communications Technology (NICT) the so-called KAshima RAy-tracing Tools (KARAT, Hobiger et al., 2008a) have been developed, which allow to obtain troposphere slant delays in real-time. Such ray-traced delays can be used as corrections for space geodetic observations (Hobiger et al., 2008b) and remote sensing applications. The Japanese Meteorological Agency (JMA) provides a variety of weather models, whereas the meso-scale 4D-Var model (Meso-scale Analysis Data, MANAL, JMA, 2002; Ishikawa, 2001) with its horizontal resolution of about 10 km is usually taken for KARAT processing. This model covers huge parts of the East Asian region, including Japan, Korea, Taiwan, and East China. The 3 hour time resolution of the datasets makes the appliance of this model for positioning applications feasible.

2.3.4 Cloud Resolving Storm Simulator (CReSS)

Other than regional numerical weather models, fine-mesh models allow to study smallest structures in the atmosphere and some models even try to resolve clouds. Thereby, the model space is limited to a few hundred kilometres, which requires some modifications of the ray-tracing code (Hobiger et al., 2010), in order to ensure that rays are not leaving the model domain laterally. Dedicated model runs of the Cloud Resolving Storm Simulator (CReSS; Tsuboki and Sakakibara, 2002) at the National Research Institute for Earth Science and Disaster Prevention (NIED) provided 1 km fine-

mesh model data with a temporal resolution of one hour during the CONT08 period, which were used for the ray-tracing. Thereby, the CReSS model is embedded within the 10 km JMA MANAL field to ensure that rays at lower elevations are not cut off due to the spatial limitations of the fine-mesh model.

The gradients of JMA/KARAT and CReSS numerical weather model solutions were calculated as follows: The mean ray-traced slant delays, one for each elevation angle, were calculated from 3° to 90° elevation angle for the case of JMA/KARAT and 4° to 90° for the case of CReSS. I.e., for each elevation angle the mean values over the 360 ray-traced slant delays (every degree in azimuth) were determined, which were then subtracted from the individual ray-traced slant delays at all azimuths and elevation angles. The north and east gradients every 3 hours for JMA/KARAT and every hour for CReSS were estimated by a classical least-squares adjustment fitting the gradient model suggested by MacMillan (1995).

3 Data analysis

This section includes the analyses and comparisons of the estimated parameters by means of descriptive statistics. Before the comparisons "troposphere ties" were introduced with respect to a reference height, which was chosen as the height of the VLBI reference point.

3.1 Agreement criteria for the comparisons

In order to assess the agreement between the estimated troposphere ZTDs and gradients basic statistics were applied. We used mean biases of the difference vectors between time series, the standard deviations as well as the Pearson correlation coefficients. As statistical test for the correlation coefficients, p-values with a critical value of 0.05 were computed. Strictly speaking, the p-value is the probability of making a Type 1 error (the error of rejecting a null hypothesis when it is actually true) where a null hypothesis is formed with no correlation between two datasets (Schervish, 1996).

3.2 Troposphere ties

The atmosphere in the layer between two instruments causes biases of the troposphere ZTDs which can be called "troposphere ties". Troposphere tie corrections were introduced to account for the height differences between the antennas of geodetic techniques at the co-located sites before determining the difference vectors (Δ), and they were derived as the sum of the hydrostatic (Saastamoinen, 1972, 1973) and the wet part (Brunner and Rüeger, 1992), as shown in Equations (3) to (5).

Preprint

$$p = p_0 \left(1 - \frac{\gamma (H - H_0)}{T_0}\right)^{\frac{g}{\gamma R_L}}, \quad (3)$$

$$\Delta ZHD = \frac{0.0022768 (p - p_0)}{1 - 0.00266 \cos(2\varphi_0) - 0.28 \times 10^{-6} H_0}, \quad (4)$$

$$\Delta ZWD = \frac{-2.789 e_0}{T_0^2} \left(\frac{5383}{T_0} - 0.7803\right) \gamma (H - H_0), \quad (5)$$

H_0 denotes the reference height (in our case the height of the VLBI reference point) in meters. The parameters e_0, p_0, and T_0 are the water vapor pressure in hPa, total pressure in hPa, and temperature in Kelvin, at the reference height, and they are derived from data of the ECMWF; H and p are the height and total pressure at the co-located site. The other parameters are the average temperature lapse rate $\gamma = -0.0065$ K m^{-1}, the gravity g in m s^{-2} at the site, and $R_L \approx 287.058$ m^{2}s^{-2}K^{-1} is the specific gas constant.

In Table 3, the height differences between VLBI, GPS, DORIS antennas as well as WVRs are shown. The troposphere ZTD ties were calculated at each common epoch from the Equations (3) to (5) based on the meteorological parameters e_0, p_0, and T_0 from the ECMWF, interpolated linearly to the ZTD epochs of the corresponding techniques. Since the variability of the ZTD ties is significant – especially for the sites where the weather is humid – we reduced ZTD ties calculated for each common epoch from the ZTDs of the techniques before comparisons. In Figure 2, the troposphere ties between the GPS antenna TSKB and the VLBI antenna TSUKUB32 during CONT08 are shown. Red and black dotted lines illustrate total and hydrostatic ties, respectively, and the negative sign of the ties is due to the fact that the lower GPS antenna TSKB has more troposphere above the station than the VLBI antenna TSUKUB32. As can be seen in Figure 2, the ZHD ties vary only slightly around the value of -4.5 mm at Tsukuba within the 15 days, but after adding the ZWD ties, the ZTD ties have significantly more variability, which is due to the fact that the atmosphere at Tsukuba is very humid in August.

Figure 2 Troposphere ties between the GPS antenna TSKB and the VLBI antenna TSUKUB32 during CONT08, calculated for all common epochs. Red and black dotted lines illustrate total and hydrostatic ties, respectively.

In Table 3, the mean ZTD, ZHD, and ZWD ties of the whole CONT08 duration are shown. The ZHD ties of the WVRs are zero since the ZHDs from VLBI were used (Table 3).

The mean ZTD biases between the VLBI antennas and the DORIS beacons at Ny-Ålesund ($H_{VLBI} - H_{DORIS}$=34.70 m) and at Hartebeesthoek ($H_{VLBI} - H_{DORIS}$= -143.88 m) were reduced to 0.79 mm

Preprint

(from -9.98 mm) and to 4.62 mm (from 41.80 mm), respectively, after introducing the mean troposphere ties. At the IGS site HARB ($H_{VLBI} - H_{GPS}$= -145.02 m) the mean ZTD bias of 37.52 mm was reduced to 0.14 mm after introducing the ZTD tie (37.39 mm), whereas at the DORIS co-located site at Kokee Park ($H_{VLBI} - H_{DORIS}$= 9.62 m) the mean bias increased from 2.32 mm to 5.16 mm after introducing the mean troposphere tie (-2.84 mm); however, this difference is comparably small. It should also be mentioned here that the distances between VLBI antennas and the DORIS beacons are rather large so that the DORIS signals (in particular at 2 GHz) do not disturb the VLBI observations. This can also be a reason for the worse agreement.

Table 3 Height differences and troposphere ties between the co-located VLBI, GPS, and DORIS antennas, and the WVRs involved in CONT08.

3.3 Data types and epochs for comparisons

In order to ensure a predicative comparison similar geophysical models were used for the analyses of space geodetic data, whereas the parameterization for the least-squares adjustment of the space geodetic techniques was optimized for each solution. In Table 4, an overview of the solutions, types of the estimates, and intervals for both zenith delays and gradients are listed. GPS-IGS and HIRLAM solutions do not provide gradients. All gradients from the techniques except WVR are total gradients.

Table 4 Summary of the data used for the comparisons.

The total number of common epochs of ZTDs (first line) and of gradients (second line) between VieVS and the other techniques during CONT08 can be found in Table 5. The reliability of the mean biases, standard deviations, and correlations increases and the vulnerability to outliers decreases directly proportional with the total number of ZTDs and gradients available (degrees of freedom). Due to the small number of gradients provided by CODE and DORIS solutions (16 estimates at maximum for the whole 15 days duration) biases, standard deviations, and correlations involving these solutions have to be interpreted with care.

The estimates from DORIS correspond to distinct epochs of actual measurements during the DORIS satellite passes. For the whole CONT08 campaign, the DORIS station at Ny-Ålesund (SPJB) provided 243 ZTDs with a gap (no observation) every day between 2 to 5 UT. The DORIS station KOLB at KOKEE Park provided in total 82 ZTDs, and each day is observed in two separate intervals between 7 to 10 and 20 to 23 UT. HBMB at Hartebeesthoek provided in total 77 ZTDs in

Preprint

CONT08 observed between 6 to 10 and 19 to 22 UT. In a first step, the zenith delays from DORIS were linearly interpolated to adjacent 2 hour intervals at UT integer hours. This interpolation was only performed for those integer hours when the time differences between the last observation before and the first observation after the integer hours is less than 6 hours. This is not optimum for DORIS ZTDs, as DORIS data are scarce and DORIS troposphere solutions are then provided using some interpolation. Bock et al. (2010) did a reverse approach interpolating the dense GPS data to the epochs of the DORIS passes. This provides a more realistic estimation of the DORIS performances. However, in this study, the current capability of all techniques was tested, so it is important to know the performances of all techniques over the complete period of observations and not only during DORIS satellite passes.

Table 5 ZTDs (first line) and troposphere gradients (second line) common epochs of VieVS with the other techniques during CONT08.

Preprint

3.4 ZTD comparisons

3.4.1 Intra-technique comparisons of ZTDs

The intra-technique biases at the co-located sites between VieVS and the IVS combined solution are between -1.6 mm and 1.9 mm with standard deviations between 2.3 mm (Wettzell) and 5.7 mm (Zelenchukskaya). This is similar to what is found for the differences between the CODE and the IGS solution, where the standard deviations are between 2.4 mm (Hartebeesthoek, HRAO) and 4.9 mm (Medicina). The biases between the GPS solutions are slightly larger with values between -4.5 (Wettzell, WTZR) and 2.9 (Medicina) mm, but it has to be clearly stated that the VieVS series is part of the IVS combined solution, whereas the IGS Kalman filter solution differs from the CODE solution in many aspects, e.g. PPP vs. network approach, NMF vs. VMF1, or different frames.

At Wettzell, we have IGS ZTD solutions for three different receivers from three different manufacturers which are only separated by a few meters and thus observe the same troposphere (WTZA, WTZJ, and WTZR). The mean biases between the ZTD series are -1.1 mm (WTZA - WTZJ) or smaller, and all standard deviations are at about 1.5 mm, which is significantly smaller than the standard deviation between the IGS and the CODE solution for WTZR (3.4 mm). Similar results are found at Ny-Ålesund, where we have two solutions from CODE (NYAL and NYA1) with no bias and a standard deviation of 1.0 mm. The standard deviation between the ZTDs at NYA1 between CODE and IGS is 2.7 mm. This discrepancy shows that the choice of analysis strategies is critical for the estimation of ZTDs whereas the hardware (antenna, receiver) or effects like multipath or antenna phase center variations only add a smaller fraction to the total uncertainty

of ZTDs. This is also confirmed by the fact that at many sites the standard deviations between IGS and CODE is nearly as large as the standard deviations between VLBI and GPS solutions.

At Tsukuba, the best agreement of two weather models is between JMA and CReSS. This can be expected because the high-resolution CReSS model is embedded in and initialized with the JMA model. On the other hand, this agreement is slightly worse than between ECMWF and HIRLAM for European stations, but it has to be mentioned, that the latter stations are not as humid as Tsukuba. More details about biases and standard deviations can be found in Table 6 and the electronic supplement.

In order to find out the amount of shared variances (degree of linear relationship) between the estimates/products of each pair of techniques, correlation coefficients were calculated. In Table 10, the correlations of gradients between VieVS and other solutions (and their p-values in parentheses) are shown. Correlation coefficients with $p>0.05$ are assumed to be statistically insignificant and are written in italic. The intra-technique correlations of ZTDs between VieVS and the IVS combined solution are between 0.96 and 1.00, between CODE and the IGS solution between 0.99 and 1.00, and between ECMWF and HIRLAM they range from 0.55 (Zelenchukskaya) to 0.96 (Ny-Ålesund, and Svetloe). The correlations between the weather models ECMWF, JMA, and CReSS at Tsukuba are at about 0.9. More details on the correlations of gradients can be found in Table 10 and all correlations including ZTDs in the electronic supplement.

Preprint

3.4.2 Inter-technique comparisons of ZTDs

As an example Figure 3 shows the ZTDs at Wettzell during CONT08. Inter-technique ZTD biases and standard deviations w.r.t. the VieVS and the CODE solutions can be found in Table 6 and the mean values are also shown in Figure 4. (Statistics about all combinations of sites and techniques are in the electronic supplement to this paper). The biases between different space geodetic techniques are mostly smaller than 5 mm after the application of troposphere ties, with the largest value remaining between the IVS combined and the CODE solution at Medicina (Italy) with 6.2 mm. In terms of standard deviation, the best inter space geodetic technique agreement of ZTDs is found between the IVS combined solution and the IGS Kalman filter solution, in particular at Ny-Ålesund with 2.7 mm. Slightly worse is the agreement between VieVS and the IGS Kalman filter solution, between CODE and the IVS combined solution, and between CODE and VieVS.

Generally, the median standard deviation of all sites between ZTDs from GPS and VLBI is about 4 to 5 mm. The agreement of ZTDs from DORIS with those from GPS and VLBI is rather good at

Ny-Ålesund with a standard deviation of about 6 mm (there is a large number of common epochs), but it is worse at Kokee Park and Hartebeesthoek with more than 12 mm. Inter-technique correlations can be found in the electronic supplement, confirming the findings for the standard deviations.

Figure 3 Troposphere ZTDs of the co-located site Wettzell during CONT08.

As far as the standard deviation of ZTDs from WVRs w.r.t. those from space geodetic techniques is concerned, the best agreement can be found at Onsala with about 5 mm. This is significantly better than for Wettzell (~11 mm) or Tsukuba (~20 mm). Also the biases of ZTDs from WVRs are larger at Tsukuba. It should be noted, that during CONT08 rainy weather mostly contaminates the measurements of the WVR (Robs) at Tsukuba although obvious outlier observations due to rain were eliminated.

The standard deviations of ZTDs from numerical weather models compared to ZTDs from space geodetic techniques are between ~6 mm at Ny-Ålesund and ~20 mm at Tsukuba. It seems that CReSS data is closer to the space geodetic results than the JMA (e.g. around August 19, see electronic supplement). The CReSS model sometimes has differences w.r.t. VLBI at 0 UT similar to the JMA model. This comes from the fact that the CReSS model is initialized with the JMA model and needs some time to settle to its own physics. From Table 6 and the electronic supplement no conclusions can be drawn whether ECMWF or HIRLAM agrees better with ZTDs from space geodetic techniques, because this varies w.r.t. station and solution.

As a general trend, the standard deviations of the ZTDs decrease with the latitude, i.e., the minimum standard deviations are at the site Ny-Ålesund. On the other hand, the low latitude sites like Kokee Park and Tsukuba have significantly larger standard deviations of ZTDs. All correlations between the ZTDs of different techniques are larger than 0.9 and statistically significant.

Table 6 Mean biases and standard deviations of the ZTD difference vectors between VLBI-VieVS and GPS-CODE with the other solutions for the co-located sites during CONT08. The zenith hydrostatic delays from VLBI were added to the zenith wet delays of WVR and HIRLAM.

Figure 4 Mean biases and standard deviations of all ZTDs during CONT08 w.r.t. VLBI-VieVS (bias: dark grey, std. dev.: light grey) and GPS-CODE (bias: dark red, std. dev.: light red).

Preprint

3.4.3 Comparison with CONT02

Comparing the level of agreement of ZTDs in this study (CONT08) with the findings for CONT02 by Snajdrova et al. (2006) the following conclusions can be drawn (see also Table 7): The biases between VLBI and GPS slightly decrease for CONT08. This might be due to a better agreement of underlying models like the terrestrial reference frames used for the analyses and improved troposphere ties. On the other hand the standard deviations between VLBI and GPS increase for all stations except Hartebeesthoek (South Africa). This is certainly caused by the fact that CONT08 was observed in August which corresponds to northern hemisphere summer, which is a more humid period for stations in the northern hemisphere compared to October when CONT02 was observed. A similar increase in standard deviations for CONT08 (except for Hartebeesthoek) can be found for the comparison of ZTDs between ECMWF and space geodetic techniques, probably caused by the same reason. On the other hand, there is a better agreement between DORIS and GPS/VLBI for CONT08, which is due to improved DORIS data processing for this investigation.

Table 7 Comparison of mean biases and standard deviations of the ZTD difference vectors from CONT02 (Snajdrova et al., 2006) and CONT08 (this study) for the common sites. At those sites, where more than one IGS antenna was situated the following antennas were used for the comparison: NYAL, WTZR, and HRAO.

Preprint

3.5 Troposphere gradients comparisons

Unlike the ZTDs, there are not as many north and east gradient series from the individual techniques available for comparison. We do not have gradients from the IGS Kalman filter solution, nor do we have gradients from HIRLAM or the WVR at Tsukuba. It has to be stressed again, that the gradients from the WVRs at Wettzell and Onsala are wet-only gradients and do not contain hydrostatic parts. All other gradients are gradients of the total delays. Exemplarily, the troposphere east gradients at Onsala are shown in Figure 5 and the most important features of the gradient comparison can already be seen there: The best agreement of gradients is found between VieVS and the IVS combined series which was expected because VieVS is part of the IVS combination (Heinkelmann et al., this issue). There are no biases and the mean standard deviation is at the level of 0.3 mm. (See also Tables 8 and 9 and the electronic supplement.) The gradients provided by CODE only have a daily resolution which makes the comparison difficult and vague: Whereas the gradients from VLBI describe the mean asymmetry over two hours, the gradients from GPS (CODE) are averaged over 24 hours. However, the general agreement of north and east gradients from the CODE solution with gradients from VLBI is quite good (~0.5 mm). Only at Tsukuba and Kokee Park, standard deviations larger than 1 mm occur (see electronic supplement with plots for all stations).

Figure 5 Troposphere east gradients of the co-located site Onsala during CONT08.

The standard deviations of DORIS gradients w.r.t. gradients from VieVS are rather large, in particular at Hartebeesthoek (South Africa) with 1.8 mm and 0.9 mm in the east and north direction, and at Kokee Park (Hawaii, U.S.A.) with 1.2 mm in east and 0.9 mm in north direction. It can also be noted here, that there is a large north gradient bias of ~1 mm for the DORIS station at Hartebeesthoek with respect to VLBI. This could come from the fact that, at this high latitude, the tracks of the DORIS satellites (all sun-synchronous, as we did not use Jason-2) are mostly east-west oriented, i.e. perpendicular to the north gradient. Willis et al. (2010a) see a similar problem for the other stations (equatorial or mid-latitude), when the tracks are north-south oriented and the east-west gradient is only loosely determined. However, since the standard deviation is of about the same size, this bias is not very significant.

There is a large standard deviation of more than 1 mm for the gradients from the WVR at Wettzell, which might be due to a tilting of the instrument (see station-wise plots with gradients in the electronic supplement). In general the wet gradients from WVRs are noisier because they are only derived from slant delays above 20° elevation (Figure 5). On the other hand, the biases should be disregarded because they might be caused from the neglected hydrostatic part.

The best intra-NWM agreement of north and east gradients is found between JMA and CReSS, which could be expected because the CReSS model is initialized with the data from the larger JMA model. One has to keep in mind that the gradients from the weather model are a snap-shot of the troposphere at a certain epoch, whereas the gradients from the space geodetic techniques are averaged over a certain period, which is related to the way how the temporal resolution of the gradients is parameterized. The gradients from VLBI are estimated from very sparse spatial sampling, i.e. one direction at a given epoch. Scan lengths are between 20 seconds to a few minutes (depending on the source flux density) for CONT08 but there are also several minutes slew times between on-source times. Thus, VLBI scans the sky with only about 25 scans per hour.

In order to find out the amount of shared variances (degree of linear relationship) between the gradients of each pair of techniques, Pearson correlation coefficients were calculated. In Table 10, the correlations of gradients between VieVS and the other solutions (and their p-values in parentheses) are shown. Correlation coefficients with $p>0.05$ are assumed to be statistically insignificant and are written in italic. The correlation coefficients of north and east gradients

Preprint

between VieVS and the IVS combined solutions are above 0.85 except for the east gradient at Hartebeesthoek (0.70), and all are significant. The correlation coefficients between the gradient estimates from VieVS and CODE are mostly below 0.7 and some of them are insignificant.

Table 8 Mean biases and standard deviations of the troposphere east gradient difference vectors between VLBI-VieVS and other solutions for the co-located sites during CONT08. All the gradients except those derived from WVR (wet gradients) are total gradients.

Table 9 Mean biases and standard deviations of the troposphere north gradient difference vectors between VLBI-VieVS and other solutions for the co-located sites during CONT08. All gradients except those derived from WVR (wet gradients) are total gradients.

Table 10 Correlation coefficients and their p-values between the estimates* of VLBI-VieVS and other solutions for the co-located sites during CONT08. Correlations written in italic are statistically insignificant (p>0.05). (* troposphere north gradients (first line) and east gradients (second line)).

4 Conclusions

The space geodetic techniques VLBI, GPS, and DORIS, including co-located WVRs and the use of NWMs (ECMWF, HIRLAM, KARAT, CReSS during CONT08) allowed to perform a comprehensive comparison of simultaneously determined troposphere parameters. Due to the lack of space not all of the results could be provided in this paper (the supplementary material can be accessed online). The comparisons done in this study are essential before starting with any combination attempt in the sense of GGOS, the Global Geodetic Observing System of the IAG.

These are the main findings of this study: Zenith total delay (ZTD) estimates of space geodetic techniques generally agree at the sub-centimetre level during CONT08. For ZTDs, the best agreement is found from the intra-technique comparisons between VieVS and the IVS combined solution as well as CODE and the IGS Kalman filter solution with median standard deviations of 3-4 mm and 4-5 mm, respectively. The best inter space geodetic technique agreement of ZTDs during CONT08 is slightly worse and it can be found between IVS and IGS with a median standard deviation of about 5 mm over all sites. Since the standard deviation between ZTDs for co-located GPS receivers from one solution (IGS at Wettzell, CODE at Ny-Ålesund) is at about 1.0 to 1.5 mm and the standard deviation between IGS and CODE is nearly as large as w.r.t. VLBI solutions, it can be argued that the choice of the analysis options adds a major part to the total uncertainty of ZTDs from GPS.

As far as the overall agreement of ZTDs is concerned between the techniques/solutions, two groups can be formed. GPS and VLBI form a group with the best agreement. The second group consists of the other models/techniques which are DORIS, ECMWF, HIRLAM, KARAT, CReSS, and WVR.

Preprint

Correlation coefficients of ZTDs are typically larger than 0.9 and all of the correlations are statistically significant.

There is a latitude- and season-dependence of the standard deviations between the techniques. The standard deviations generally decrease with increasing northern and southern latitudes, which is due to the lesser amount of humidity at higher latitudes. Additionally, the comparison with the results from the CONT02 campaign in October 2002 showed, that standard deviations are generally larger during CONT08, which was observed in August 2008. In particular observations at Tsukuba are affected by the humid conditions in August.

The best intra-technique agreement of north and east gradients are found between VieVS and the IVS combined solution, which was not surprising because VieVS was part of the IVS combination for CONT08. In general it has to be stressed, that the results of the comparison of gradients have to be used with care. Not only because of different time intervals but also due to basic differences in the observed quantities and setups, in the case of gradients the reader is rather referred to the station-wise plots in the electronic supplement than to the numbers in the tables.

Organizing regular inter-technique comparison campaigns with consistent analysis models dedicated to the investigation of the troposphere would help to improve the data w.r.t. the weaknesses of the individual space geodetic techniques (e.g. low degrees of freedom, inadequacy of gradient models) and the weaknesses of NWMs in terms of conventions on data assimilation, time and spatial resolution of the profiles, and the ray-tracing technique.

Preprint

Acknowledgements

We use in this study the data provided by the International VLBI Service for Geodesy and Astrometry (IVS), the International GNSS Service (IGS), the International DORIS Service (IDS), the Center for Orbit Determination in Europe (CODE), the European Centre for Medium-Range Weather Forecast (ECMWF), the Japan Meteorological Agency (JMA), and the Swedish Meteorological and Hydrological Institute (SMHI), and the authors would like to thank all components of the aforementioned services. Part of this work was supported by Centre National d'Etudes Spatiales (CNES). This is IPGP contribution XXX. Thomas Hobiger and Ryuichi Ichikawa were supported by a Grant-in-Aid for Scientific Research (KAKENHI-21241043).

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Table 1 Geodetic instruments co-located at the VLBI sites during the CONT08 campaign.

VLBI station	IGS acronym and GPS Solutions	IDS acronym	WVR name (site)
Ny-Ålesund	NYA1 (CODE + IGS) NYAL (CODE only)	SPJB	-
Svetloe	SVTL (CODE + IGS)	-	-
Onsala	ONSA (CODE + IGS)	-	ASTRID
Wettzell	WTZR (CODE + IGS) WTZA (IGS only) WTZJ (IGS only)	-	RADIOMETRIX
Medicina	MEDI (CODE + IGS)	-	-
Zelenchukskaya	ZECK (IGS only)	-	-
Westford	WES2 (CODE + IGS)	-	-
Tsukuba	TSKB (CODE only) TSK2 (IGS only)	-	ROBS
Kokee Park	KOKB (CODE + IGS)	KOLB	-
Hartebeesthoek	HRAO (CODE + IGS) HARB (CODE only)	HBMB	-
Tigo Concepcion	CONZ (CODE + IGS)	-	-

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Table 2 ITRF2005 ellipsoidal heights and approximate horizontal distances of the co-located VLBI, GPS, and DORIS antennas, and WVRs involved in CONT08.

VLBI Station (order w.r.t. lat.)	Country	VLBI height (m)	GPS phase center height (m) (reference point height + up eccentricity**)	WVR height (m)	DORIS height (m)	VLBI-DORIS approximate horizontal distance (m)	VLBI-GPS approximate horizontal distance (m)
Ny-Ålesund	Norway	87.30	84.18 + 0.00 ([1]) 78.45 + 5.22 ([2])	-	52.60 (SPJB)	1475 (SPJB)	106 ([1]) 112 ([2])
Svetloe	Russia	86.01	77.13* + 0.03	-	-	-	82
Onsala60	Sweden	59.28	45.56 + 1.00	~ 46.57 (ASTRID)	-	-	78
Wettzell	Germany	669.13	666.03 + 0.07 ([3]) 665.92* + 0.08 ([4]) 665.91* + 0.07 ([5])	~ 667.56	-	-	139 ([3]) 140 ([4]) 137 ([5])
Medicina	Italy	67.17	50.04 + 0.00	-	-	-	60
Zelenchukskaya	Russia	1175.43*	1167.27 + 0.05	-	-	-	65
Westford	USA	86.77	85.02 + 0.00	-	-	-	58
Tsukuba	Japan	84.72	67.25 + 0.00 ([6]) 70.35* + 0.00 ([7])	25.20 (ROBS)	-	-	302 ([6]) 306 ([7])
Kokee Park	USA	1176.60	1167.37 + 0.06	-	1166.98 (KOLB)	398 (KOLB)	45
Hartebeesthoek	South Africa	1416.12*	1414.16 + 0.08([8]) 1558.09 + 3.05 ([9])	-	1560.00 (HBMB) *	2239 (HBMB)	164 ([8]) 2212 ([9])
Tigo Concepcion	Chile	170.95	180.69 + 0.06	-	-	-	120

([1]) NYA1, ([2]) NYAL, ([3]) WTZR, ([4]) WTZJ, ([5]) WTZA, ([6]) TSKB, ([7]) TSK2, ([8]) HRAO, ([9]) HARB.
* Heights taken from the log file of the stations because not available in ITRF2005.
** Antenna reference point eccentricities are provided in the station log files at the IGS web site.

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Table 3 Height differences and troposphere ties between the co-located VLBI, GPS, and DORIS antennas, and the WVRs involved in CONT08.

VLBI Station	VLBI-GPS height difference (m)	Mean GPS troposphere ties ZTD = ZHD + ZWD (mm)	VLBI-DORIS height difference (m)	Mean DORIS troposphere ties ZTD = ZHD + ZWD (mm)	VLBI-WVR height difference (m)	Mean WVR troposphere ties ZTD = ZHD + ZWD (mm)
Ny-Ålesund	3.12 ([1]) 3.63 ([2])	-0.97 = -0.88 + (-0.09) -1.13 = -1.02 + (-0.11)	34.70	-10.77 = -9.78 + (-0.99)	-	-
Svetloe	8.85	-2.92 = -2.38 + (-0.54)	-	-	-	-
Onsala60	12.72	-4.16 = -3.43 + (-0.73)	-	-	~12.71	-0.73 = 0.00 + (-0.73)
Wettzell	3.03 ([3]) 3.13 ([4]) 3.15 ([5])	-0.94 = -0.79 + (-0.15) -0.97 = -0.82 + (-0.15) -0.97 = -0.82 + (-0.16)	-	-	~ 1.57	-0.08 = 0.00 + (-0.08)
Medicina	17.13	-5.52 = -4.51 + (-1.01)	-	-	-	-
Zelenchukskaya	8.11	-2.35 = -1.91 + (-0.44)	-	-	-	-
Westford	1.75	-0.56 = -0.46 + (-0.10)	-	-	-	-
Tsukuba	17.47 ([6]) 14.37([7])	-6.11 = -4.58 + (-1.52) -5.02 = -3.77 + (-1.25)	-	-	59.52	-5.30 = 0.00 + (-5.30)
Kokee Park	9.17	-2.72 = -2.21 + (-0.52)	9.62	-2.84 = -2.30 + (-0.54)	-	-
Hartebeesthoek	1.88 ([8]) -145.02 ([9])	-0.51 = -0.46 + (-0.05) 37.39 = 33.40 + 3.99	-143.88	37.18 = 33.19 + (3.99)	-	-
Tigo Concepcion	-9.80	3.07 = 2.66 + 0.40	-	-	-	-

(1) NYA1, ([2]) NYAL, ([3]) WTZR, ([4]) WTZJ, ([5]) WTZA, ([6]) TSKB, ([7]) TSK2, ([8]) HRAO, ([9]) HARB.

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Table 4 Summary of the data used for the comparisons.

Technique	Zenith total/wet delay	Estimation interval of zenith delay	Estimation interval of gradients
VLBI-VieVS	ZWD, ZTD	30 minutes	2 hours (total gradients)
VLBI-IVS	ZWD, ZTD	1 hour	1 hour (total gradients)
GPS/IGS	ZTD	5 minutes	-
GPS/CODE	ZTD	2 hours	1 day (total gradients)
DORIS/IGN	ZTD	per satellite pass (but not all), using time constraints between passes	1 day (total gradients)
WVR	ZWD	30 minutes	2 hours (wet gradients)
ECMWF	ZWD, ZTD	6 hours	6 hours (total gradients)
JMA/KARAT	ZTD	3 hours	3 hours (total gradients)
CreSS	ZTD	1 hour	1 hour (total gradients)
HIRLAM	ZWD	3 hours	-

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Table 5 ZTDs (first line) and troposphere gradients (second line) common epochs of VieVS with the other techniques during CONT08.

	IVS	IGS	CODE	IGN	WVR	ECMWF	HIRLAM	KARAT	CReSS
Ny-Ålesund	357	714 ([1])	180 ([1])	149	-	60	120	-	-
	179	-	16 ([1])	15	-	60	-	-	-
Svetloe	360	672	181	-	-	60	121	-	-
	180	-	16	-	-	60	-	-	-
Onsala60	360	623	181	-	593	60	121	-	-
	180	-	16	-	181	60	-	-	-
Wettzell	360	662 ([3]) 616 ([4]) 670 ([5])	181 ([3])	-	548	60	121	-	-
	180	-	16 ([3])	-	169	60	-	-	-
Medicina	360	720	181	-	-	60	121	-	-
	180	-	16	-	-	60	-	-	-
Zelenchukskaya	326	552	-	-	-	55	110	-	-
	163	-	-	-	-	55	-	-	-
Westford	360	672	169	-	-	60	-	-	-
	180	-	15	-	-	60	-	-	-
Tsukuba	360	719 ([7])	181 ([6])	-	560	60	-	121	361
	180	-	16 ([6])	-	-	60	-	61	181
Kokee Park	360	720	181	66	-	60	-	-	-
	180	-	16	15	-	60	-	-	-
Hartebeesthoek	360	720 ([8])	181 ([8])	60	-	60	-	-	-
	180	-	16 ([8])	15	-	60	-	-	-
Tigo Concepcion	242	192	122	-	-	39	-	-	-
	121	-	11	-	-	39	-	-	-

([1]) NYA1, ([2]) NYAL, ([3]) WTZR, ([4]) WTZJ, ([5]) WTZA, ([6]) TSKB, ([7]) TSK2, ([8]) HRAO, ([9]) HARB.

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Table 6 Mean biases and standard deviations of the ZTD difference vectors between VLBI-VieVS and GPS-CODE with the other solutions for the co-located sites during CONT08. The zenith hydrostatic delays from VLBI were added to the zenith wet delays of WVR and HIRLAM.

	Ny-Ålesund	Svetloe	Onsala	Wettzell	Medicina	Zelenchukskaya	Westford	Tsukuba	Kokee Park	Hartebeesthoek	Tigo Concepcion
VLBI/VieVS–VLBI/IVS	-1.6±2.8	0.3±3.3	-0.4±2.6	-0.4±2.3	-1.0±4.7	1.9±5.7	-0.2±3.1	-0.1±4.8	-0.2±4.7	-0.7±3.2	-1.0±4.0
VLBI/VieVS–GPS/IGS	-2.0±3.9 (NYA1)	1.2±5.5	1.0±4.5	2.2±4.1 (WTZR)	2.3±7.0	2.8±11.1	-4.5±6.1	-0.6±11.1 (TSK2)	0.8±8.3	-0.2±4.7 (HRAO)	-4.0±5.1
VLBI/VieVS–GPS/CODE	0.0±3.9 (NYAL)	1.0±6.1	3.1±5.0	-2.1±4.6 (WTZR)	5.1±7.9	-	-3.7±6.4	1.4±11.6 (TSKB)	1.9±9.5	0.1±5.2 (HRAO)	-4.5±5.0
VLBI/VieVS–DORIS/IGN	0.8±6.4	-	-	-	-	-	-	-	5.2±14.7	4.6±12.7	-
VLBI/VieVS–WVR	-	-	-0.4±5.1	-14.3±10.3	-	-	-	-24.8±22.2	-	-	-
VLBI/VieVS–ECMWF	-3.4±6.5	0.9±10.9	3.4±11.2	-2.1±11.8	-2.1±19.8	4.1±20.0	-3.8±16.6	-0.3±20.2	2.9±18.1	3.0±8.4	0.9±11.2
VLBI/VieVS–JMA/KARAT	-	-	-	-	-	-	-	7.8±25.7	-	-	-
VLBI/VieVS–CreSS	-	-	-	-	-	-	-	6.0±20.0	-	-	-
VLBI/VieVS–HIRLAM	0.6±11.1	0.8±16.2	6.4±11.0	2.5±10.1	2.4±18.0	6.0±20.7	-	-	-	-	-
GPS/CODE –VLBI/IVS	-1.4±2.9 (NYA1)	-0.7±5.1	-3.3±4.5	1.8±4.2 (WTZR)	-6.2±8.7	-	3.7±5.5	-1.5±9.7	-2.0±7.3	-0.9±4.0 (HRAO)	2.4±7.3
GPS/CODE–GPS/IGS	-1.9±2.7 (NYA1)	0.5±4.1	-2.0±4.0	4.5±3.4 (WTZR)	-2.9±4.9	-	-0.3±4.7	-	-1.0±4.5	-0.2±2.4 (HRAO)	1.2±2.6
GPS/CODE–DORIS/IGN	0.7±5.4 (NYA1)	-	-	-	-	-	-	-	3.2±13.0	4.1±13.1 (HRAO)	-
GPS/CODE–WVR	-	-	-3.1±5.7	-12.5±11.6 (WTZR)	-	-	-	-26.1±20.2	-	-	-
GPS/CODE–ECMWF	-3.4±5.9 (NYA1)	0.1±10.6	-0.1±11.1	-0.8±11.5 (WTZR)	-8.8±18.4	-	-1.7±14.7	0.2±20.6	1.9±16.5	2.0±8.3 (HRAO)	4.4±9.7
GPS/CODE–JMA/KARAT	-	-	-	-	-	-	-	7.1±20.6	-	-	-
GPS/CODE–CreSS	-	-	-	-	-	-	-	5.3±18.9	-	-	-
GPS/CODE–HIRLAM	1.2±10.2 (NYA1)	0.4±14.6	3.6±9.6	2.5±9.4 (WTZR)	-3.2±16.7	-	-	-	-	-	-

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Table 7 Comparison of mean biases and standard deviations of the ZTDs difference vectors from CONT02 (Snajdrova et al., 2006) and CONT08 (this study) for the common sites. (The IGS antennas are NYAL, WTZR, and HRAO at sites with more than one antenna.)

	Ny-Ålesund		Onsala60		Wettzell		Westford		Kokee Park		Hartebeesthoek	
	CONT02	CONT08	CONT02	CONT08	CONT02	CONT08	CONT02	CONT08	CONT02	CONT08	CONT02	CONT08
VLBI*-GPS**	0.1±3.3	0.0±3.9	0.7±4.1	3.1±5.0	-2.1±4.5	-2.1±4.6	-6.5±3.5	-3.7±6.4	-5.7±6.6	1.9±9.5	-3.4±5.8	0.1±5.2
VLBI*-ECMWF	7.1±4.7	-3.4±6.5	8.1±5.7	3.4±11.2	13.2±8.8	-2.12±11.8	-16.2±5.9	-3.8±16.6	-8.8±21.0	2.9±18.1	-4.8±19.4	3.0±8.4
VLBI*-DORIS	1.5±7.9	0.8±6.4	-	-	-	-	-	-	-7.2±32.1	5.2±14.7	2.7±14.0	4.6±12.7
VLBI*-WVR	-	-	-2.8±6.7	-0.4±5.1	-17.2±9.0	-14.3±10.33	-	-	-	-	-	-
GPS**-ECMWF	6.6±3.5	-3.8±6.0	7.6±5.5	-0.1±11.1	15.1±7.8	-0.8±11.4	-9.1±7.1	-1.7±14.7	-1.9±17.4	1.9±16.5	-0.3±18.6	2.0±8.3
GPS**-DORIS	1.2±8.1	0.5±5.2	-	-	-	-	-	-	2.7±34.7	3.2±13.0	5.5±14.5	4.1±13.1
GPS**-WVR	-	-	-3.7±5.4	-3.1±5.7	-14.7±8.1	-12.5±11.6	-	-	-	-	-	-
ECMWF-DORIS	-6.8±8.5	4.1±7.7	-	-	-	-	-	-	-	-	-	
ECMWF-WVR	-	-	-11.7±10.2	-3.1±10.9	-26.2±7.5	-11.9±15.6	-	-	-	-	-	-

* VieVS solution
** CODE solution

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Table 8 Mean biases and standard deviations of the troposphere east gradient difference vectors between VLBI/VieVS and other solutions for the co-located sites during CONT08. All the gradients except those derived from WVR (wet gradients) are total gradients.

	Ny-Ålesund	Svetloe	Onsala	Wettzell	Medicina	Zelenchukskaya	Westford	Tsukuba	Kokee Park	Hartebeesthoek	Tigo Concepcion
VLBI/VieVS–VLBI/IVS	0.0±0.2	0.0±0.2	0.0±0.2	0.0±0.2	0.0±0.2	0.1±0.4	0.0±0.2	0.1±0.4	0.0±0.2	-0.1±0.3	0.1±0.3
VLBI/VieVS–GPS/CODE	0.2±0.5 (NYA1)	0.2±0.5	-0.1±0.5	-0.3±0.6 (WTZR)	0.0±0.5	-	-0.4±0.8	0.2±1.1 (TSKB)	0.1±0.7	0.0±0.5 (HRAO)	0.1±0.8
VLBI/VieVS–DORIS/IGN	0.2±0.7	-	-	-	-	-	-	-	-0.2±1.2	0.2±1.8	-
VLBI/VieVS–WVR	-	-	0.3±0.8	0.0±1.3	-	-	-	-	-	-	-
VLBI/VieVS–ECMWF	0.0±0.4	0.2±0.5	0.0±0.4	-0.1±0.6	0.0±0.5	0.1±0.7	0.0±0.5	-0.3±0.9	-0.2±0.6	0.1±0.4	0.2±0.5
VLBI/VieVS–JMA/KARAT	-	-	-	-	-	-	-	0.1±0.9	-	-	-
VLBI/VieVS–CreSS	-	-	-	-	-	-	-	0.1±0.9	-	-	-

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Table 9 Mean biases and standard deviations of the troposphere north gradient difference vectors between VLBI-VieVS and other solutions for the co-located sites during CONT08. All gradients except those derived from WVR (wet gradients) are total gradients.

	Ny-Ålesund	Svetloe	Onsala	Wettzell	Medicina	Zelenchukskaya	Westford	Tsukuba	Kokee Park	Hartebeesthoek	Tigo Concepcion
VLBI/VieVS–VLBI/IVS	0.0±0.2	0.0±0.2	0.0±0.2	0.0±0.2	0.0±0.3	-0.2±0.4	0.0±0.2	0.0±0.4	0.0±0.3	0.3±0.4	0.0±0.3
VLBI/VieVS–GPS/CODE	0.0±0.4 (NYA1)	-0.2±0.5	0.3±0.6	-0.1±0.4 (WTZR)	-0.1±0.8	-	-0.5±0.5	0.3±1.1 (TSKB)	0.2±1.1	0.5±0.5 (HRAO)	0.3±0.5
VLBI/VieVS– DORIS/IGN	0.4±0.7	-	-	-	-	-	-	-	-0.3±1.2	1.2±0.9	-
VLBI/VieVS–WVR	-	-	-0.4±0.8	-0.6±1.1	-	-	-	-	-	-	-
VLBI/VieVS–ECMWF	0.0±0.4	-0.1±0.5	0.0±0.5	-0.1±0.4	0.0±0.8	-0.7±1.0	0.0±0.4	0.5±1.0	-0.2±0.8	0.3±0.6	0.3±0.5
VLBI/VieVS–JMA/KARAT	-	-	-	-	-	-	-	0.2±1.0	-	-	-
VLBI/VieVS–CreSS	-	-	-	-	-	-	-	0.2±1.0	-	-	-

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Table 10 Correlation coefficients and their p-values between the estimates* of VLBI/VieVS and other solutions for the co-located sites during CONT08. Correlations written in italic are statistically insignificant (p>0.05). (* troposphere north gradients (1st line) and east gradients (2nd line)).

	Ny-Ålesund	Svetloe	Onsala	Wettzell	Medicina	Zelenchukskaya	Westford	Tsukuba	Kokee Park	Hartebeesthoek	Tigo Concepcion
VLBI/VieVS–VLBI/IVS	0.93 (0.00)	0.94 (0.00)	0.93 (0.00)	0.89 (0.00)	0.91 (0.00)	0.86 (0.00)	0.93 (0.00)	0.92 (0.00)	0.89 (0.00)	0.87 (0.00)	0.86 (0.00)
	0.93 (0.00)	0.89 (0.00)	0.93 (0.00)	0.95 (0.00)	0.88 (0.00)	0.92 (0.00)	0.87 (0.00)	0.93 (0.00)	0.91 (0.00)	0.70 (0.00)	0.85 (0.00)
VLBI/VieVS–GPS/CODE	0.74 (0.00) NYA1	0.75 (0.00)	0.69 (0.00)	*0.39 (0.13) WTZR*	0.54 (0.03)	-	0.64 (0.01)	*0.49 (0.05)*	*-0.19 (0.48)*	0.68 (0.00) HRAO	*0.58 (0.06)*
	0.57 (0.02) NYA1	*0.34 (0.20)*	0.70 (0.00)	0.80 (0.00) WTZR	0.56 (0.02)	-	0.25 (0.34)	0.55 (0.03)	*0.34 (0.20)*	0.25 (0.35) HRAO	*0.23 (0.50)*
VLBI/VieVS–DORIS/IGN	*0.19 (0.49)*	-	-	-	-	-	-	-	*-0.06 (0.83)*	*0.16 (0.57)*	-
	-0.16 (0.56)	-	-	-	-	-	-	-	*0.41 (0.13)*	*0.40 (0.14)*	-
VLBI/VieVS–WVR	-	-	0.49 (0.00)	0.31 (0.00)	-	-	-	-	-	-	-
	-	-	0.57 (0.00)	*0.11 (0.14)*	-	-	-	-	-	-	-
VLBI/VieVS–ECMWF	0.62 (0.00)	0.51 (0.00)	0.52 (0.00)	0.51 (0.00)	0.28 (0.03)	*0.17 (0.20)*	0.74 (0.00)	0.40 (0.00)	*0.01 (0.94)*	*0.24 (0.06)*	0.34 (0.04)
	0.61 (0.00)	*0.21 (0.10)*	0.76 (0.00)	0.31 (0.02)	0.48 (0.00)	0.42 (0.00)	0.51 (0.00)	0.28 (0.03)	*0.10 (0.43)*	*0.14 (0.28)*	0.60 (0.00)
VLBI/VieVS–JMA/KARAT	-	-	-	-	-	-	-	0.39 (0.00)	-	-	-
	-	-	-	-	-	-	-	0.50 (0.00)	-	-	-
VLBI/VieVS–CreSS	-	-	-	-	-	-	-	0.45 (0.00)	-	-	-
	-	-	-	-	-	-	-	0.41 (0.00)	-	-	-

Preprint

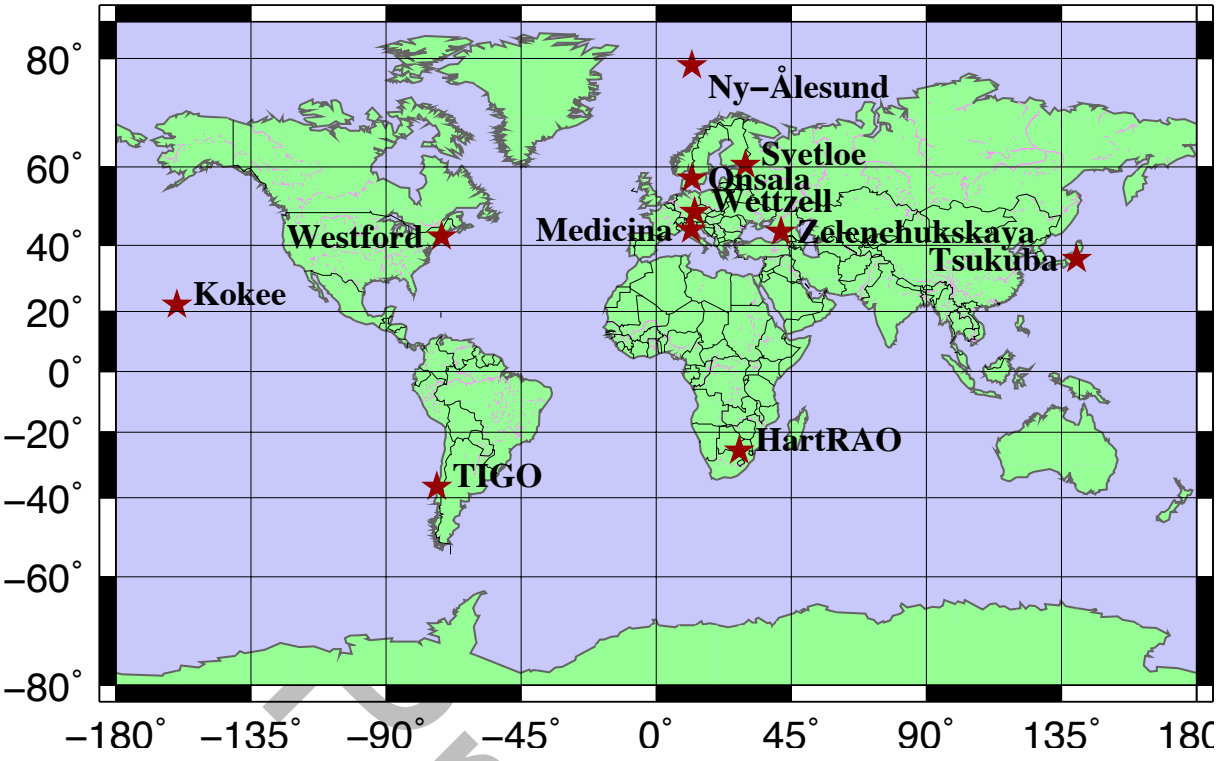

Figure 1 IVS CONT08 stations.

Preprint

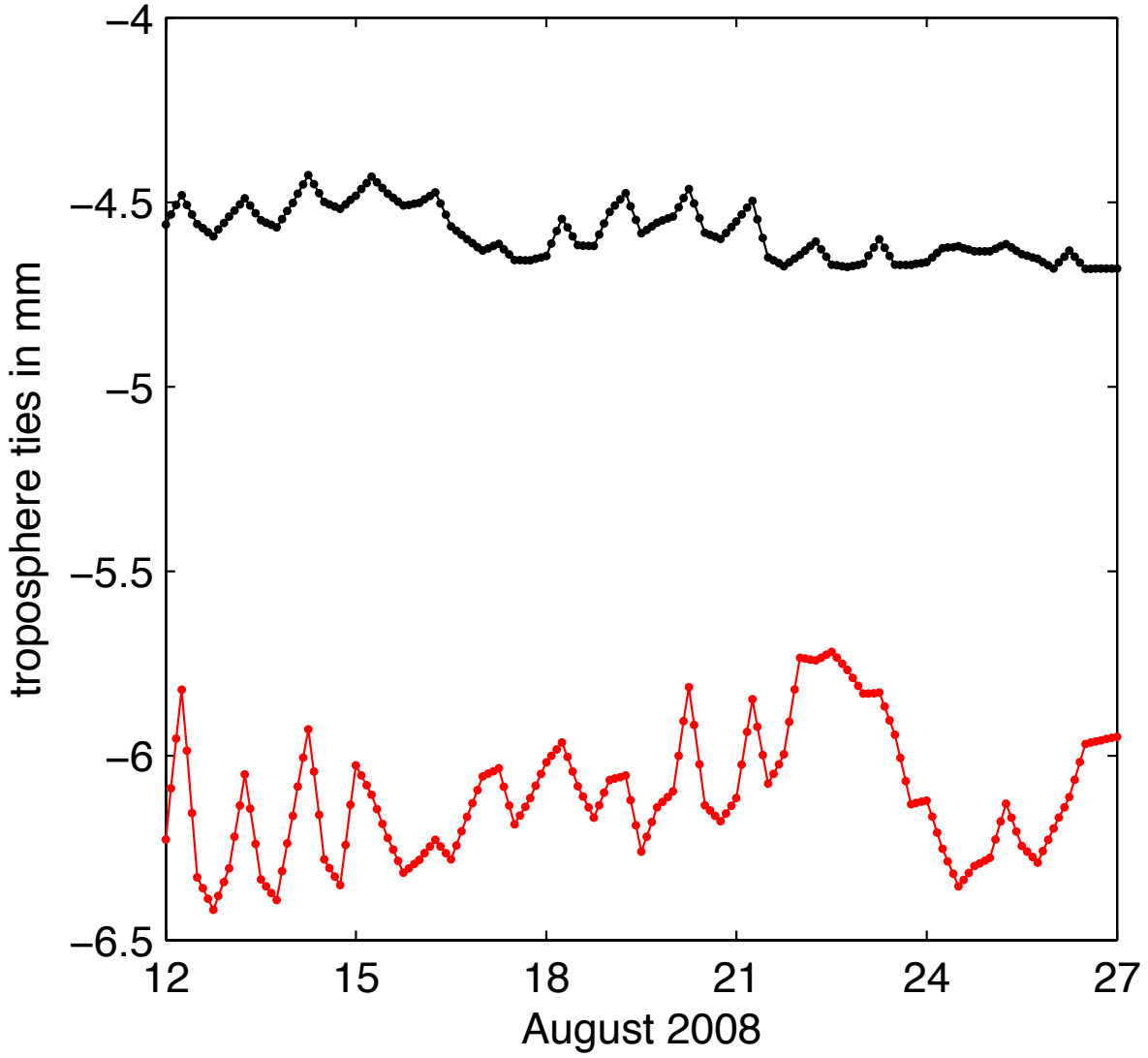

Figure 2 Troposphere ties between the GPS antenna TSKB and the VLBI antenna TSUKUB32 during CONT08, calculated for all common epochs. Red and black dotted lines illustrate total and hydrostatic ties, respectively.

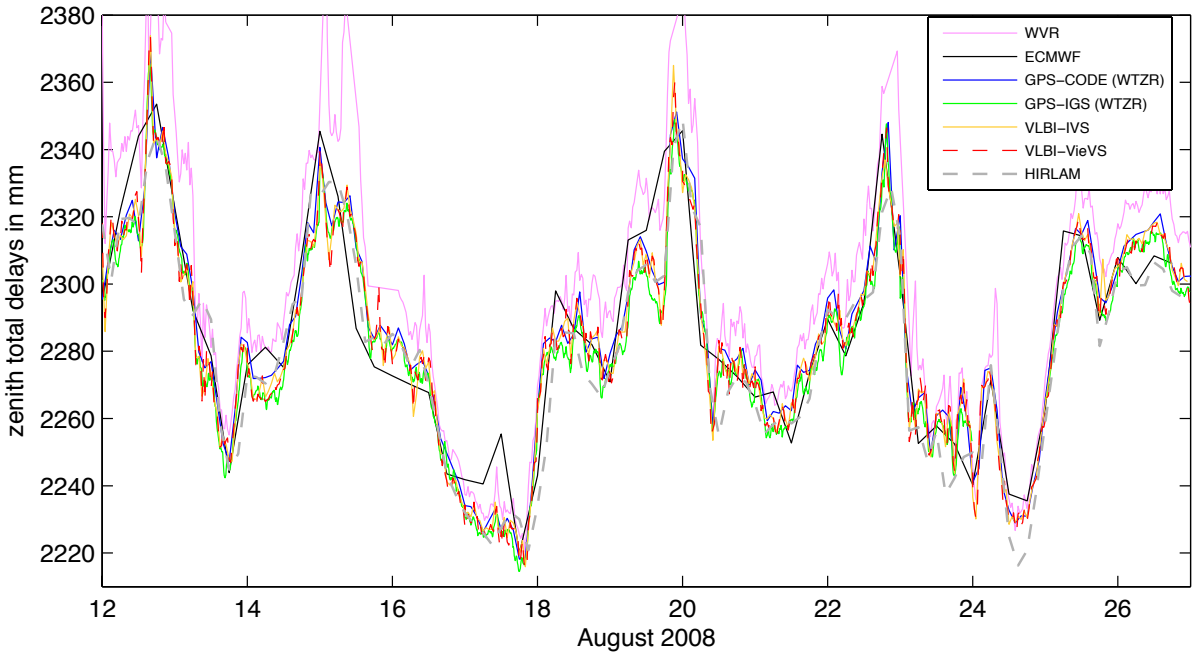

Figure 3 Troposphere ZTDs of the co-located site Wettzell during CONT08.

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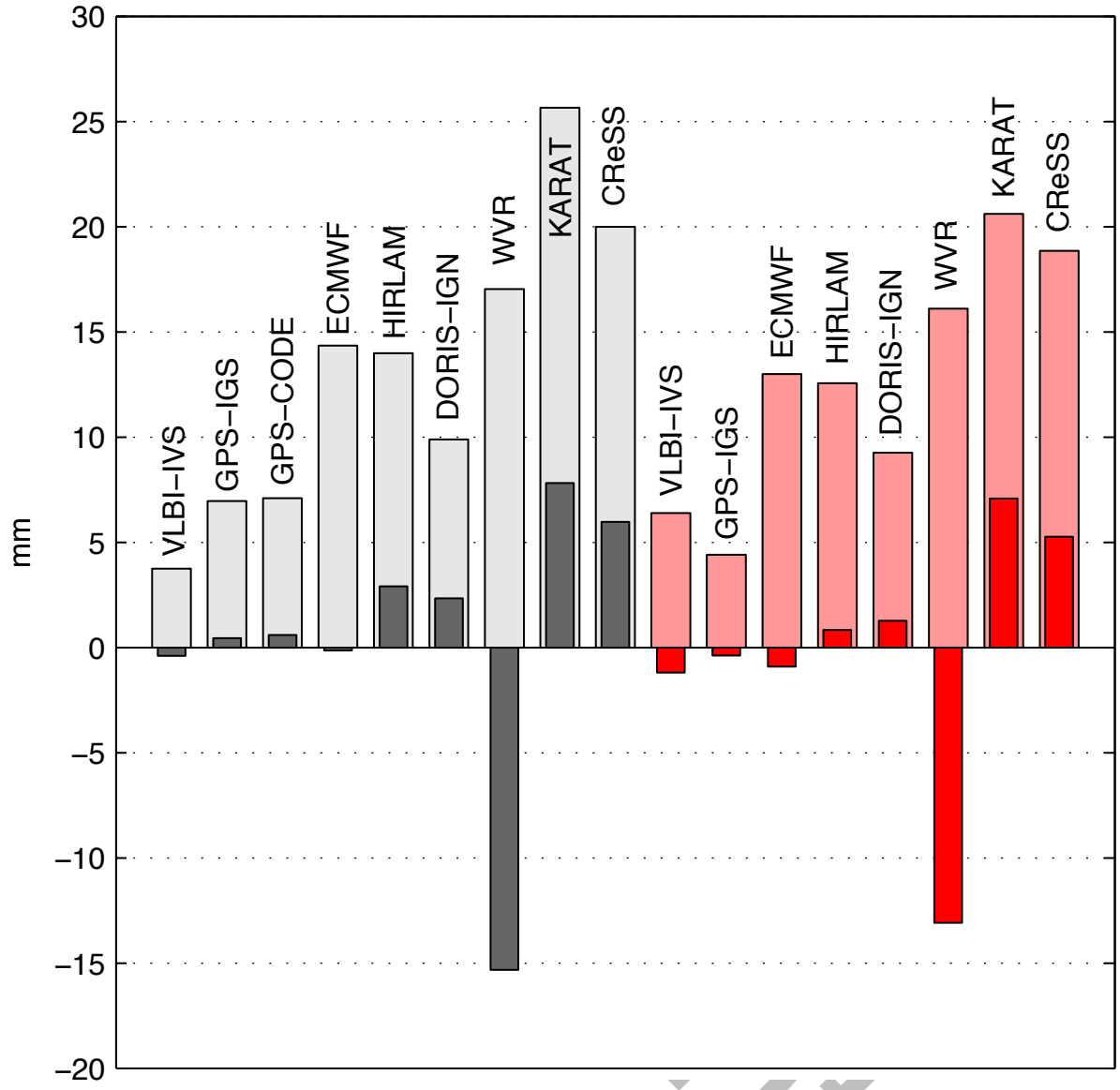

Figure 4 Mean biases and standard deviations of all ZTDs during CONT08 w.r.t. VLBI-VieVS (bias: dark grey, std. dev.: light grey) and GPS-CODE (bias: dark red, std. dev.: light red).

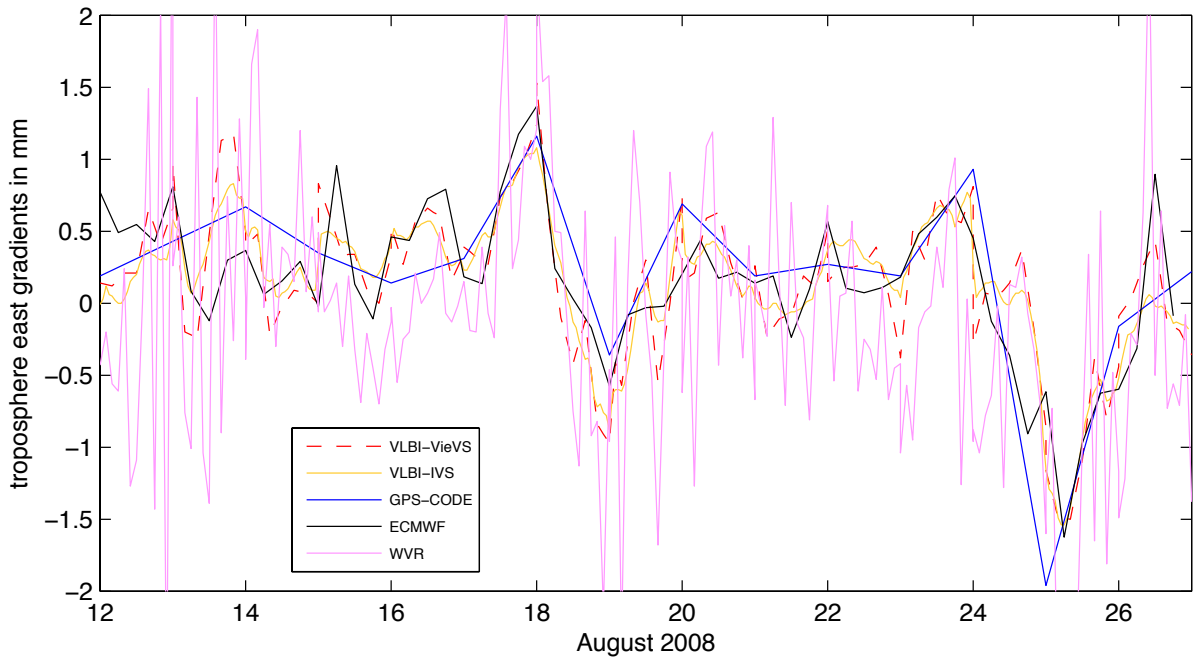

Figure 5 Troposphere east gradients of the co-located site Onsala during CONT08.

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