A spatial and temporal comparison of Five Total Electron Content providers

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Abstract. The Total Electron Content (TEC) is an important part for the GNSS community and the users because of their effect on the obtained accuracy for computing the higher order ionospheric delay and the study of the ionosphere layer. Many analysis centres are generating those TEC values on daily basis. This can provide the users with different alternatives TEC values for the same location. Thus, this paper critically tries to investigate the generated TEC values from four scientific analysis centres (ACs). Those ACs are COD, ESA, JPL and WHU. A temporal for one year (2018), and spatial for -87.5 to 87.5 latitude and from -180 to 180 longitude TEC values statistical comparison have been investigated to understand the accuracy level of the four provided products. Those value have been compared to the international GNSS Service (IGS) TEC values for the same temporal and spatial resolution. Four-time scale in the day have been examined in this analysis to cover different times for one day. The statistical results show that all the differences from the four ACs comparing to the IGS could reach accuracies within ~1 TECu which is equivalent to 1/3 nanosecond.

Keywords: Ionospheric Delay; Total Electron Content; IGS, Accuracy assessment.

1. Introduction
Dual-frequency carrier-phase and code-delay GPS observations are combined to obtain ionospheric observables related to the Slant Total Electron Content (STEC) along the satellite-receiver. The signals from Global Navigation Satellite Systems (GNSS) travels through the upper layer of the earth calling the ionosphere on the way towards the GNSS receiver. That delay could reach up to 300 metres if it is not corrected. To achieve the most accurate results for the position accuracy, a dual frequency (or a triple frequency) receiver has to be used for formulating “ionospheric free combination” to remove 98% of the effect of ionospheric delay. On the other hand, the single frequency receivers which is less costly receivers, use prediction models for removing the ionospheric delays e.g. Kloubture. These models are available to be sent to the users through the navigation massage to compute the ionospheric delay based on the observer latitude.

The international GNSS Service (IGS) produced, as a by-product, the IONEX-interpolated Vertica Total Electron Content (VTEC) map data which represents an important observable in the space weather. However, the important VTEC maps have been generated from combining different VTEC maps those delivered from different analytical centres.

The precise TEC map is very important for ionospheric dispersive delay calibration for the techniques in the space measurements such as GPS and VLBI. It is applicable in those space measurements, mainly because of the recent rapid development in the GNSS. Those TEC maps can not ignore the Differential Code Biases (DCBs) of the receiver and the satellites because it could result
in up to 20, 40 TECU error for satellites and receiver, respectively, if not handled probably. Following that, [1] presented a procedure for removing the DCB of the receiver based on the derived-ionospheric TEC from GPS observation. Their results demonstrate an agreement about 1.6 to 6.0 TECu comparing to incoherent Scatter Radar (ISR). The error also could reach up to 100 TEC unit (TECu) in extremist ionospheric scenarios [2].

[3] presented a technique by estimating the DCB for one receiver as a reference to be used as a known parameter. This was applied for constraining the solution of the global ionospheric estimation. That is different from the IGS strategy that assumes a zero mean for the involved satellites DCBs. Their method based on hardware signal simulator that resulted 3ns offset between the IGS and their solution. They also evaluated their method for Galileo constellation against the European Space Agency published DCBs which found to be in the level of 1−2 ns. Although [4] have computed Zenith Total Delay (ZTD) directly from GNSS observables, [5] show that the second order ionospheric delay could affect the estimated Zenith Wet Delay (ZWD) by the orders of milimeters.

For automating processing, [6] developed an automated software for processing GPS data to produce TEC map. They explained that the largest sources of errors observed in TEC is the determination of the unknown biases in the used GPS receivers. They also compared their results with the TEC map produced by NASA Jet Propulsion Laboratory (JPL), and found that 10% disagreement of TEC. While [7] used the so-called levelling process to assess the code-delay errors to reduce the carrier phase ambiguity from the data. They also attempt to analyse the stability in short term of the Inter Frequency Bias (IFB) at the receiver part. They found that a systematic error could affect the ionospheric observable at the levelled carrier phase. In addition, they found that the IFB could significantly experience changing in their values for 24 hours. Then [8] produced different methods to process TEC in a real time scenario with a validation results from Jason Satellite Mission.

A year later, [9] account for the line of sight TEC effect which found to be a useful tool for estimating TEC from GPS data using Kalman filter. They also estimated the satellite and receiver instrument biases with the ionospheric TEC based on a local fit. That was based on three GPS stations and validated against ARPALTIR measurements. They found their method is very effective, and they highlighted the spatial distributions of electron density differences. Furthermore, [10] and [11] attempted to model the variations of the ionosphere using least-square based on harmonic estimation. They applied that to the TEC time series provided by JPL Analysis Centre (AC). They found that, if applying their analysis, the maximum range of low and high solar periods could reach up to ±6 TECu and ±15 TECu.

[12] also presented two comparisons, local TEC maps comparing to VLBI TEC measurements and the Centre for Orbit determination in Europe (CODE) Global Ionosphere Maps (GIMs) to VLBI. They found that CODE products could reach to an accuracy of 3.9 TECU. While the derived phase delay from CODE has a correlation that could reach up to 0.8 when using intercontinental baseline. Later [13] introduced a service for the computation of slant TEC at www.ionolab.org. While [14] analysed the TEC temporal behaviour during four years of different solar activity and their effect on Precise Point Positioning (PPP) accuracy. They found that there was a significant increase in the RMS of PPP altitude that could reach up to 26 cm. Although [15] found that GPS and GLONASS PPP could provide the same accuracy, [16] suggested that the estimated TEC from GPS/GLONASS arises systematic error. They mentioned that the reason for that systematic bias is related to the different frequencies travelled through the ionosphere layer. They also mentioned that ~2.9 TECU error obtained is equivalent to 1 nanosecond (ns). In addition, they found that environmental parameters such as temperature and humidity could make a variation in the estimated TEC that could reach up to 20 TECu.

In Brazil, the scintillation effect on the Precise Point Positioning (PPP) is noticeable and many studies have the focus on improving the mitigation of the scintillation in that region. Recently [17] proposed a mitigation techniques based on the variances of signal tracking error and demonstrated that the positioning error in 3D could be improved by 75% using their techniques.
Thus, ionosphere layer is important for many studies. One of the focus of the IGS is to improve the positioning accuracy by helping in computing the TEC based on Continuously Operating Reference Stations (CORS) that are available through the observations obtained from the GNSS. Also, it is important to understand the layer that is surrounding the earth for many navigation and climate studies. Different analysis centres (ACs) are now providing different products. Those produced as by-products of their local or global ionospheric analysis. Thus, it is vitally important to evaluate those products temporally. One of these products are the Total Electron Content which is computed in gridded values.

This paper aims to analyse the accuracy differences obtained from different TEC providers and explaining the level of accuracies that could be obtained from different ACs compared to the IGS. The structure of the paper is as follows: next the methodology section which explains how TEC content computed and the assessment which should take in place for evaluating the differences between all those products. Later, the results section is provided which address all the significant statistics that have been found for the assessment. Then after, some of the conclusions delivered from methodology outcomes are highlighted.

2. Methodology (Data source and analysis method descriptions)

In order to analyse the accuracy of TEC maps produced by different providers, it is important to understand the structure of these products. CODE provider generates, daily, Global Ionospheric map. They used about 300 station occupied with GNSS receivers from IGS and other institutions. Spherical harmonics expansions in a solar reference system are used for modelling VTEC. The time domain is represented by a Piece-wise linear function. CODE adopted the extended slab model as a mapping function from JPL to obtain the vertical VTEC from the line of sight TEC, with an evaluation elevation angles of the geodetic satellite. They also assumed 6821 Km as a radius of the spherical layer for ionospheric pierce points computations. A combination analysis for the middle day of a 3-day observation period were followed for producing those results. This is for solving 18688 VTEC parameters (73 times 256) with three sets of daily GNSS cod bias parameters.

The five analysis centres are; COD: CODE (Centre for Orbit Determination in Europe); ESA: European Space Agency; IGS: International GNSS Service; JPL: NASA Jet Propulsion Laboratory (JPL); WHU: Wuhan University (WHU).

Although all those ACs are contributing to the IGS products and services, each of those centres has its own strategy that has been followed for processing the observables. Table 1 summarises the differences between TEC files from the five ACS.

The temporal resolution of TEC dataset files used in this paper is from 1/1/2018-31/12/2018 which cover a one-year period. Those TEC files have been downloaded from IGS server for all of the five ACs. Because of the different time interval, as seen in table 1. The author has used the relative time interval that is available in all files which is 7200s (equivalent to 2 hours). This has been done for the consistency purpose that is needed to be followed when we compare the TEC values for each point from the five ACs. The structure of the TEC files is in latitude and longitude coordinates.

The spatial resolution of the coordinates covered from 87.5° to -87.5° (North and South the Equator) and from -180° to 180° (West and East the Greenwich) for latitude and longitude, respectively. The latitude resolution used in the TEC files is 2.5° while for the longitude is 5.0°. all the values of the TEC or the RMS of the TEC were represented in an 0.1 TEC unit (TECu). Bear in mind that 2.9 TECu is equivalent to one nanosecond. While other centres generate Global Ionospheric Map (GIM) on hourly and daily basis which represent the TEC output. The used reference frame was in a solar and geomagnetic reference frame. The bi-cubic splines are done on spherical grid. Whereas all the instrumental biases are being solved simultaneously with VTEC and being solved simultaneously using Kalman filter or Least square.
Table 1. Summary of the difference between the five investigated ACs.

| Provider | COD | ESA | IGS | JPL | WHU |
|----------|-----|-----|-----|-----|-----|
| Satellite | GNSS | GPS+ | mix | GPS | GNSS |
|          | ADDNEQ2 | GLONASS | CMPCMB v1.2 | GIM V3.0 | IRIS V2.0 |
| Software | 5.3 | PAR2IONEX | 7200 s | 7200 s | 7200 s |
| Mapping Function | NONE | COSZ | NONE | NONE |
| Elev. angle | 10 | 0 | 10 | Not mentioned |
| Observable used | One-way carrier phase levelled to code | One-way carrier phase levelled to code | Combined TEC calculated as weighted mean of input TEC values |
| interval | 7200 s | 7200 s | 7200 s |

There are 365 files for each provider which result in 1825 files. To cover the four-time scales, the number of files that needs to be analysed are 7300 scenarios. To deal with this number of datasets, a MATLAB function was created for downloading and collecting those data. The datasets were collected to be in a matrix format so that it could be easily dealt with similar to equation (1) below:

\[
\text{Data}_{\text{provider}} (\text{time}, \text{day}) = \begin{bmatrix}
\text{TEC}(\text{Lat}_1, \text{Lon}_1) & \cdots & \text{TEC}(\text{Lat}_1, \text{Lon}_n) \\
\vdots & \ddots & \vdots \\
\text{TEC}(\text{Lat}_m, \text{Lon}_1) & \cdots & \text{TEC}(\text{Lat}_m, \text{Lon}_n)
\end{bmatrix}
\]

Where: \( \text{Lat}_1 = 87.5, \text{Lat}_m = -87.5 \) with the mentioned interval of 2.5; While \( \text{Lon}_1 = -180; \text{Lon}_n = 180 \) with the mentioned interval of 2.5; Time = 0 (mid-night), 2, 4, 8, 10, 12, 14, 16, 18, 20, 22 (for the purpose of this paper, only 0, 6, 12 have been chosen).

Day = 1, 2, 3 ….. 365 (of year 2018); Provider: COD, ESA, IGS, JPL, WHU.

While for the differences from the IGS:

\[
\text{Differences}_{\text{IGS}} (\text{time}, \text{day}) = \text{Data}_{\text{IGS}} (\text{time}, \text{day}) - \text{Data}_{\text{provider}} (\text{time}, \text{day})
\]

Where; provider: COD, ESA, IGS, JPL, WHU.

Equation 2 represents the gridded spatial differences between IGS and other providers. This matrix represents a one-time gridded value of TEC. In this paper four times during each day have been selected to cover the most important hours during the day. Figure 1 below represents a flow chart for how the data has been analysed.

3. Results

3.1. Sample of TEC values

This section covers the result analysis for the comparisons to be followed. It also covers the statistical analysis for the differences between the TEC values from different providers (COD, ESA, JPL and WHU) as well as trying to understand if there are significant differences from the IGS TEC solution. In addition to their accuracy comparing to the IGS solution.

To analyse the differences of the TEC from different providers, four times scale for each day have been chosen for the analysis. Those times were 00:00 UTC (mid-night) where almost no solar activity from the sun (at that time on that specific place), where a limited 06:00 UTC (where a limited solar activity) 12:00 UTC where maximum solar activity during the day and 18:00 UTC hours where normal solar activity is occurred.

The values of TEC are varying spatially between each other for the same point on the Earth. Figure 2 below represents an example of the TEC maps from different providers for day of year (DOY) 1 in 2018 at 06:00 UTC.
The TEC files also contain the Root Mean Square error (RMS) of the computed TEC values. These RMS computed spatially for each gridded point on the Earth and formulated similar to the TEC values. They also have been generated in a temporally manner like the TEC values. These RMS varies based on the strategy that have been followed by each provider. Figure 3 below represents an example of the RMS values of the computed TEC from different providers for day of year 1 in 2018 at 06:00 UTC.

It could be seen from figure 3, that different RMS map could be obtained for the corresponding TEC values. To analyse the computed TEC values from different providers, it is important to choose one provider to represent the basis for the remaining TEC maps. This base value was chosen, in this paper, as the IGS TEC maps because it could represent the most stable values. The reason for that, it is computed based on the combined solution from the JPL and COD TEC values. In addition, the IGS products has been used formally for all GNSS users. Thus, it is important to compute the differences between each provider and the IGS.

3.2. Validating Differences

All the data sets, from COD, ESA, IGS, JPL and WHU, have been collected and analysed. The differences between the providers values of TEC gridded have been subtracted following Equation (2) from the IGS TEC gridded values. A gridded difference was delivered for each provider. Those differences have been averaged for the specific provider and the specific time with their standard deviation as shown in figure 4 below for the 365 days of 2018, for four different time scales during the day (00:00, 06:00, 12:00 and 18:00 UTC).
Figure 2. Samples of TEC values for COD, ESA, IGS, JPL and WHU for DOY 1, 2018 at 06:00 UTC (in TECu).

Figure 3. Samples of RMS TEC values for COD, ESA, IGS, JPL and WHU for DOY 1, 2018 at 06:00 UTC (in TECu).

What is interesting from figure 4 is that almost the best solution from those providers is the COD TEC products based on the mean differences from the IGS TEC solution. This could be justified due to the fact that the strategy used to produce the TEC values in this specific model was CODE. The followed strategy (summarized in table 1) produce that TEC values in higher temporal resolution than the other provides which is an hourly value at each gridded point. This could explain the reason behind the stability of the TEC values from CODE.
It is also noticeable that from the mean values of the differences between JPL products and IGS products, there is almost a constant bias which is around \(-1\) TECu that is almost stable over the 2018 year. This stable bias is significant because it has the lowest standards deviation for all the four chosen time scales during the day and it is also stable over the 365 days of the 2018 year. In order to investigate more, it is important to see what is the factor that made their solution, more stable than the other solutions. Thus, it is found from figure 5 that JPL uses a stable number of the stations which result in a stable difference from the IGS TEC and stable RMS solution.

![Figure 4](image)

**Figure 4.** Mean (a, c, e and g) and standards deviation (b, d, f, h) of the differences for 365 days during 2018, for COD, ESA, JPL and WHU at four-time scales (in TECu).

While the mean of the differences between ESA solution and the IGS solution, has a constant bias around \(+1\) TECu. This bias is also stable over the year. Similarly, to the JPL product, ESA uses almost the same number of the stations for producing the TEC maps (see figure 5). Although the number of the stations used in ESA processing strategy is much higher than the number of the stations used in JPL processing, it can be seen that the more stable solution over the year is JPL solution based on the mean values that is temporally stable. This could be attributed to that; JPL uses only GPS for producing the TEC map in their strategy while ESA uses GLONASS in addition to GPS (see table 1). That could lead us to conclude that using GLONASS constellation in the processing to produce TEC maps could affect the accuracy of produced TEC maps compare to the IGS TEC maps, as GLONASS satellites have different frequencies for each satellite, which is the function for the computed TEC values.
Figure 5. Number of Stations (Left) and number of Satellites (Right) used for the processing strategy for 365 days during 2018, for COD, ESA, IGS, JPL and WHU.

It is clear that all the STD values in Figure 4 are stable, however, it was noticed that the solution from WHU has dropped STD values on three time frames (06:00, 12:00 and 18:00 UTC) which is DOY 74 and 75. It may be understandable when looking at the RMS from the ionospheric files of WHU from Figure 6. It is indicating that the computed RMS for the computed values of TEC have been better for DOY 73 while a clear jump in the DOY 74 then stabilize from DOY 75 and after as shown in Figure 6.

Figure 6. Samples of RMS TEC values for WHU (DOY 73 (Left), 74 (Middle) and 75 (Right), 2018) at 06:00 UTC (in TECu).

To summarize the results, the mean value for one year over the gridded value differences between IGS and the other providers are presented in Table 2 below.

Table 2. Mean values of the differences over one year and the mean of the four-time scale (last right column) for COD, ESA, JPL and WHU in TECu.

| Provider | 00:00  | 06:00  | 12:00  | 18:00  | Mean (TECu) |
|----------|--------|--------|--------|--------|-------------|
| COD      | -0.047 | -0.270 | -0.143 | -0.086 | -0.137      |
| ESA      | 0.977  | 1.195  | 1.044  | 1.019  | 1.059       |
| JPL      | -1.091 | -1.085 | -1.057 | -1.095 | -1.082      |
| WHU      | 0.722  | 0.766  | 0.633  | 0.687  | 0.702       |
It is apparent from table 2 that, the best comparable results of the estimated TEC values comparing to the IGS TEC values is the COD product because of the followed strategy with almost a negative small bias. While the second-best solution could be the WHU solution with a bias of ~ 0.7 TECu. Whereas ESA and JPL, even that they have the most spatially stable behaviour over the year of 2018, could be almost the same results but in different sign which indicates a bias that could be related to the chosen station that has been assumed to have a zero value and treated as a zero mean. Although the values are very small in the unit of TECu, those value have a very significant impact on the results in term of GNSS metres unit. Taking into consideration that each 2.9 TECu is equal to 1 nanosecond which is equivalent to 30 cm. Those mean values could be written as -1.4, 11.0 -11.2 and 7.3 cm for COD, ESA, JPL and WHU, respectively. While the objective of this study is to analyse the accuracy of the produced TEC, the accuracy impact of these levels could be significant and may affect the long term analysis from GNSS like dam monitoring studies or any studies those require a precise and accurate result like tectonic plates motion studies.

4. Conclusions
The aim of this study started with the question of how the estimated values of TEC from different providers are varying between each other. To answer that question GNSS readings of a single year have been chosen to analysis differences between multiple providers. Four different scientific analytics centres (COD, ESA, JPL and WHU) have been chosen to analyse their data due to their stable solution and their availability for end GNSS users. It was found that almost all the TEC values from the used analysis centres have differences values (biases) from the IGS TEC values that could be up to ~ 0.1 TECu (that is equivalent to ~nanoseconds). The study has shown that, it is important to choose the network stations very carefully because it could affect the stability of the produced TEC.
In addition, the most accurate products as compared to the IGS, was found to be the COD product with a mean value of -0.1 cm while the ESA and JPL products have almost the same differences to the IGS but in a different sign which could be attributed to the number of the geometry of the stations locations that has been chosen. Although the WHU have almost a better absolute difference from the IGS with a value of 0.7 cm, it cannot be treated as a better solution than both of ESA and JPL. That is because of the unstable standard deviation of the computed mean as well as computed RMS by WHU centre which need more investigations.
Although all those ACs are part of the IGS community, they are following different processing strategies for providing not only TEC maps but also other products like satellite precise ephemeris and tropospheric delay. That strategies have the clear impacts on the result accuracies and precisions. This impact could be neglectable or significant based on the application of that the products or based on the referenced that have been chosen.

5. References
[1] Themens D R, Jayachandran P T, Langley R B, MacDougall J W and Nicolls M J 2012 Determining receiver biases in GPS-derived total electron content in the auroral oval and polar cap region using ionosonde measurements GPS Solutions 17 357-69
[2] Sardón E, Rius A and Zarraoa N 1994 Estimation of the transmitter and receiver differential biases and the ionospheric total electron content from Global Positioning System observations Radio Science 29 577-86
[3] Ammar M, Aquino M, Vadakke Veettil S and Andreotti M 2018 Estimation and analysis of multi-GNSS differential code biases using a hardware signal simulator GPS Solutions 22
[4] Mohammed J, Moore T, Hill C and Bingley R M 2020 Alternative strategy for estimating zenith tropospheric delay from precise point positioning In 2020 IEEE/ION Position, Location and Navigation Symposium (PLANS) 247-58
[5] Zhang S, Fang L, Wang G and Li W 2020 The impact of second-order ionospheric delays on the ZWD estimation with GPS and BDS measurements *GPS Solutions* 24 41

[6] Rideout W and Coster A 2006 Automated GPS processing for global total electron content data *GPS Solutions* 10 219-28

[7] Ciraolo L, Azpilicueta F, Brunini C, Meza A and Radicella S M 2006 Calibration errors on experimental slant total electron content (TEC) determined with GPS *Journal of Geodesy* 81 111-120

[8] Burrell A G, Bonito N A and Carrano C S 2008 Total electron content processing from GPS observations to facilitate ionospheric modeling *GPS Solutions* 13 83-95

[9] Carrano C S, Anghel A, Quinn R A and Groves K M 2009 Kalman filter estimation of plasmospheric total electron content using GPS *Radio Science* 44 1-14

[10] Brunini C and Azpilicueta F 2010 GPS slant total electron content accuracy using the single layer model under different geomagnetic regions and ionospheric conditions *Journal of Geodesy* 84 293-304

[11] Amiri-Simkooei A R and Asgari J 2011 Harmonic analysis of total electron contents time series: methodology and results *GPS Solutions* 16 77-88

[12] Sekido M, Kondo T, Kawai E and Imae M 2003 Evaluation of GPS-based ionospheric TEC map by comparing with VLBI data *Radio Science* 38 8-1

[13] Tuna H, Arikan O, Arikan F, Gulyaeva T L and Sezen U 2014 Online user-friendly slant total electron content computation from IRI-Plas: IRI-Plas-STEC *Space Weather* 12 64-75

[14] Rodriguez-Bilbao I, Moreno Monge B, Rodriguez-Caderot G, Herrera M and Radicella S M 2015 Evaluation of precise point positioning accuracy under large total electron content variations in equatorial latitudes *Adv. Space Res.* 55 605-16

[15] Mohammed J, Moore T, Hill C, Bingley R M and Hansen D N 2016 An assessment of static precise point positioning using GPS only, GLONASS only, and GPS plus GLONASS *Measurement* 88 121-30

[16] Yasyukevich Y V, Mylnikova A A, Kunitsyn V E and Padokhin A M 2015 Influence of GPS/GLONASS differential code biases on the determination accuracy of the absolute total electron content in the ionosphere *Geomagnetism and Aeronomy* 55 763-9

[17] Vadakke Veettil S, Aquino M, Marques H A and Moraes A 2020 Mitigation of ionospheric scintillation effects on GNSS precise point positioning (PPP) at low latitudes *Journal of Geodesy* 94 1-10