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Conference Paper · July 2007

DOI: 10.1109/RAST.2007.4283998 · Source: IEEE Xplore

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GPS/TEC Estimation with IONOLAB Method

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Abstract- **Total Electron Content (TEC) is a key variable to measure the ionospheric characteristics and disturbances. The Global Positioning System (GPS) can be used for TEC estimation making use of the recorded signals at the GPS receiver. Reg-Est method that is developed by F.Arıkan, C.B. Erol and O. Arıkan can be used to estimate high resolution, robust TEC values combining GPS measurements of 30 s resolution obtained from the satellites which are above the 10° elevation limit. Using this method, it is possible to estimate TEC values for a whole day or a desired time period both for quiet and disturbed days of the ionosphere. Reg-Est provides robust TEC estimates for high-latitude, mid-latitude and equatorial stations. In this study, some important parameters of Reg-Est such as ionospheric thin shell height, weighting function and receiver-satellite biases are investigated. By incorporating the results of the investigation, Reg-Est algorithm is developed into IONOLAB method. Thin shell model height is an important parameter for Single Layer Ionosphere Model (SLIM). In this study, it is shown that IONOLAB provides reliable and robust TEC estimates independent of the choice of the maximum ionization height. Signals from the low elevation satellites are prone to multipath effects. In order to reduce the distortion due to multipath signals, the optimum weighting function is implemented in IONOLAB, minimizing the non-ionospheric noise effects. GPS receivers record both pseudorange and phase data of signals. IONOLAB can input absolute TEC computed from the pseudorange measurements or phase-corrected low-noise TEC. The TEC estimates for both of these inputs are in good accordance with each other. Thus, taking either pseudorange or phase-corrected measurement data as input, high resolution, robust TEC estimates can be obtained from IONOLAB. Another important parameter for TEC estimation is satellite-receiver instrumental biases. The biases are the frequency dependent delays due to satellite and receiver hardware. In order to compute TEC, satellite and receiver biases should be removed from GPS measurements correctly. However, the proper procedure of how to include them in the TEC computation is generally vaguely defined. IONOLAB suggests a technique for inclusion of the hardware biases obtained from the web for TEC estimates that are consistent with the results from the IGS analysis centers.**

I. INTRODUCTION

Ionosphere forms the most important atmospheric layer for HF and satellite communication systems. Ionosphere varies with time, frequency, and location. Total Electron Content (TEC) provides a convenient measure for observing the variability of the ionosphere and characterization of the distortion on radio signals. TEC is defined as the total number of free electrons along a ray path of 1 m^2 cross section. TEC is closely related to solar and geomagnetic activities. TEC is measured in TECU units (1 TECU = 10^{16} el/m^2). The Global Positioning System (GPS), due to its availability for civilian use in the last 10 years, provides a cost-effective alternative for estimating TEC through recorded signals at the GPS receiver. Although the ionospheric group delay or phase advance on the recorded GPS signals is a major source of positioning errors, these parameters can be used to compute TEC efficiently.

Reg-Est method developed by F.Arıkan, C.B. Erol and O. Arıkan is new alternative for estimation of robust TEC by combining GPS measurements of 30 s resolution obtained from the satellites which are above the 10° elevation limit [1], [2], “in press” [3]. The method is based on combining GPS measurements in least squares sense. An optional weighting function and median filter is also applied. The method is capable of deriving TEC estimates for a whole day or for a limited period within a day.

The ionospheric thin shell height, weighting function and the use of web based satellite-receiver instrumental biases in Reg-Est are the parameters that are investigated in this study. The choice of ionospheric thin shell height, appropriate weighting function that minimizes the non-ionospheric irregularities and different methods for incorporation of instrumental biases are studied in detail. The method for phase-corrected TEC is developed and used as an alternative for absolute TEC in Reg-Est. The proper choice of alternative are incorporated into Reg-Est and the new method is called as IONOLAB.

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II. REG-EST PARAMETERS

In previous studies, Reg-Est algorithm is tried for various days and stations. It is shown that the method produces robust TEC estimates for various stations for both quiet and disturbed days in studies [1],[2] and “in press” [3]. The results are also compared with IRI-2001 and IGS analysis centers results. It is shown that Reg-Est TEC estimates are in good accordance with various analysis centers. Using Reg-Est method, estimates are obtained at higher time resolution compared to IRI-2001 and IGS results. Therefore, Reg-Est provides an important alternative for tracking the sudden ionospheric irregularities and disturbances.

In this paper, Reg-Est is applied to a larger range of GPS stations from mid-latitude, high-latitude and equatorial regions as given in TABLE 1. The days are selected from quiet and disturbed days of October 2003. The list of quiet and disturbed days are available at Ionospheric Dispatch Center (IDCE) [8]. As provided in [8], 10 October is quiet, 27-28-29 October are positively disturbed, 30-31 October are negatively disturbed days. In the last days of October 2003, a major geomagnetic and solar storm caused severe ionospheric disturbances. Kp index rose up to 9 and Dst index fell as low as -400 nT. In this section, the effect of ionospheric parameters such as ionospheric thin shell height, weighting function and satellite-receiver instrumental biases are studied.

TABLE 1
List of GPS recevier stations

Receiver Station	Country	Latitude °	Longtitude °
Ankara	Turkey	39,53 N	32,45 E
Brüksel	Belgium	50,47 N	4,21 E
Graz	Austria	47,04 N	15,29 E
İstanbul	Turkey	41,06 N	29,01 E
Zelenchukskaya	Russia	43,17 N	41,33 E
Arti	Russia	56,25 N	58,33 E
Kiruna	Sweden	67,51 N	20,58 E
Metsahovi	Finland	60,13 N	24,41 E
Petropavlosk	Russia	53,04 N	158,36 E
Lae	Papua New Guinea	06,40 S	146,59 E
Manila	Philippines	14,38 N	121,04 E
Nanyang	Singapore	01,20 N	103,40 E

A. Inclusion of satellite and receiver instrumental biases

Instrumental satellite and receiver biases are important parameters for TEC estimation. GPS measurements include both ionospheric delay and satellite-receiver instrumental biases. In order to estimate ionospheric TEC, these instrumental biases should be removed from measurements in an appropriate way. In the literature, there is no standard procedure for inclusion of satellite and receiver bias parameters in TEC estimation. In this study, two satellite and receiver bias inclusion methods are tried for Reg-Est. These methods are given in the following equations. In Method 1, the satellite and receiver instrumental biases are used in *STEC* computation as in Eq. (1) [6],[7],[14].

Bias inclusion method 1:

$$STEC_u^m(n)=\frac{1}{A}\frac{f_1^2 f_2^2}{f_1^2-f_2^2}\left[P_{4,u}^m(n)+c\left(DCB^m+DCB_u\right)\right] \quad (1)$$

$$VTEC_u^m(n)=STEC_u^m(n)/M(\varepsilon^m(n)) \quad (2)$$

where

$$M(\varepsilon_m(n))=\left[1-\left(\frac{R\cos\varepsilon_m(n)}{R+h}\right)^2\right]^{-1/2} \quad (3)$$

In the above equations, P_4 is the geometry free linear combination of pseudorange values (P_4=P_2-P_1). A is constant which is equal to 40,3 m^3/s^2. DCB_m and DCB_u are the frequency dependent satellite and receiver instrumental biases, respectively. m denotes satellite, u denotes receiver and n is the time sample. In Eq. (2), *STEC* is converted to *VTEC* using a mapping function that is given in Eq. (3). M is the mapping function and ε is the satellite elevation angle. In Method 1, instrumental biases are in time units (s).

Method 2 includes satellite and receiver biases in *VTEC* computation. The biases are added in TECU units [1],[2] as shown below in Eq. (5).

Bias inclusion method 2:

$$STEC_u^m(n)=\frac{1}{A}\frac{f_1^2 f_2^2}{f_1^2-f_2^2}\left[P_{4,u}^m(n)\right] \quad (4)$$

$$VTEC_u^m(n)=STEC_u^m(n)/M(\varepsilon^m(n))+b^m+b_u \quad (5)$$

Bias inclusion Method 1 and 2 are used in the computation of *STEC* and *VTEC* in preprocessing of input data for Reg-Est method for stations given TABLE 1. The instrumantal biases are available in IONEX files of IGS analysis centers [12]. As an example, results for Petropavlovsk 12.10.2003 is given in Fig. 1. In Fig. 1, solid line and dashed line display the Reg-Est TEC estimates with bias inclusion method 1 and method 2, respectively. TEC estimates of various IGS analysis centers are also provided in Fig. 1. These TEC maps are obtained from [12]. In Fig. 1, JPL, CODE, ESA/ESOC, UPC estimates are displayed with diamond, square, circle and triangle symbols, respectively. As can be observed from Fig. 1 that the TEC estimates from Method 1 is very close to the results of CODE and estimates from both methods are in very good accordance.

Reg-Est estimates using both bias inclusion methods are compared with results of other analysis centers in by using D_1, D_2, and D_3 defined below. $\boldsymbol{x}_{b1}$, and $\boldsymbol{x}_{b2}$ are TEC estimation results of Reg-Est using method 1 and method 2 respectively. $\boldsymbol{x}_{CODE}$ represents the results of CODE analysis center. N is the total number of GPS recordings for 24 hour period. In TABLE 2 computed TEC differences are listed for various days and stations. In general, D_2 results are smaller when compared to D_3. Thus, including instrumental biases as in Method 1 gives TEC estimation results closer to CODE analysis center.

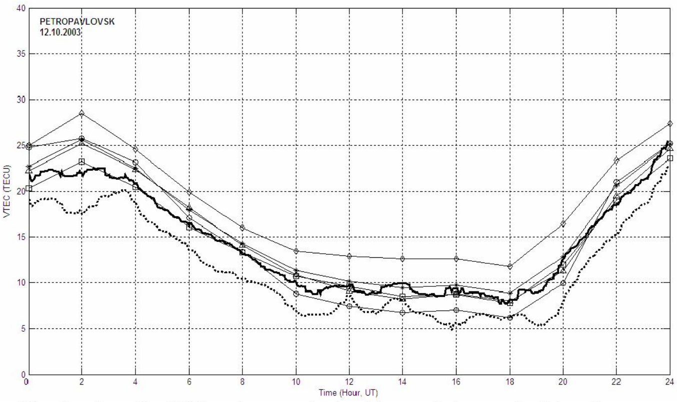

Fig. 1. Reg-Est TEC estimates obtained by applying method 1 and method2 bias inclusion methods for Petropavlovsk 12.10.2003 (quiet day).

$$D_1 = \frac{\sum_{n=1}^{N} |\boldsymbol{x}_{b1} - \boldsymbol{x}_{b2}|^2}{\sum_{n=1}^{N} |\boldsymbol{x}_{b1}|^2} \qquad (6)$$

$$D_2 = \frac{\sum_{n=1}^{N} |\boldsymbol{x}_{b1} - \boldsymbol{x}_{CODE}|^2}{\sum_{n=1}^{N} |\boldsymbol{x}_{b1}|^2} \qquad (7)$$

$$D_3 = \frac{\sum_{n=1}^{N} |\boldsymbol{x}_{b2} - \boldsymbol{x}_{CODE}|^2}{\sum_{n=1}^{N} |\boldsymbol{x}_{b2}|^2} \qquad (8)$$

TABLE 2

Reg-Est TEC estimation differences obtained using different bias inclusion methods.

Receiver Station	Day	D_1	D_2	D_3
Zelenchukskaya	Oct 12, 2003	$1.17\text{x}10^{-2}$	$2.85\text{x}10^{-3}$	$1.48\text{x}10^{-2}$
Graz	Oct 31, 2003	$8.71\text{x}10^{-3}$	$1.73\text{x}10^{-2}$	$2.03\text{x}10^{-2}$
Arti	Oct 10, 2003	$6.72\text{x}10^{-2}$	$4.21\text{x}10^{-3}$	$9.80\text{x}10^{-2}$
Petropavlovsk	Oct 29, 2003	$1.81\text{x}10^{-2}$	$5.98\text{x}10^{-3}$	$4.17\text{x}10^{-2}$
Nanyang	Oct 12, 2003	$1.27\text{x}10^{-4}$	$5.12\text{x}10^{-3}$	$5.27\text{x}10^{-3}$
Lae	Oct 28, 2003	$8.94\text{x}10^{-3}$	$3.53\text{x}10^{-2}$	$7.23\text{x}10^{-2}$

Although using both bias inclusion methods in Reg-Est gives reasonable TEC estimates, bias inclusion Method 1 results are closer to IGS analysis centers' estimates compared to Method 2. Since using instrumental biases in *STEC* computation is more suitable for the model for GPS observation equations, Method 1 will be used in IONOLAB for inclusion of instrumental biases.

B. Computation of Carrier Phase- Corrected VTEC

Theoreticaly TEC can be computed using pseudorange data, carrier phase data or using combination of both [1]. Using pseudorange in TEC computation is simple and robust [1]. Pseudorange measurements are more noisy compared to carrier phase measurements. Using only carrier phase data in TEC computation is difficult because of initial phase ambiguity and cycle slips. Third method is to use both pseudorange and phase measurements to overcome phase ambiguity and cycle slip problems. These methods are discussed in various studies such as [5],[7],[9],[10],[14]. Previously, only the absolute TEC was used as an input to Reg-Est. For IONOLAB, the measurement input range is enlarged to include the phase-corrected measurements. Carrier phase measurements are levelled using pseudorange measurements to eliminate phase ambiguity. The levelling process is based on computing a baseline (*B*) for each connected arc of phase measurements. Then, the computed baseline is used in *STEC* computation as in Eq. (10).

$$B^m = \frac{1}{N_{me}} \sum_{n_{me}=1}^{N_{me}} P_{4,u}{}^m(n_{me}) - L_{4,u}{}^m(n_{me}) \qquad (9)$$

$$STEC_u{}^m(n) = \frac{1}{A}\frac{f_1^2 f_2^2}{f_1^2 - f_2^2}\left[L_{4,u}{}^m(n) + B^m + c\left(DCB^m + DCB_u\right)\right] \qquad (10)$$

Fig. 2 provides an example of the comparison of Reg-Est estimates obtained using pseudorange and carrier phase data. In Fig. 2.a., solid line and dotted line denote estimates obtained using carrier phase data and pseudorange data in Reg-Est, respectively. In Fig. 2.b., Reg-Est estimates are compared with the TEC estimates of IGS analysis centers. JPL, CODE, ESA/ESOC, UPC estimates are displayed with diamond, square, circle and triangle symbols, respectively. As can be observed from Fig. 2.b. that, using either pseudorange or carrier phase data as input, Reg–Est produces consistent TEC estimation results with IGS analysis centers especially with JPL and CODE. Therefore, IONOLAB can use both absolute TEC and phase-corrected TEC as input.

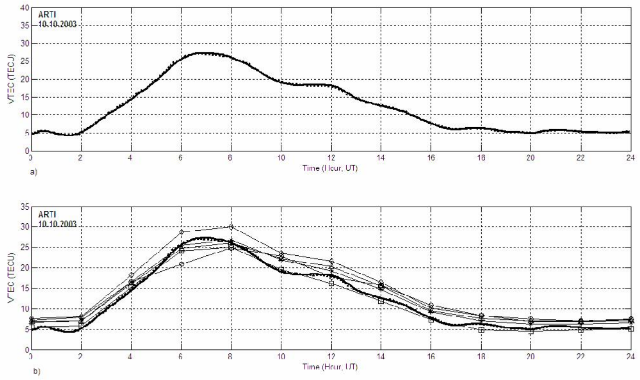

Fig. 2. Comparison of Reg-Est TEC estimates using pseudorange and carrier phase data, Arti 10.10.2003 (quiet day).

Detailed comparison of pseudorange and phase derived Reg-Est estimates with other analysis centers is done by computing normalized TEC differences as in equations (11) through (13), where $\boldsymbol{x}_{pr}$ and $\boldsymbol{x}_{ph}$ are Reg-Est estimates obtained using pseudorange and carrier phase data respectively. $\boldsymbol{x}_{JPL}$ and $\boldsymbol{x}_{CODE}$ denotes the TEC estimates of JPL and CODE, respectively. The comparison results are given in TABLE 3 for various days and stations.

$$D_4 = \frac{\sum_{n=1}^{N} \left| \boldsymbol{x}_{pr} - \boldsymbol{x}_{ph} \right|^2}{\sum_{n=1}^{N} \left| \boldsymbol{x}_{pr} \right|^2} \qquad (11)$$

$$D_5 = \frac{\sum_{n=1}^{N} \left| \boldsymbol{x}_{pr} - \boldsymbol{x}_{JPL} \right|^2}{\sum_{n=1}^{N} \left| \boldsymbol{x}_{pr} \right|^2} \qquad (12)$$

$$D_6 = \frac{\sum_{n=1}^{N} \left| \boldsymbol{x}_{ph} - \boldsymbol{x}_{JPL} \right|^2}{\sum_{n=1}^{N} \left| \boldsymbol{x}_{ph} \right|^2} \qquad (13)$$

TABLE 3
Reg-Est TEC estimation differences obtained using pseudorange or carrier phase data.

Receiver Station	Day	D_4	D_5	D_6
Ankara	Oct 31, 2003	$1.75\mathrm{x}10^{-4}$	$1{,}30\mathrm{x}10^{-3}$	$1.93\mathrm{x}10^{-3}$
Graz	Oct 10, 2003	$8.20\mathrm{x}10^{-4}$	$3.20\mathrm{x}10^{-2}$	$3.21\mathrm{x}10^{-2}$
Zelenchukskaya	Oct 29, 2003	$2.68\mathrm{x}10^{-4}$	$1.99\mathrm{x}10^{-3}$	$1.49\mathrm{x}10^{-3}$
Petropavlovsk	Oct 31, 2003	$5.07\mathrm{x}10^{-4}$	$2.87\mathrm{x}10^{-3}$	$2.68\mathrm{x}10^{-3}$
Arti	Oct 10, 2003	$2.29\mathrm{x}10^{-3}$	$4.53\mathrm{x}10^{-2}$	$4.59\mathrm{x}10^{-2}$
Kiruna	Apr 28, 2003	$9.08\mathrm{x}10^{-4}$	$3.43\mathrm{x}10^{-2}$	$4.31\mathrm{x}10^{-2}$
Manila	Oct 27, 2003	$2.38\mathrm{x}10^{-5}$	$4.05\mathrm{x}10^{-3}$	$3.84\mathrm{x}10^{-3}$
Lae	Oct 10, 2003	$1.89\mathrm{x}10^{-4}$	$6.42\mathrm{x}10^{-3}$	$7.68\mathrm{x}10^{-3}$
Nanyang	Oct 30, 2003	$4.94\mathrm{x}10^{-4}$	$2.90\mathrm{x}10^{-3}$	$3.36\mathrm{x}10^{-3}$

In TABLE 3, D_4 is small for all days and stations, that means using either pseudurange as input, Reg-Est estimation results are very close to each other. Comparison with JPL results given as D_5 and D_6 are relatively small, therefore Reg-Est estimates are in good agreement with 2 hour TEC estimates of JPL.

C. Effect of Ionospheric Thin Shell Height

Slant Ray Total Electron Content (*STEC*) can be computed using Eq. (1). Vertical Total Electron Content (*VTEC*) can be computed as in Eq. (2) and using a thin shell approximation which is known as Single Layer Ionosphere Model (SLIM). In Eq. (3), M is the mapping function and ε is the local satellite elevation angle.

In SLIM model, ionosphere is assumed to be a layer of infinitesimal thickness. Ionospheric shell height is the height of maximum electron density and it is a function of time and geographic location [4]. Various methods in the literature have different ionospheric selection choices such as [1], [4], [6], [11], [14]. In [4], choosing different ionospheric heights can result TEC differences at 2 TECU level. In Fig. 3, Reg-Est estimates for 300 km, 428.8 km and 450 km are given for an example scenario. In Fig. 3, it is seen that TEC estimation results are very close to each other. To obtain a quantitative measure for the difference between TEC estimates, the following differences are defined.

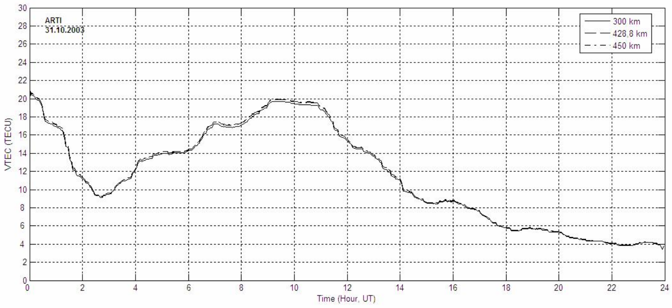

Fig. 3. Reg-Est TEC estimates for 300 km, 428.8 km and 450 km ionospheric shell height, Arti 31.10.2003, negatively disturbed day.

$$D_7 = \frac{1}{N} \sum_{n=1}^{N} \left| \boldsymbol{x}_{h2} - \boldsymbol{x}_{h1} \right| \qquad (14)$$

$$D_8 = \frac{1}{N} \sum_{n=1}^{N} \left| \boldsymbol{x}_{h3} - \boldsymbol{x}_{h2} \right| \qquad (15)$$

In Eq. (14) and Eq. (15), the mean TEC differences are given. $\boldsymbol{x}_{h1}$, $\boldsymbol{x}_{h2}$, and $\boldsymbol{x}_{h3}$ are the Reg-Est TEC estimation results for 300 km, 428.8 km and 450 km, respectively. N is the total number of GPS recordings for 24 hour period. The differences are shown for various days and stations in TABLE 4. In TABLE 4, all TEC differences are below 1 TECU level. Thus, it can be concluded that the choice of the ionospheric shell height does not have any significant effect on Reg-Est TEC estimates. Thus, in IONOLAB, the height of 428.8 km can be used.

TABLE 4
Reg-Est TEC estimation differences with respect to ionospheric height

Receiver Station	Day	D_7	D_8
Ankara	Oct 10, 2003	0.244	0.038
Ankara	Oct 31, 2003	0.286	0.044
Zelenchukskaya	Oct 10, 2003	0.207	0.032
Zelenchukskaya	Oct 28, 2003	0.303	0.047
Arti	Oct 10, 2003	0.162	0.025
Arti	Oct 31, 2003	0.143	0.022
Metsahovi	Oct 10, 2003	0.168	0.026
Metsahovi	Oct 28, 2003	0.214	0.033
Nanyang	Oct 10, 2003	0.534	0.083
Nanyang	Oct 30, 2003	0.374	0.058

D. Weighting GPS measurements

Signals from satellites of low elevation angles are more susceptible to multipath effects compared to signals from satellites of high elevation angles [13]. Therefore, it is important to apply an appropriate weighting procedure to minimize the multipath effects. In some studies, measurements obtained from satellites that are below a certain elevation angle limit are ignored. In [6], a $\sin^2(\varepsilon_m)$ is used as a weighting function where ε_m is the satellite elevation angle. In this study, three different weighting options are tried for the Reg-Est method. These weighting options are given below.

1. Weighting Function :

$$w1_m(n) = \begin{cases} 0, & \varepsilon_m(n) \le 10^\circ \\ \exp\left(-(90-\varepsilon_m(n))^2/2\sigma^2\right), & 10^\circ \le \varepsilon_m(n) \le 60^\circ \\ 1, & 60^\circ \le \varepsilon_m(n) \le 90^\circ \end{cases} \quad (16)$$

2. Weighting Function :

$$w2_m(n) = \begin{cases} 0, & \varepsilon_m(n) \le 10^\circ \\ \exp\left(-(60-\varepsilon_m(n))^2/2\sigma^2\right), & 10^\circ \le \varepsilon_m(n) \le 60^\circ \\ 1, & 60^\circ \le \varepsilon_m(n) \le 90^\circ \end{cases} \quad (17)$$

3. Weighting Function :

$$w3_m(n) = \sin^2(\varepsilon_m(n)) \quad (18)$$

The first weighting function is the one that is used previously in Reg-Est. This function ignores the measurements below 10° elevation angle. The measurements between 10° and 60° are weighted using a Gaussian function which has a mean at 90°. The measurements above 60° are directly used. The second weighting function is similar to first one except the gaussian function has a mean at 60°. The third weighting function is the one that is used in [6]. These weighting options are tried in Reg-Est method for various days and receiver stations that are listed in TABLE 1. An example is provided in Fig. 4 and TEC estimates for Ankara 10.10.2003 using $w1$, $w2$ and $w3$ are given. In Fig. 4, the estimates obtained by $w2$ and $w3$ weighting functions are close to each other. These two functions provide smooth transitions in time compared to those of $w1$. In order to examine the TEC estimates in detail, the following normalized difference functions are defined. The normalized differences obtained using these three difference functions are given in TABLE 5 for some stations and days as an example.

$$\mathrm{D}_9 = \frac{1}{N}\sum_{n=1}^{N} \frac{\left|\boldsymbol{x}_{w3} - \boldsymbol{x}_{w2}\right|^2}{\left|\boldsymbol{x}_{w2}\right|^2} \quad (19)$$

$$D_{10} = \frac{1}{N}\sum_{n=1}^{N} \frac{\left|\boldsymbol{x}_{w2} - \boldsymbol{x}_{w1}\right|^2}{\left|\boldsymbol{x}_{w2}\right|^2} \quad (20)$$

$$D_{11} = \frac{1}{N}\sum_{n=1}^{N} \frac{\left|\boldsymbol{x}_{w3} - \boldsymbol{x}_{w1}\right|^2}{\left|\boldsymbol{x}_{w2}\right|^2} \quad (21)$$

In TABLE 5, D_9 values are smaller than D_{10} and D_{11} which shows that TEC estimation results of $w2$ and $w3$ are in relatively better accordance for all stations compared to results of $w1$. Since $w2$ provides smooth transitions and reduces sudden irregularities in TEC estimates, $w2$ can be used in IONOLAB.

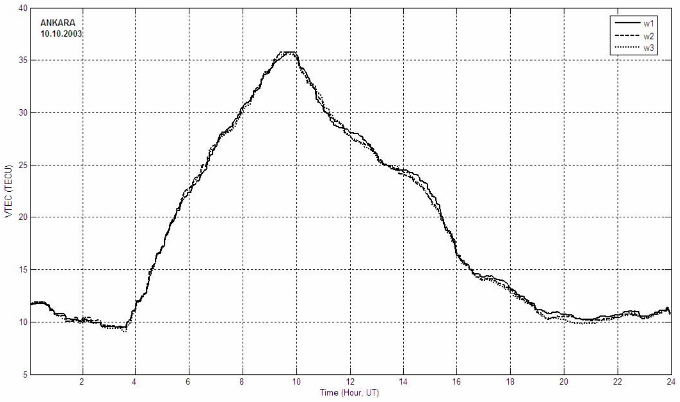

Fig. 4. Reg-Est TEC estimates obtained w1, w2 and w3 weighting functions for Ankara 10.10.2003.

TABLE 5

Reg-Est TEC estimation differences with respect to weighting functions w1, w2 and w3.

Receiver Station	Day	D_9	D_{10}	D_{11}
Ankara	Oct 10, 2003	9.51×10^{-5}	2.34×10^{-4}	3.06×10^{-4}
Ankara	Oct 31, 2003	1.20×10^{-4}	2.34×10^{-4}	3.31×10^{-4}
Zelenchukskaya	Oct 10, 2003	8.69×10^{-5}	4.03×10^{-4}	4.34×10^{-4}
Zelenchukskaya	Oct 28, 2003	5.14×10^{-5}	1.92×10^{-4}	1.68×10^{-4}
Arti	Oct 10, 2003	7.77×10^{-5}	4.09×10^{-4}	3.42×10^{-4}
Arti	Oct 31, 2003	2.67×10^{-4}	8.72×10^{-4}	8.36×10^{-4}
Metsahovi	Oct 10, 2003	1.53×10^{-4}	5.06×10^{-4}	5.95×10^{-4}
Metsahovi	Oct 28, 2003	1.62×10^{-4}	3.04×10^{-4}	5.20×10^{-4}
Nanyang	Oct 10, 2003	1.71×10^{-4}	7.39×10^{-4}	9.41×10^{-4}
Nanyang	Oct 30, 2003	2.78×10^{-4}	6.98×10^{-4}	1.40×10^{-3}

III. CONCLUSION

Reg-Est, developed in [1], [2], and [3], is a high resolution, robust TEC estimation technique. In this paper, the use of satellite and receiver biases, the effects of ionospheric shell height and the choice of weighting functions are investigated for further improvement of Reg-Est. Although there is no standard way of using satellite and receiver instrumental biases in the literature, two methods for adding these biases is applied and the results are compared with IGS analysis centers. The results are consistent with IGS centers especially with JPL and CODE. The method which estimates TEC closest to IONEX estimates for the use the instrumental biases is selected for IONOLAB. In previous studies of Reg-Est, only pseudo-range measurement were used as input to the regularization algorithm. In this paper, phase measurements are used in Reg-Est method with an appropriate leveling technique. The TEC estimation results are very close to the results of pseudorange measurements but TEC estimates from phase-leveled measurements are less noisy.

Ionospheric shell height is a parameter used in Reg-Est. In this paper, different ionospheric height values are used in Reg-Est method and the TEC estimates are compared. It is observed that the Reg-Est method is nearly independent of the choice of ionospheric height. Weighting function helps to reduce the multipath effect in the measurements of satellites which are at low elevation angles. Three different weighting options are tried and the weighting function which reduces the non-ionospheric effects best is selected for IONOLAB. It is also shown that the TEC estimation results of IONOLAB is consistent with IGS analysis centers especially with CODE and JPL.

ACKNOWLEDGMENT

This study is supported by TUBITAK EEEAG grant no: 105E171.

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