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Key Points:

- The role of spatial gradient is more significant on the equatorial region as compared to other areas
- Spatial gradients improve accuracy of the VTEC (vertical total electron content) estimates from very long baseline interferometry (VLBI) observation, especially in periods when the solar activity is high
- The role of the spatial gradient in estimating VLBI VTEC is related to the latitude of the VLBI station

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The Role of Spatial Gradient on Vertical Total Electron Content Extraction From Geodetic Very Long Baseline Interferometry Observation: Case Study CONT08 to CONT17-L1

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Abstract Geodetic very long baseline interferometry (VLBI) observations are carried out, with the legacy system, using two well-separated frequency bands in order to determine first-order ionospheric delay corrections corresponding to the combined effect of total electron content (TEC) at two stations forming a baseline. On the other hand, it is possible to obtain the vertical TEC (VTEC) above the VLBI antennas from VLBI data. This research intends to investigate the role of the ionospheric spatial gradient on VTEC which is derived from VLBI observations based on the latest four Continuous VLBI Campaigns (CONT08 to CONT17-L1). For this purpose, station-based VTEC values were computed in two modes, with and without spatial gradients. Then, these two approaches were evaluated by comparison to global ionospheric maps (GIMs). The differences between the GIM-based VTEC values and the VLBI VTEC values derived using two parameterization approaches were used to compute the Root Mean Square Error (RMSE) for each VLBI station during the CONTs. In addition, the improvement percentages of the VLBI VTEC's error were calculated to understand the spatial gradient role. Based on the obtained results, the role of spatial gradient is more significant on the equatorial region as compared to the polar area. Using the ionospheric spatial gradient decreases the RMSE values of VLBI-derived VTEC values from CONT08, CONT11, CONT14, and CONT17-L1 by 26.4%, 37.6%, 32.4%, and 27.4%, respectively. In addition, it is also shown that this parameter reduces the RMSE values during the high solar activity, as in 2011 and 2014.

Plain Language Summary In this study, we tried to use a special tool to estimate part of the atmosphere. To use the data of this technique, we used two common models. Here we examined them and identified the effect of the component in which they differ. The results showed that different geographical locations and years of study of this quantity are very effective.

1. Introduction

Very long baseline interferometry (VLBI) geodetic 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 (Nothnagel, 2020). These observations are carried out at two distinct frequency bands, S-band (2.3 GHz) and X-band (8.4 GHz), in order to determine ionospheric delay corrections to first order (Anderson & Xu, 2018). The ionospheric delay corresponds to the two slant total electron content (STEC) values along the ray paths through the ionosphere. On the other hand, it is possible to obtain the vertical TEC (VTEC) above the VLBI antennas (Hobiger, 2006). Kondo (1993) mentioned it was already mentioned that the ionosphere is not only an obstacle which has to be considered for processing geodetic VLBI sessions, but the station-dependent ionospheric parameters can also be obtained from VLBI data. In 2003, the accuracy of VLBI TEC has been evaluated with GPS-based ionospheric TEC map that indicated correlation around 0.6–0.8 on intercontinental baselines (Sekido et al., 2003). Hawarey et al. (2005) studied the second order ionospheric term effects on VLBI measurements and revealed a maximum difference between baseline lengths with and without second order ionospheric terms equivalent to 0.5 mm. As shown by Hobiger

et al. (2006), the TEC values derived by VLBI agree well with the outcomes from GPS and satellite altimetry measurements. The ionospheric corrections derived for VLBI based on co-located GNSS have been suggested to improve the single-frequency tracking of GNSS satellites (Männel & Rothacher, 2016). In addition to that, the VTEC from VLBI has been studied in the ionospheric modeling for low frequency radio astronomy (Arora, 2016).

From the mathematical point of view of VTEC extraction from VLBI measurements, in an earlier study, Kondo (1991) explained how station-dependent VTEC values could be obtained by taking into account harmonics up to the fourth order (i.e., 6-h period). This method described the time variation of TEC above a VLBI station but the spatial gradients around the station were neglected. Later, another approach based on the idea of neglecting spatial gradients used piece-wise linear functions (Hobiger & Schuh, 2004). The two approaches were compared internally and against results from GPS. The comparison showed that the two methods provide nearly the same outcomes but, the approach using piece-wise linear functions has the advantage that it is not sensitive to data gaps and can detect ionospheric variations with much shorter periods as no periodicity is set by default. Latitudinal gradients were taken into account by Hobiger et al. (2006) who used the physical nature of the ionosphere to relate the VTEC at the ionospheric pierce point (IPP) to the one that would be observed directly above the station. In a later study, the latitudinal gradients were modeled by two coefficients, a north and a south gradient, depending on the site-specific azimuthal angle (Dettmering et al., 2011).

Research on VLBI observations is mostly done on campaigns and sessions, the Continuous VLBI campaigns (CONT) is one of them. The CONT campaigns have not been used for ionospheric study and research until now. The first CONT campaign started in 1994 with the goal of demonstrating state of the art VLBI over a continuous period of time (Thomas et al., 2016). Three CONT campaigns were observed in 1994, 1995, and 1996 before the creation of the International VLBI Service for Geodesy and Astrometry (IVS) (MacMillan, 2017). So far, the IVS has carried out six continuous VLBI campaigns from 2002 to 2017 (CONT02: October 16–31, 2002, CONT05: September 12–27, 2005, CONT08: August 12–26, 2008, CONT11: September 15–29, 2011, CONT14: May 6–20, 2014 and CONT17: November 28 to December 12, 2017). All past six CONT campaigns provide a snapshot of the legacy S/X systems' capabilities in various stages of its development (Thomas et al., 2016).

Based on the above, this research intends to investigate quantitatively the role of ionospheric spatial gradients on VTECs derived from VLBI (VLBI VTEC) through the CONTs' campaigns. For this purpose, we computed VLBI VTEC by following the station-based approach described by Hobiger (2006) in two conditions, with and without spatial gradient; what is introduced in Section 2. Then, we compared our estimates, based on these two approaches, to VTEC parameters from global ionospheric maps (GIMs) which are published in IONosphere map Exchange (IONEX) format (Schaer et al., 1998). Since, the continuous sessions of the IVS have been considered a tool for assessing the VLBI technique and are of special scientific value (Rieck et al., 2010), CONT 08, 11, 14 and 17 have been taken into account for the assessment part. In Section 3, we discuss the assessment and evaluation of the results.

2. Methods Applied to Model the Ionosphere From VLBI

Since VLBI is a differential technique, the observed ionospheric delays represent the differences in the behavior of the propagation media above each pair of stations forming a certain baseline. Additionally, there is a constant instrumental delay offset per baseline that contributes to the observed ionospheric delay (Hobiger, 2006). Since the instrumental delay offsets are independent of the azimuth and elevation at which the antennas point, one can separate them from the variable ionospheric parameters for each station and estimate them as station-dependent constant unknowns during a VLBI session (Hobiger, 2006). The observation equation at a certain time t valid for X-band – with f_x being the frequency in Hertz (Hz) – can be written as given by Dettmering et al. (2011)

$$d_{ion}(t) = \frac{40.3}{f_x^2}\left[mf\left(EL_2\right)VTEC_2' - mf\left(EL_1\right)VTEC_1'\right] + d_{offset2} - d_{offset1} \tag{1}$$

where $d_{ion}(t)$ is the differential dispersive delay at time t. $VTEC_i'$ is the VTEC at the specific IPP observed at station i. The $d_{offset\,i}$ parameter is the constant instrumental offset for station i. The $mf(EL)$ is the mapping function that can be computed according to Dettmering et al. (2011)

$$mf(EL) = \frac{1}{\sqrt{1 - \frac{r^2 \cos^2 EL}{(r+h)^2}}}. \tag{2}$$

Here, $EL$is the elevation angle. The variable r is the geocentric distance of the specific site and $h = 450$ km the adopted effective height of the single layer approximation of the ionosphere lying close to the height of the F2 peak of the electron density.

From an algebraic point of view Equation 1 clarifies the problem that without any model assumptions it will be impossible to solve for ionospheric parameters as each new measurement, represented by the left side of this equation, corresponds to two new unknown values of VTEC. The only way to overcome the problem and to gain an overdetermined system is to set up an analytical model.

In the approach without gradients, $VTEC'$ is assumed equal to the VTEC above the corresponding station. Based on this assumption, the VTEC above each station is modeled with a modified piece-wise linear function approach (Hobiger et al., 2003). Instead of the classical piece-wise linear function with constant interval length, adaptive interval lengths are chosen according to the equation below (Hobiger, 2006).

$$\begin{aligned} VTEC_i(t) &= offset_i + rate_1(t_1 - t_0) + rate_2(t_2 - t_1) + \cdots + rate_J(t_{J+1} - t_J) + rate_J(t - t_{J+1}) \\ &= offset_i + \sum_{j=0}^{J} rate_j(t_{j+1} - t_j) + rate_{J+1}(t - t_{J+1}). \end{aligned} \tag{3}$$

The parameterds $offset_i$ and $rate_j$ define the offset of station i and the coefficient of linear function in the j-th time interval. They can be directly estimated within least-squares adjustment as they do not have to be linearized and the unit weight has been applied in this method. The parameter J shows the last time interval. The implementation is done by a reflective Newton method to avoid negative values which are impossible due to the physical nature of wave propagation (Hobiger et al., 2004).

In the case of using spatial gradients, following Hobiger et al. (2006), the $VTEC'$ at the specific IPP is modeled as a function of VTEC, the VTEC above the telescope

$$\begin{aligned} &VTEC(\varphi, \lambda, t) = \left(1 + c(\varphi' - \varphi)\right) VTEC'(\varphi', \lambda', t') \\ &t = t' + (\lambda' - \lambda) / 15 \end{aligned} \tag{4}$$

where t is observation epoch and φ, and λ denote latitude, longitude of the station, respectively. $\varphi'$and λ' are latitude and longitude of the IPP. The latitudinal parameters are in rad. The unit of c as the gradient coefficient is 1/rad when φ is given in rad. The latitudinal difference is multiplied by c, which is 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 the Earth takes to rotate the angle of the longitudinal difference, that is, the epoch of the ionospheric delay observation is shifted forward or backward in time until the longitudes of the IPP and the observation site coincide. The readers can refer to Hobiger et al. (2006) for more detail.

The instrumental offset and the gradients are defined constant over the duration of the observing session of about 24 h. 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, which is hereafter called the spatial gradient method, VTEC values above the VLBI stations were estimated.

Table 1
The VLBI Stations' Contribution in the CONT08 to CONT17-L1Campaigns Showed by Tick Mark

Stations	BADARY	FORTLEZA	HOBART12	HARTRAO	HOBART26	HART15M	KASHIM11	KATH12M	KOKEE	MATERA	MEDICINA	NYALES20	ONSALA60	SVETLOE	TIGOCONC	TSUKUB32	Wettzell	Westford	WARK12 M	YARRA12 M	YEBES40 M	Zelenchk
	Bd	Ft	Hb	Hh	Ho	Ht	K1	Ke	Kk	Ma	Mc	Ny	On	Sv	Tc	Ts	Wz	Wf	Ww	Ya	Ys	Zc
CONT08	χ	χ	χ	✓	χ	χ	χ	χ	✓	χ	✓	✓	✓	✓	✓	✓	✓	✓	χ	χ	χ	✓
CONT11	✓	χ	✓	✓	χ	χ	χ	χ	✓	χ	χ	✓	✓	χ	✓	✓	✓	✓	χ	χ	✓	✓
CONT14	✓	✓	✓	χ	✓	✓	χ	✓	✓	✓	χ	✓	✓	χ	χ	✓	✓	✓	✓	✓	✓	✓
CONT17-L1	✓	✓	χ	χ	✓	✓	✓	✓	✓	✓	χ	✓	✓	χ	χ	χ	✓	χ	✓	χ	✓	✓

3. Numerical Results

The necessity of using ionospheric spatial gradients is evaluated through VTEC estimated from VLBI observations by investigating four CONT data sets. For this purpose, the VTEC from GIMs is assumed to be the benchmark and the accuracy of the VLBI is assessed with respect to the GIM VTEC.

As mentioned above, the CONT campaigns are used to assess the spatial gradient contribution to VLBI VTEC estimation. The ionospheric activity monitoring goal and a large geographical coverage are two reasons why the CONT08 to CONT17-L1 were chosen for this research. It should be mentioned that the data from the CONT17-L1 network (Behrend et al., 2020) has been used in this research. The CONTs' exact date has been explained in Section 1 and their VLBI stations are mentioned in Table 1.

Based on that, there are 11, 13, 17, and 14 VLBI stations in CONT08, CONT11, CONT14, and CONT17-L1, respectively. Figure 1 shows a schematic representation of the VLBI stations' geographical distribution on the world map.

The ionospheric delays are given in the VLBI observation files, provided by the IVS (Nothnagel et al., 2017), along with a number of other quantities necessary for geodetic and astrometric analyses. The National Geodetic Survey card files (version 4) have been used as the input to the program that we developed to derive the VLBI VTEC in MATLAB and used a part of ionospheric subroutine from VieVS@GFZ software (Nilsson et al., 2015). It should be mentioned that the mean value of band frequency has been applied as the effective ionosphere frequency of observation for computing the VLBI VTECs (Petrov, 2006). In addition to that, GIMs were taken from the International GNSS Service (IGS) in IONEX format.

VLBI VTECs were computed without and with the spatial gradient term by applying Equations 3 and 4, respectively. Then, VTECs were derived from GIMs at the same positions as the following equation:

$$\begin{aligned} TEC(\varphi',\lambda',h) &= (1-p)(1-q)TEC(\varphi_0,\lambda_0,h) + p(1-q)TEC(\varphi_1,\lambda_0,h) \\ &+ q(1-p)TEC(\varphi_0,\lambda_1,h) + pqTEC(\varphi_1,\lambda_1,h) \end{aligned} \tag{5}$$

Here, the h is the epoch of ionospheric map grid data which is selected from the IONEX file. The parameters p and q are equal to $(\varphi' - \varphi_0) / 2.5°$ and $(\lambda' - \lambda_0) / 5°$, respectively; while the φ_0 and $\lambda_0$are the lower latitude and longitude of the cell nodes where the IPP is located in that grid cell. Similarly, φ_1 and λ_1 are the maximum value of the latitude and longitude in that cell. For calculating the TEC in the arbitrary time between two consecutive epoch h and $h + 1$ is:

$$TEC(\varphi',\lambda',t) = TEC(\varphi',\lambda',h) + \left[TEC(\varphi',\lambda',h) - TEC(\varphi',\lambda',h+1)\right](t - t_h) / (t_h - t_{h+1}) \tag{6}$$

where t_h and t_{h+1} are earlier and latter nearest epoch to t in the GIM data, respectively. The difference between the GIM VTEC and the two types of the VLBI VTECs has been used to compute the Root Mean Square Error (RMSE) for each VLBI station during the CONTs, separately. The RMSE has been calculated in accordance with the following equation.

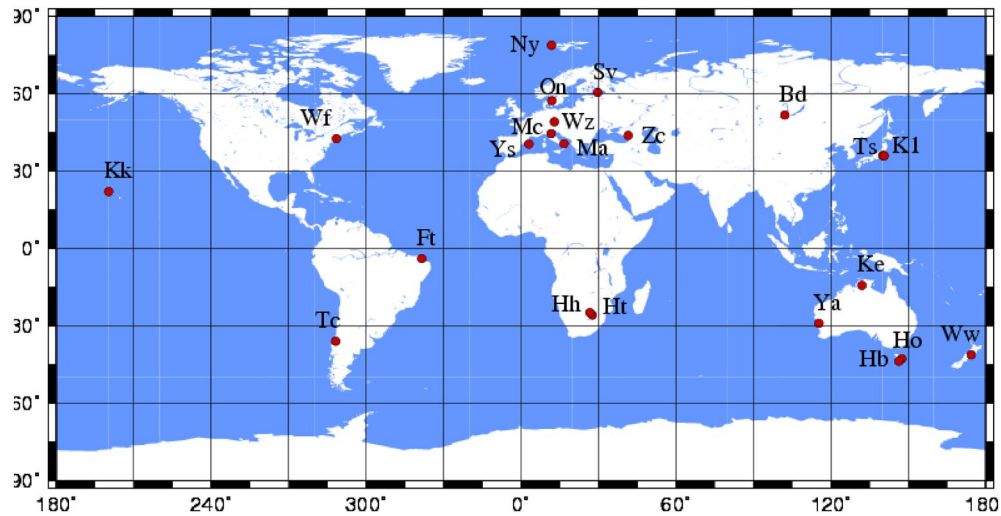

Figure 1. Geographical distribution of the VLBI stations in CONT08, CONT11, CONT14, and CONT17-L1.

$$RMSE_i^d = \sqrt{\left(\sum_{j=1}^{N_d}\left[TEC_i^{VLBI}\left(\varphi',\lambda',t_j\right) - TEC_{GIM}\left(\varphi',\lambda',t_j\right)\right]^2\right) / N_d} \tag{7}$$

The parameters d and N_d are the days of the CONT and the number of VLBI observation in that day, respectively. The RMSE is the key parameter in this research and has been computed for with and without the spatial gradient methods. The solar cycle effects on the spatial gradient are discussed in the last subsection based on the overall analysis of CONT sessions.

3.1. CONT08 Results

This campaign started from the Day of Year (DOY) 225 and continued to the DOY 239 in 2008. There are 11 stations during CONT08 located in different geographical locations. The RMSEs are shown in Figure 2 for the VLBI VTECs for the two cases that apply (with) or not apply (without) gradients. In addition, the percentage of improvement of using the spatial gradient term can be seen as a criterion to understand the role of spatial gradients in the estimation of VTEC values from VLBI observations.

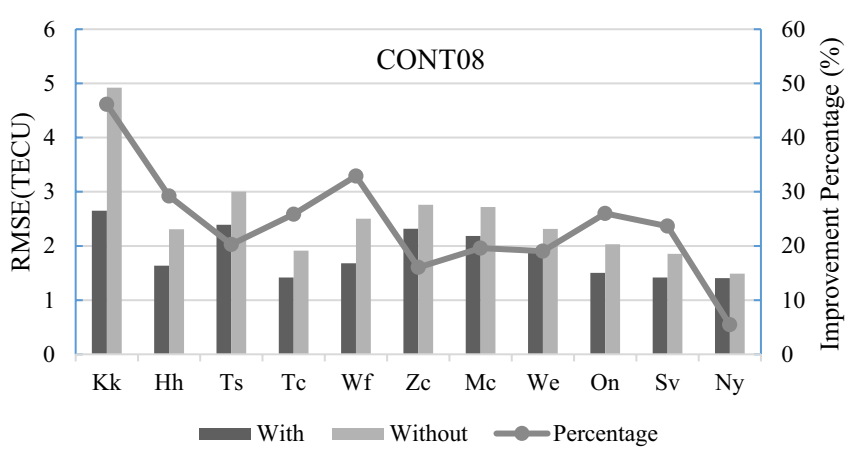

Figure 2. The RMSE of CONT08 stations with using spatial gradient (dark gray bars), without using (light gray bars) and their improvement percentage (gray point line).

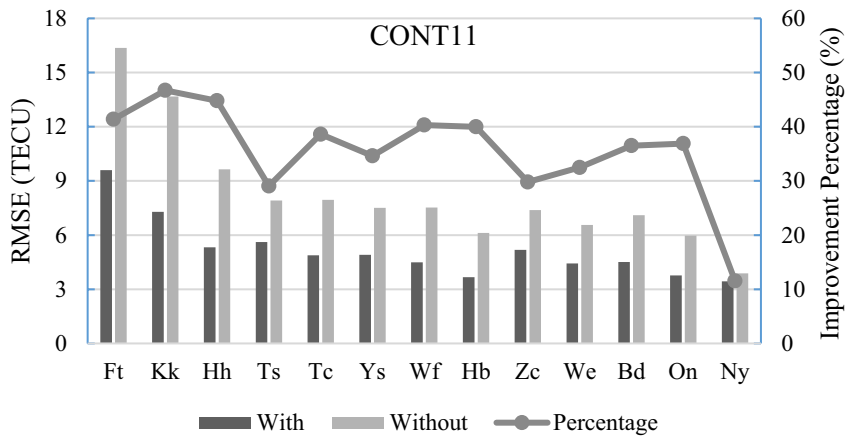

Figure 3. The RMSE of CONT11 stations with using spatial gradient (dark gray bars), without using (light gray bars) and their improvement percentage (gray point line) It can be seen that the RMSE is more than six TECU except for the Ny station in the case where the parameterization did not include spatial gradients. For 11 stations from 13 VLBI stations, the RMSE is less than 6 TECU in the case of with spatial gradient, which indicates the effectiveness of this parameter. RMSE based on CONT11 data is higher than the same statistics calculated based on CONT08 observations. This parameter is vividly different for the Ft, Kk and Ny stations. Since, the value of the RMSE shows difference of the VLBI VTECs (with or without gradient) with the GIM VTECs, the role of the spatial gradient for the Ft is more than other VLBI stations and it is the lowest for the Ny. In the other words, the gradient term in the VLBI VTEC computation is more effective and important in the equatorial region rather than at the Arctic region and its role decreases from low to high latitude from the absolute value point of view at the CONT11.

The averages of RMSEs are 1.86 and 2.53 TECU (TECU = 10^{16} electron/m^2) for with and without the spatial gradient methods, respectively. The chart above shows the greatest impact for the Kk station, where the application of the spatial gradient has resulted in a 46.1% improvement in the VLBI TEC estimation. The lowest effect of this parameter is related to the Ny polar station, which is equal to 5.5%. Overall, the use of ionospheric spatial gradients in the estimation of VTEC parameters from VLBI data for CONT08 results in an average of 24% increase in accuracy in TEC estimates.

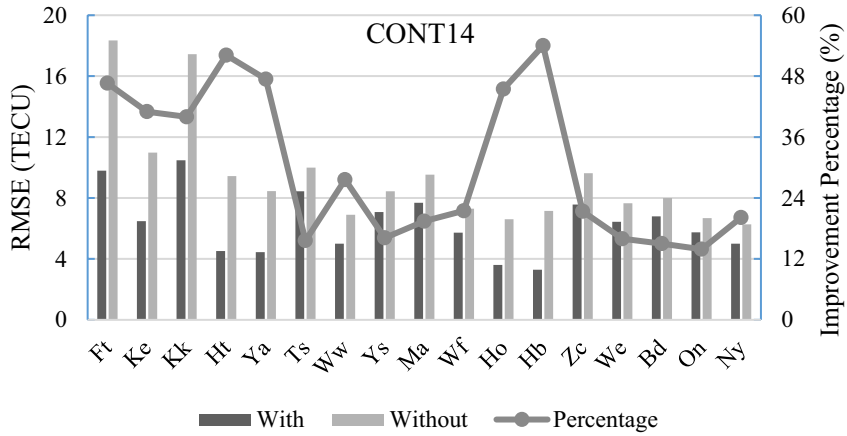

Figure 4. The RMSE of CONT14 stations with using spatial gradient (dark gray bars), without using (light gray bars) and their improvement percentage (gray point line) Based on Figure 4, the RMSE values show that ionospheric gradient rather than others affect the equatorial stations (Ft, Ke and Kk). In the other view, the Ft, Ke, Ht, Ya, Ww, Ho, and Hb stations have the most improvement during CONT11 located in the southern hemisphere. The role of the ionospheric spatial gradient in the southern hemisphere and equatorial stations is more than 30%. The lower numerical value of VTEC in the three stations Hb, Ho and Ww compared to the other mentioned stations is due to their location in the middle latitude, but their high improvement rate is related to the above-mentioned reason. In general, the RMSE values and improvement rates in this CONT were much more variable than in the previous two CONTs.

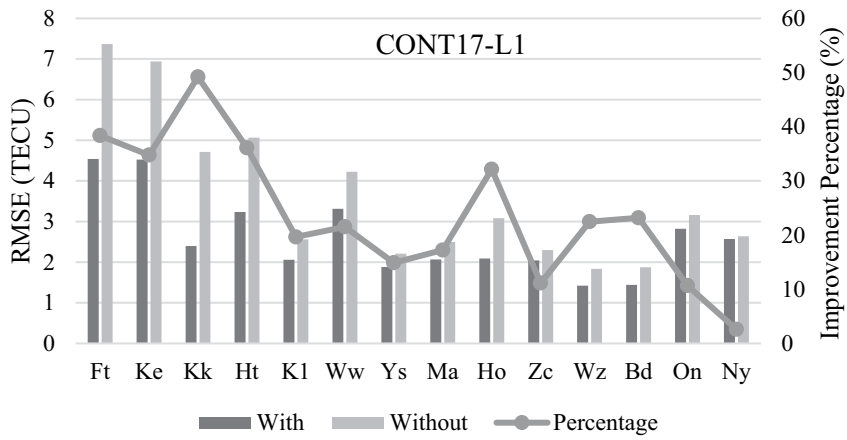

Figure 5. The RMSE of CONT17-L1 stations with using spatial gradient (dark gray bars), without using (light gray bars) and their improvement percentage (gray point line) According to the results, the RMSE values decreases almost from the equator (Ft) to pole (Ny) where the stations have been sorted based on the latitude. This downward trend corresponds to the percentage of improvement. The use of the ionosphere spatial gradient in the Ny station (located in the Arctic region) has an effect of about 2% that shows the improvement percentage is much lower than the other CONT sessions. In other word, the spatial gradient term can be neglected for the Ny station in this campaign.

3.2. CONT11 Results

The results of CONT11 are the RMSEs of 13 VLBI stations. It includes 2 weeks campaign data in 2011 September, from DOY 258 to DOY 272. The RMSE of CONT11 stations has been shown in Figure 3 computed using two parameterization approaches, similarly to CONT08 data. The improvement percentage has been drawn on the chart (Figure 3).

3.3. CONT14 Results

CONT14 starts from DOY 126 and ends at DOY 140 in 2014. The RMSEs of the 17 stations have been computed and illustrated in Figure 4.

3.4. CONT17-L1 Results

CONT17, as the last VLBI campaign until now, was performed from DOY 332 to DOY 346 in 2017. As mentioned before, this study covers only L1 network of CONT17, the detail can be seen in Table 1 and Figure 1. The CONT17-L1 results are shown in Figure 5.

3.5. Comparison of the Results Obtained for the Last Four CONT Campaigns

Since the ionosphere layer is directly related to radiation emitted from the Sun, the movement of the Earth about the Sun or changes in the solar activity will result in variations in the ionosphere. Ionospheric gradient might have remarkable impacts on the ionospheric variation, which are normally identified by four periods: daily, seasonal, 27 days and 11 years (Charbonneau, 2020). Since the campaigns' dates are fixed, seasonal and 27-day periods cannot be investigated here. But the CONT sessions at different years present a chance to study the 11-year solar cycle effects on the spatial gradients of ionosphere.

The role of the ionospheric gradients separately obtained at the stations of each campaign was examined in the first four subsections, and in this part we focus on an overall quality of VTEC estimates during each CONT campaign. For this purpose, the mean of RMSEs and the improvement percentage were computed for each CONT. The corresponding results are shown in Figure 6.

Figure 6 shows that the mean of RMSE value is lower in the first and last CONTs. According to the solar cycle, 2008 was the minimum of solar activity in the considered period, and 2017 was close to the minimum.

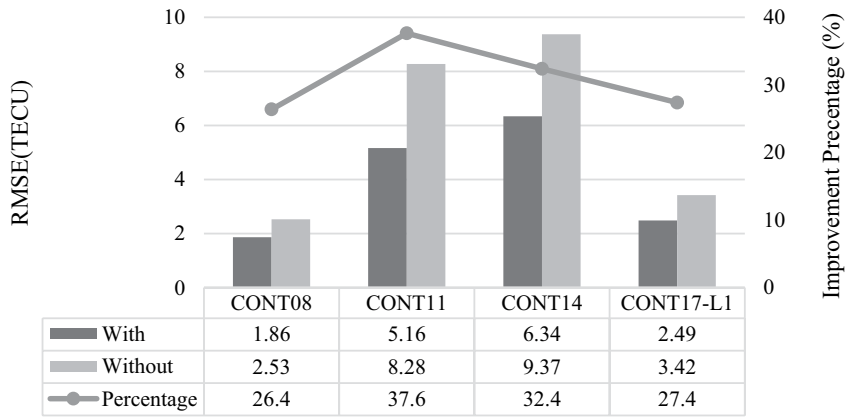

Figure 6. The mean of CONTs RMSE with using spatial gradient (dark gray bars), without using (light gray bars) and their improvement percentage (gray point line).

In other words, the low solar activity in these campaigns has resulted in the low absolute values derived from VLBI data from 5 to 11 TECU and taking into consideration the quality of the GIM-based TEC parameters, one can notice little numerical difference estimating VTEC with or without gradients (from 2 to 3 TECU). Accordingly, the improvement percentage is low and the importance of the ionosphere gradients will be small.

In 2011 and 2014, where the solar activity is high, the RMSE quantities are larger than for CONT08 and CONT17-L1. Consequently, the improvement percentage is more than 30% indicating the importance of the ionosphere gradients in the estimation of the VLBI VTEC for CONT11 and CONT14.

4. Conclusions

This research addressed the role of ionospheric gradients for the VLBI VTEC determination using the four latest Continuous VLBI campaigns CONT: CONT08, CONT11, CONT14 and CONT17-L1. Accordingly, VLBI VTEC were computed following two approaches, with and without spatial gradients. The relevant differences between the results and the GIM VTEC were used as a basis to evaluate the necessity of applying the gradient method.

The difference between the GIM VTEC and the two types of the VLBI VTECs has been used to compute the RMSE for each VLBI station during the CONTs. The mean RMSE values for the four investigated CONT sessions are 2.5, 8.3, 9.4 and 3.4 TECU, respectively. These values represent the VLBI VTEC estimation error without using the gradient parameter. Using the ionospheric spatial gradient decreases the RMSE values of the CONT sessions by 26.4%, 37.6%, 32.4% and 27.4%, respectively. On the other hand, the RMSE values indicate that the error value is reduced using this parameter when the solar activity is high. This is visible in the case of the comparison of the VLBI campaigns in 2011 and 2014 as compared to the other campaigns.

Based on the obtained results, the role of the spatial gradient in estimating VLBI VTEC is related to the latitude of the VLBI station. It is concluded that the percentage of improvement decreases from the equator to the poles from nearly 50% to 5% in the investigated CONT campaigns. In general, the application of ionospheric spatial gradients has an important role in the estimation of VTEC from VLBI observations.

Data Availability Statement

All GIM is available at International GNSS Service (IGS) and CODE website (http://ftp.aiub.unibe.ch.CODE/). The VLBI's repositories can be accessed starting from ftp://ivs.bkg.bund.de/pub/vlbi/ivsdata/ngs/. The authors would like to acknowledge IVS and IGS for providing the data.

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