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Regularized estimation of vertical total electron content from GPS data for a desired time period

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[1] In this paper a new algorithm for short-term regularized estimation of vertical total electron content (VTEC) from Global Positioning System (GPS) data is developed. The regularization technique can combine signals, from all GPS satellites for a given instant and a given receiver, for a desired time duration within the 24 hour period without missing any important features in the temporal domain. The algorithm is based on the minimization of a cost function which includes a high pass penalty filter and detrend processing. With an optional weighting function the multipath effects are reduced. A final sliding window median filter is added to enrich the processing and smoothing of the data. The developed regularized estimation algorithm is applied to GPS data for various locations for the solar maximum week of 23–28 April 2001. The parameter set that is required by the estimation algorithm is chosen optimally using appropriate error functions. For this data set the chosen robust and optimum parameters can be used for all latitudes and for both quiet and disturbed days for a minimum of one hour time period. It is observed that the estimated TEC values are in very accordance with the TEC estimates for the 24 hour period. Owing to its 30 s time resolution, the regularized VTEC estimates from the developed algorithm are very successful in representation and tracking of sudden temporal variations of the ionosphere, especially for high latitudes and during ionospheric disturbances. *INDEX TERMS:* 2409 Ionosphere: Current systems (2708); 2494 Ionosphere: Instruments and techniques; 6974 Radio Science: Signal processing; 6979 Radio Science: Space and satellite communication; 9820 General or Miscellaneous: Techniques applicable in three or more fields; *KEYWORDS:* total electron content, GPS, signal processing

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1. Introduction

[2] Global Positioning System (GPS) data provide a direct and efficient way to estimate total electron content (TEC) values as widely discussed in the literature including *Davies and Hartmann* [1997], *Hocke and Pavelyev* [2001], *Calais and Bernard Minster* [1998]. Both short-term and long-term variations in the ionospheric structure, including irregularities and disturbances can be observed by examining TEC. TEC is defined as the number of free electrons along the ray path above one square meter. Since the frequencies that are used in GPS system are sufficiently high, the signals are minimally affected by the ionospheric absorption and Earth's magnetic field.

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[3] Most of the methods that estimate TEC from GPS data follow one satellite which is above a certain elevation angle for limited time periods and time average the received signals from 5 min to 15 min [*Wang et al.*, 1998; *Fraile*, 1995]. This way some of the important spatial and temporal variations over the receiving station may be missed or not observed at all. In the work of *Arikan et al.* [2003], a regularization algorithm for estimation of vertical TEC (VTEC) values for 24 hours period is introduced. The method combines the received signals from all the satellites that are above GPS elevation angle limit of 10° and obtains VTEC estimates with 30 s time resolution. The regularization algorithm is designed to obtain accurate VTEC estimates for the 24 hour period. In order to obtain VTEC values for time frames shorter than 24 hours, the above mentioned regularization technique has to be modified. In this paper, we further develop the regularized estimation algorithm in the work of *Arikan et al.* [2003] to be applied for short time frames and obtain estimates of VTEC for focusing on desired features of ionospheric structure. The first step of the regularization algorithm requires computed VTEC data for each satellite above the 10° elevation angle limit with 30 s time resolution. The contamination due to multipath is reduced by applying a weighting function on the computed TEC data according to the satellite positions with respect to the local zenith. As discussed in the work of *Arikan et al.* [2003], the first step of the regularization includes the minimization of a cost function which includes a high pass penalty filter. For time periods shorter than 24 hours, the cost function is modified by detrend processing. The trend in the data is removed by applying a linear least squares fit. The regularization step requires the determination of two parameters which are to be chosen from the error function formed by the $\mathcal{L}2$ norm of the difference between the estimated and actual VTEC values. The second step of regularization includes a sliding window median filter which further reduces the jagged features in the estimated VTEC values. The window length of the sliding median filter is another parameter to be determined. The estimation algorithm is applied to the computed VTEC data for four stations, namely Kiruna, Norway, Kiev, Ukraine, Ankara, Turkey and M. Dragot, Israel for the solar maximum period of 23–28 April 2001. Within this period, we observed both the typical quiet day TEC structure of the ionosphere and also the VTEC values of the most positively and the most negatively disturbed days of the month. The results of the proposed estimation algorithm are compared with the appropriate sectors of 24 hour TEC estimation. It is observed that the developed estimation procedure for a desired time period is highly accurate in construction of TEC values from various satellites and the estimation results closely follow the temporal and spatial variations in the ionosphere. The parameters that need to be determined for the estimation algorithm can be chosen robustly. Thus for the given data set, the same parameter set can be used both for the quiet and the disturbed days, all latitudes and any desired time sector. The robustness of the parameters are an important indication of the strength of proposed estimation algorithm.

[4] In section 2, the preprocessing of GPS data and the estimation of the VTEC values from various satellites for any desired time period are discussed. The procedure to choose the parameter set and examples of the estimated TEC values are provided in the Results section.

2. Regularized TEC Estimation for a Short Time Duration

[5] In this section, we discuss the developed regularized estimation of the total electron content in the zenith direction of the GPS receiver for any desired time duration within the 24 hour period. The algorithm combines the computed VTEC data from all available satellites for within the desired time frame and obtains accurate and robust estimates of vertical TEC.

[6] The regularized estimation algorithm requires the computed VTEC values for each satellite which are above the 10° elevation angle limit over the GPS station. Thus the raw GPS signals for each station and for all satellites are downloaded from the Internet site of the International GPS Service (IGS) for Geodynamics (http://igs.ens.ign.fr) in Receiver Independent Exchange (RINEX) format for every 30 s. Some of the GPS recordings could be missing or inaccurate due to satellite and/or receiver failures, so all the data that have been downloaded are thoroughly examined and inaccurate or missing recordings are expelled from the data set. The receivers at GPS stations record signals transmitted at two L band frequencies namely, f_1 at 1575.42 MHz, and f_2 at 1227.60 MHz. The time delay which occurs while these signals are propagating through the ionosphere are converted to pseudoranges and recorded as P1 and P2 signals. The carrier phase delay measurements on the f_1 and f_2 coherent frequencies are also recorded as L1 and L2, respectively. The TEC values can be calculated from the difference of P2 and P1 signals which is called the absolute TEC; the difference of L1 and L2 can be used to compute TEC which is called as relative TEC; and it is possible to compute TEC by using both (L1–L2) and (P2–P1) measurements and also solving for instrumental biases. Any of the above mentioned methods can be used to compute TEC and they can be used as inputs to the estimation algorithm. The TEC computation methods and their advantages and disadvantages are widely discussed in the literature.

[7] As discussed in the work of *Arikan et al.* [2003] in detail, we chose to compute TEC values from the difference of pseudoranges due to computational simplicity. The computation of absolute TEC is simple and unambiguous but usually corrupted by noise and multipath signals especially at low elevation angles. The first step is to obtain the absolute total electron content on the slant ray path (STEC) from the satellite to the receiver for all satellites and for all stations. Usually, the computed slant TEC is projected to the local zenith direction to obtain the vertical TEC (VTEC) through a mapping function, assuming a thin shell model of the ionosphere. The daily positions of the satellites in Earth Centered and Earth Fixed (ECEF) coordinate system are downloaded from the Internet site of National Imagery and Mapping Agency (http://164.214.2.59). In the downloaded files in ECEF coordinates, the satellite coordinates are given for every 15 min. Thus, in order to obtain the satellite locations corresponding to P1 and P2 measurements with 30 s period, the 15 min coordinates are interpolated with 30 s separation. Then the coordinates of the satellites are converted to the local coordinate system of each receiver location. The 10° elevation angle is the geometrical limit for the GPS receiver to lock to the passing satellite. The vertical TEC values are then computed for all receiver locations, all satellites over the 10° elevation angle limit with 30 s period. The satellite and receiver bias pairs, that are obtained from Center for Orbit Determination in Europe (CODE), University of Berne, Switzerland (ftp.unibe.ch/aiub/CODE/2001/P1P20104_ALL.DCB.Z), are also added to the computed VTEC values.

[8] Since the ionosphere is spatially inhomogeneous and time varying, the computed STEC and VTEC values have different characteristics for each satellite path. Missing data points cause discontinuities in computed VTEC. Generally, in order to avoid missing and inaccurate data, the computed VTEC values are averaged for certain periods of time. Multipath corruption is another problem which affects the accuracy of the computed VTEC data. Thus, in order to overcome multipath, generally in the literature, the satellite which has the highest elevation angle is tracked for limited time periods. In our study, once VTEC values for all locations, for all satellites and for the desired time period are prepared, a weighting function is utilized to include all the contributions from satellites at an elevation angle higher than 60°. This weighting function also scales down the data from other satellites between 10° and 60° with a Gaussian function. As it has been discussed in detail in the work of *Arikan et al.* [2003], with the weighting function, the effect of multipath is reduced, and at the same time, the contribution from the satellites at lower elevation angles are included in the estimation.

[9] In order to combine all the computed VTEC values from different satellites for the desired period and obtain a smooth estimate, the following algorithm is proposed. Let

$$\mathbf{x}_m = [x_m(0) \ \ldots \ x_m(n) \ \ldots \ x_m(N-1)]_N^T \tag{1}$$

denote a set of computed VTEC values obtained from the mth satellite, where $1 \leq m \leq M$ and M is the total number of satellites; and also $0 \leq n \leq N-1$ where N is the total number of recordings in the desired time period. For a 24 hour period, with a measurement of every 30 s, $N = 2 \times 60 \times 24 = 2880$ samples/day. To obtain estimates of TEC which minimize the error between the computed VTEC and the estimated VTEC in the least square sense for the 24 hour period, we defined a cost function in the work of *Arikan et al.* [2003], which includes the $\mathcal{L}2$ norm error between the estimated and computed VTEC values summed over all satellites plus a high pass penalty filter multiplied by a regularization parameter, μ, as follows:

$$J_{\mu,k_c}(\mathbf{x}) = \sum_{m=1}^{M} (\mathbf{x}-\mathbf{x}_m)^T \mathbf{W}_m (\mathbf{x}-\mathbf{x}_m) + \mu \mathbf{x}^T \mathbf{H}(k_c)\mathbf{x} \tag{2}$$

where $\mathbf{W}_m = \mathrm{diag}(\mathbf{w}_m)$, and $\mathbf{w}_m$ is the optional weighting according to the elevation angle of the satellite in the work of *Arikan et al.* [2003]. $\mathbf{H}(k_c)$ is the high pass penalty function. $\mathbf{H}(k_c)$ is designed to pass all signals up to a cutoff frequency, k_c. The purpose of adding a penalty function to the cost function is to control the smoothness of the data. In order to represent the 24-hour cycle of the ionosphere, the high pass penalty function, $\mathbf{H}(k_c)$ was designed as a Toeplitz matrix obtained from filters $h_n(k_c)$ in the following manner:

$$\mathbf{H}(k_c) = \begin{bmatrix} h_0(k_c) & h_1(k_c) & \cdots & h_{N-1}(k_c) \\ h_{N-1}(k_c) & h_0(k_c) & \cdots & h_{N-2}(k_c) \\ \vdots & \vdots & \vdots & \vdots \\ h_1(k_c) & h_2(k_c) & \cdots & h_0(k_c) \end{bmatrix}_{N\times N} \tag{3}$$

where

$$h_n(k_c) = \frac{1}{N}\sum_{k=0}^{N-1} \mathbf{H}_k(\omega_c) \exp\left(j\frac{2\pi}{N}kn\right) \tag{4}$$

where $\omega_c = 2\pi k_c/N$. $\mathbf{H}_k(\omega_c)$ was chosen as follows:

$$H_k(\omega_c) = \begin{cases} 1, \ \text{if} \ \pi - \omega_c \leq \dfrac{2\pi}{N}k \leq \pi + \omega_c \\ 0, \ \text{otherwise} \end{cases} \tag{5}$$

Then the filter $h_n(k_c)$ becomes:

$$h_n(k_c) = \begin{cases} 1 - \dfrac{1}{N}(2k_c + 1), & \text{for } n = 0 \\ -\sin\left(\dfrac{\pi n}{N}(2k_c + 1)\right) \Big/ \left(N \sin\left(\dfrac{\pi n}{N}\right)\right), & \text{for } n \neq 0 \end{cases} . \tag{6}$$

This regularized estimation algorithm provides accurate and robust estimates for the 24 hour period. Yet, when it is used for time periods shorter than 24 hours which do not present cyclic symmetry, this form of the high pass penalty filter is not appropriate since the penalty function tries to bring the end points of the data to the same values. In order to use the underlying structure and the same filter for shorter time periods, we estimated the trend in the data with a linear least squares fit. Then the estimated trend is removed from the data. This well-known signal processing operation is applied to the estimation of TEC by redefining the cost function in equation (2) as follows:

$$J_{\mu,k_c}(\mathbf{x}) = \sum_{m=1}^{M} (\mathbf{x} - \mathbf{x}_m)^T \mathbf{W}_m (\mathbf{x} - \mathbf{x}_m) + \mu(\mathbf{x} - a\mathbf{t})^T \mathbf{H}(k_c)(\mathbf{x} - a\mathbf{t}) \tag{7}$$

In the above equation, the trend in the data is extracted using a line. The slope of this line is a and $\mathbf{t}$ represents the time vector for the desired sector. For a given parameter set μ, k_c and a, we investigate the values $\mathbf{x}$ which will minimize J. Thus we search for $\mathbf{x}$ which will satisfy $\nabla_{\mathbf{x}} J_{\mu,kc}(\mathbf{x}) = \mathbf{0}$ and $\partial J / \partial a = 0$. The optimal solution to the minimization of the cost function in equation (10) reduces to the solution of the following linear system

$$\mathbf{A}(\mu, k_c) \begin{bmatrix} \mathbf{x} \\ a \end{bmatrix} = \mathbf{b} \tag{8}$$

where

$$\mathbf{A}(\mu, k_c) = \begin{bmatrix} \sum_{m=1}^{M} \mathbf{W}_m + \mu \mathbf{H}(k_c) & -\mu \mathbf{H}(k_c)\mathbf{t} \\ \mathbf{t}^T \mathbf{H}(k_c) & -\mathbf{t}^T \mathbf{H}(k_c)\mathbf{t} \end{bmatrix} \tag{9}$$

and

$$\mathbf{b} = \begin{bmatrix} \sum_{m=1}^{M} \mathbf{W}_m \mathbf{x}_m \\ 0 \end{bmatrix}. \tag{10}$$

Then the estimate of $\mathbf{x}$, $\tilde{\mathbf{x}}$, is obtained from the above relations as

$$\begin{bmatrix} \tilde{\mathbf{x}}(\mu, k_c) \\ a \end{bmatrix} = \mathbf{A}^{-1}(\mu, k_c)\mathbf{b}. \tag{11}$$

[10] In order to determine the optimum choice for μ and k_c, an error function which will minimize the error between the estimated VTEC, $\tilde{\mathbf{x}}$, and the data from each satellite, $\mathbf{x}_m$, can be defined as follows:

$$e(\mu, k_c) = \sum_{m=1}^{M} \| \mathbf{W}_m (\tilde{\mathbf{x}} - \mathbf{x}_m) \|^2 \tag{12}$$

where $\| \cdot \|$ denotes the $\mathcal{L}_2$ norm.

[11] After investigating for the optimum choice of μ and k_c by computing the $\mathcal{L}_2$ norm of the error between the computed and estimated VTEC values, an optional sliding window median filter can be applied to further reduce the jagged features and irregularities in the estimated TEC values. The window length of the median filter is another parameter that needs to be determined optimally. For the optimum choice of the median filter length, another error function which computes the square of the $\mathcal{L}_2$ norm between the estimated VTEC and the median filtered VTEC with the filter length N_f as follows:

$$e_f(N_f) = \| \tilde{\mathbf{x}} - \tilde{\mathbf{x}}_{N_f} \|^2 \tag{13}$$

where $\tilde{\mathbf{x}}_{N_f}$ denotes the median filtered $\tilde{\mathbf{x}}$ for the filter length N_f. In the following section, we will demonstrate the choice of the optimum filter length using the above error function on the estimated VTEC values by applying the developed the regularized estimation algorithm of vertical total electron content for Kiruna, Kiev, Ankara and M. Dragot for the week of 23–28 April 2001 and discuss various properties and novelties of the new estimation procedure.

3. Results

[12] The regularized estimation method described in section 2 is applied to GPS data obtained from four GPS receiver stations, namely, Kiruna, Norway (67.32°N, 20.09°E), Kiev, Ukraine (50.22°N, 30.30°E), Ankara, Turkey (39.53°N, 32.45°E) and M. Dragot, Israel (31.35°N, 35.23°E). All of these stations are in the same time zone and they are roughly equidistant from each other in latitude. Selected data period is described in detail in the work of *Arikan et al.* [2003].

[13] In order to estimate the TEC values for the desired time duration, the parameters of the algorithm defined in section 2 have to be determined optimally. In the first part of this section, we will demonstrate how to choose these parameters and discuss their robustness. In the second part, we will apply the regularization algorithm with the chosen parameters to the GPS receiver station signals for desired time periods.

[14] According to the regularized estimation method in section 2, the algorithm has three main parameters that

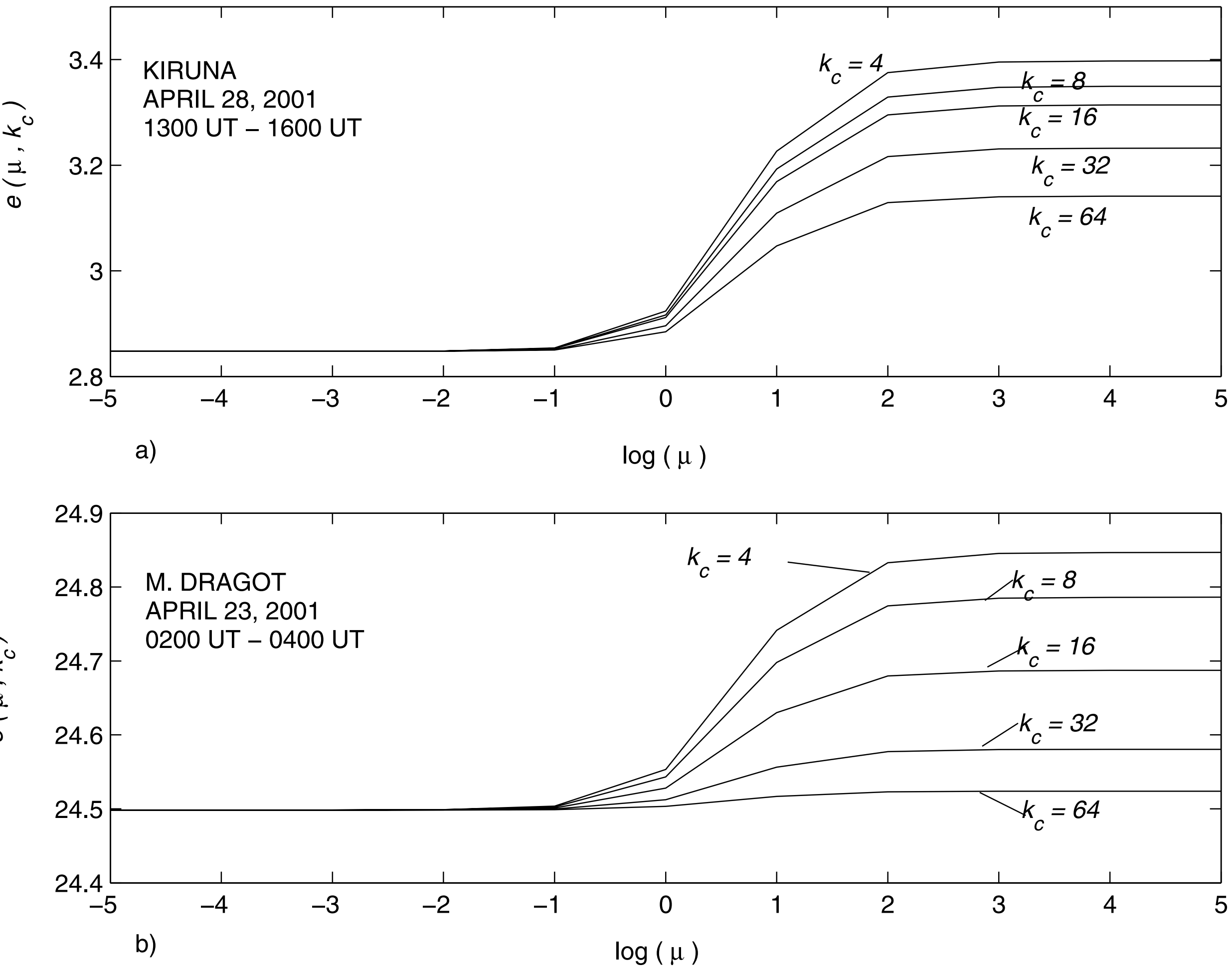

Figure 1. Error function to determine the optimum values of the regularization parameter, μ, and the cutoff frequency, k_c (a) for Kiruna on 28 April 2001 (1300–1600 UT) and (b) for M. Dragot on 23 April 2001 (0200–0400 UT).

needs to be determined optimally; the regularization (or smoothness) parameter, μ; the cutoff frequency, k_c; and the sliding window filter length, N_f. μ and k_c are defined in equation (7) and the error function for the optimal choice of these parameters is provided in equation (12). We have applied the estimation algorithm with various values of the parameters to the GPS signals from the four stations and an example of the error function is provided in Figure 1. In Figure 1a, the error function for an high latitude station, Kiruna, on the most positively disturbed day of the month of April 2001 is provided. Between 1300 and 1600 UT, the VTEC values deviate significantly from the quiet day structure due to the positive phase of the storm. In Figure 1b, the error function for a midlatitude latitude station, M. Dragot on the most negatively disturbed day of the month is given for 0200 UT to 0400 UT. This time period corresponds to rising of the sun combined with the negative phase of the storm. For all other locations, on other days and various time frames, the error function has similar behavior. The optimal choice of μ occurs at 0.1 where the error curve starts to increase with a significant slope for all values of the cutoff frequency k_c. Higher values of μ cause smoother TEC estimates and more regularization. Since the penalty function starts to dominate the cost function in equation (7), the smoother estimates with high values of μ may not follow the desired features of TEC data. For higher values of k_c, the estimates follow the local trends in the data very well, but since the cutoff frequency increases, more high frequency components are included. Thus the estimates look more jagged and there may be undesired jumps and irregularities. In order to have a

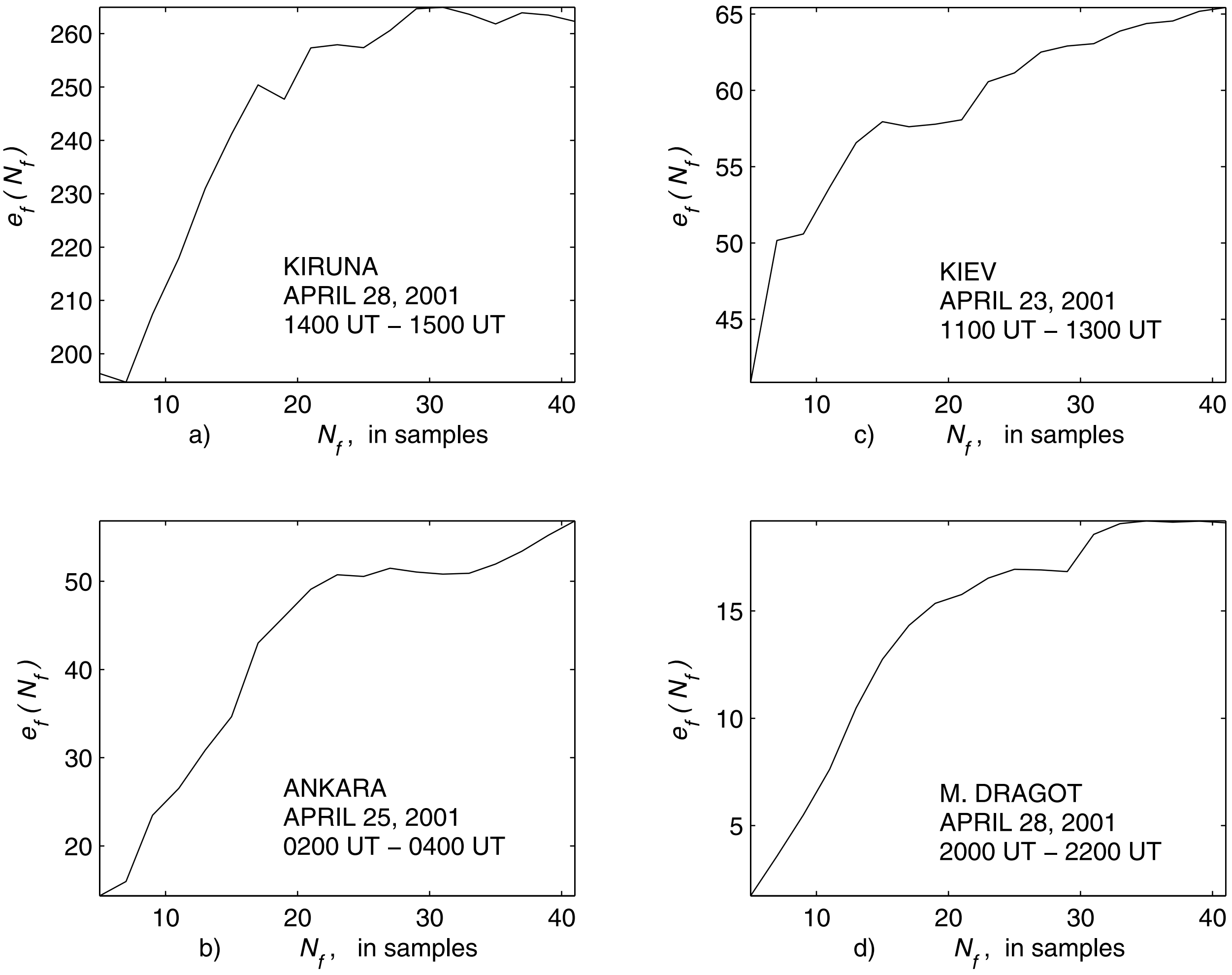

Figure 2. Error function to determine the optimum value of the sliding window median filter length, N_f: (a) Kiruna, 28 April 2001, 1400–1500 UT; (b) Kiev, 23 April 2001, 1100–1300 UT; (c) Ankara, 25 April 2001, 0200–0400 UT; and (d) M. Dragot, 28 April 2001, 2000–2200 UT.

trade off, we choose the lowest possible smoothness parameter and a higher value of cutoff frequency. Thus for all stations, for all days, and for all time frames, the optimum choice of μ is 0.1 and k_c is 8. The remedy for this choice of regularization parameters is to employ the sliding window median filter to improve the smoothness of the data as mentioned in the previous section.

[15] The sliding window median filter is a nonlinear filter. We expect that at the optimum value of the filter length, the output should follow all the local trends of the data closely, yet the filtered output should be free of the undesired irregularities. The optimum choice of the filter length is discussed in equation (13). The error function for to determine the optimum value of the sliding window median filter length, N_f is plotted in Figure 2a for Kiruna on 28 April 2001 between 1400 and 1500 UT, in Figure 2b for Kiev, on 23 April 2001 between 1100 and 1300 UT, in Figure 2c for Ankara, on 25 April 2001 between 0200 and 0400 UT, and in Figure 2d for M. Dragot, on 28 April 2001 between 2000 and 2200 UT. The optimum choice of median filter length can be obtained at a point where the error function settles to a plateau. As can be observed from Figure 2 and other plots we have obtained for the above mentioned dates and locations for various time periods, filter length, N_f = 25 to 31, is appropriate for this data set for a minimum of one hour time duration. This filter length in samples corresponds to 12.5–15.5 min.

[16] The optimum parameters for the regularized TEC estimation algorithm are then chosen as μ = 0.1, k_c =

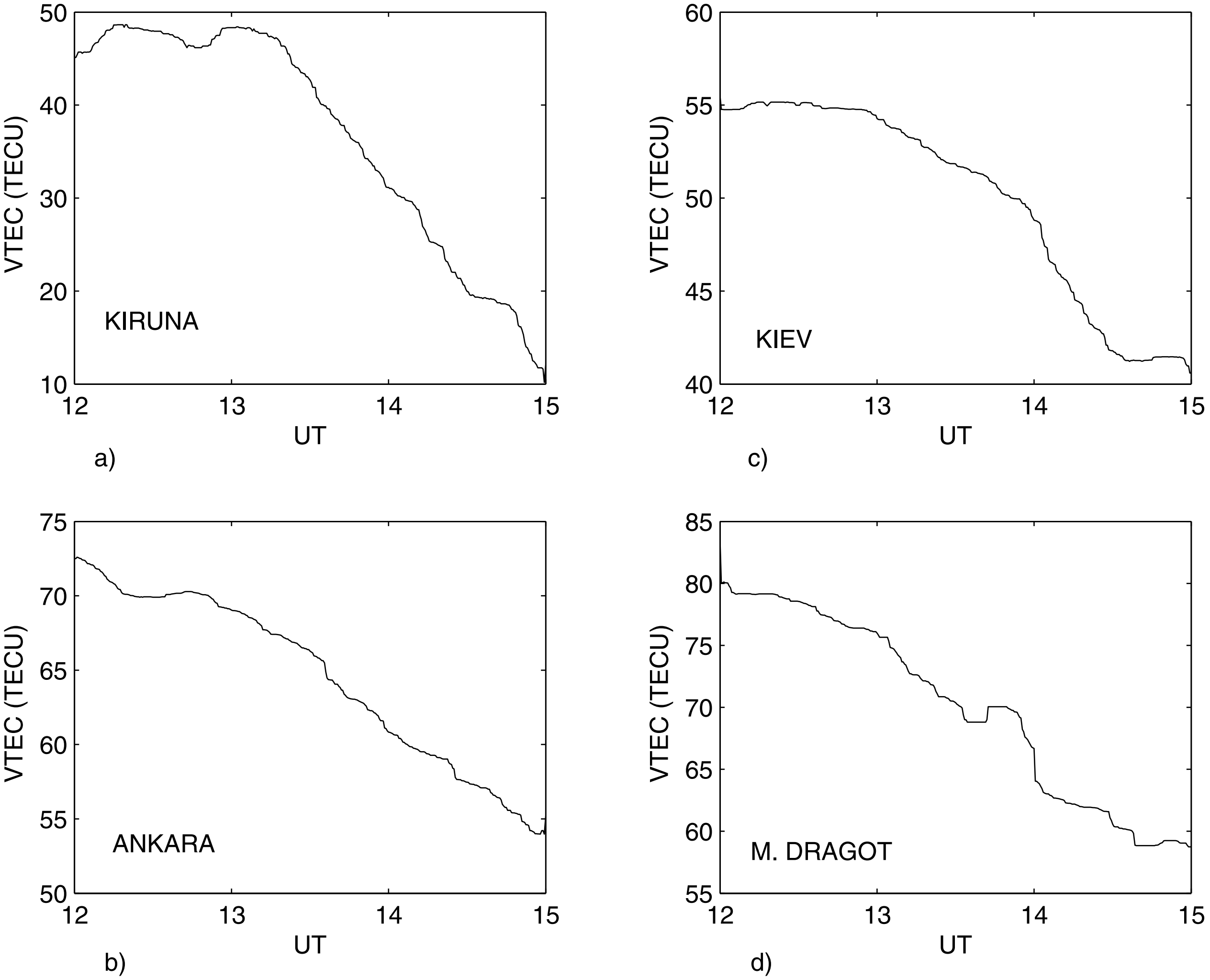

Figure 3. Estimated VTEC values for 28 April 2001 between 1200 and 1500 UT for (a) Kiruna, (b) Kiev, (c) Ankara, and (d) M. Dragot.

8 and $N_f = 29$ samples. It is assumed that the same parameter set can be used for all the stations, both for the disturbed and quiet days and for time durations of at least one hour. The robustness of these parameters denotes the power of the estimation algorithm.

[17] The estimated and median filtered VTEC values for Kiruna, Kiev, Ankara and M. Dragot are provided in Figures 3 and 4. In Figure 3, the VTEC values are plotted for 28 April 2001 between 0400 and 0700 UT. From Figure 3, the effect of the irregularities in the TEC values due to positive disturbance can easily be observed in all stations, especially for those in higher latitudes. In Figure 4, the plots are provided for 23 April 2001 (solid line) and 25 April 2001 (dashed line) between 0400 and 0700 UT for Kiruna and Kiev and between 0900 and 1200 UT for Ankara and M. Dragot. The negative phase of the ionospheric storm on 23 April 2001 can be observed in Kiruna and Kiev even in the first hours of the day. For Ankara and M. Dragot, the ionospheric disturbance shows its effect at later hours of the day starting about 0800 UT. When compared with the quiet day values, the total electron content is reduced in all stations. For both days and all the stations, the TEC values decrease with increasing latitude. The high time resolution of the regularized estimation algorithm allows the observation of short timescale variations in TEC.

[18] Finally, we would like to compare the estimated TEC values for a shorter time duration with the ones estimated for the 24 hour period. In Figures 5a and 5b,

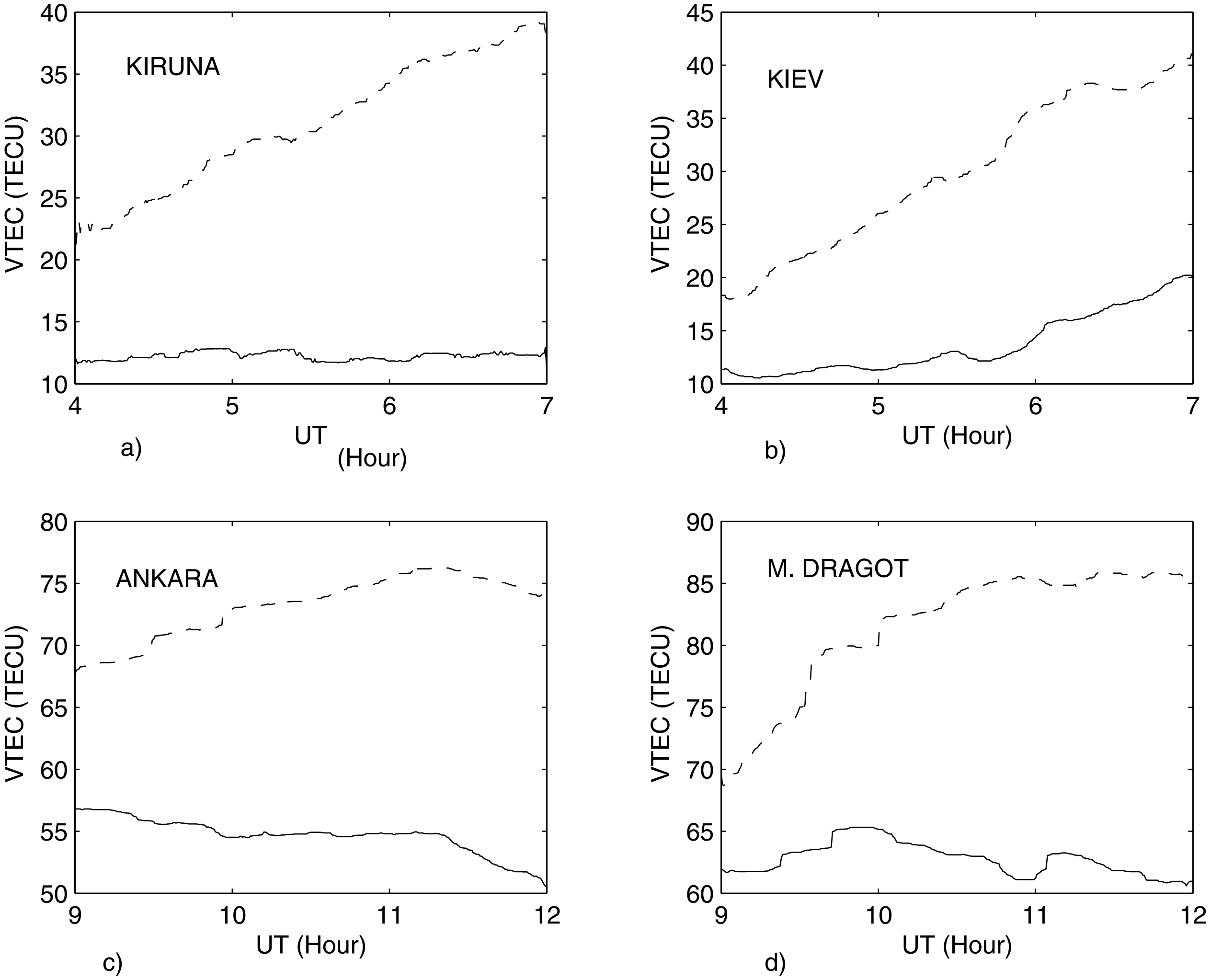

Figure 4. Estimated VTEC values for 23 April 2001 (solid line) and for 25 April 2001 (dashed line) for (a) Kiruna and (b) Kiev between 0400 and 0700 UT and for (c) Ankara and (d) M. Dragot between 0900 and 1200 UT.

the solid line represents the estimated VTEC values on 28 April 2001 in Kiruna. Owing to the effect of positive phase of the ionospheric storm, a sharp decrease is observed between 1300 and 1600 UT, in Kiruna. The asterisk line in Figures 5a and 5b denotes the estimated VTEC values for shorter time periods as denoted in the figure caption. It is observed from Figures 5a and 5b that the regularization algorithm is very successful in estimating the VTEC values for one hour, two hours and three hours periods. In Figure 5c, the VTEC values for the three hour period between 1300 and 1600 UT (solid line) and one hour period between 1400 and 1500 UT (asterisk line) are provided. The minimum time period for reliable and robust estimation of VTEC can be determined using the cutoff wavelength of the smoothing function defined in equations (2) to (6). The period of estimation should be longer than and a multiple of N/k_c, for the desired sample number N. The penalty function uses samples up to the cutoff frequency k_c and as k_c increases, a smoother estimate is obtained as shown in Figure 1. Yet, as discussed before due to higher frequency components, the estimates look more jagged. Therefore for this data set, we determined lowest possible smoothness parameter and a higher value of cutoff should be appropriate. In order to reduce the undesired irregularities, we utilized a sliding window median filter. For one hour of data, and $k_c = 8$, the optimum length of the median filter was determined to

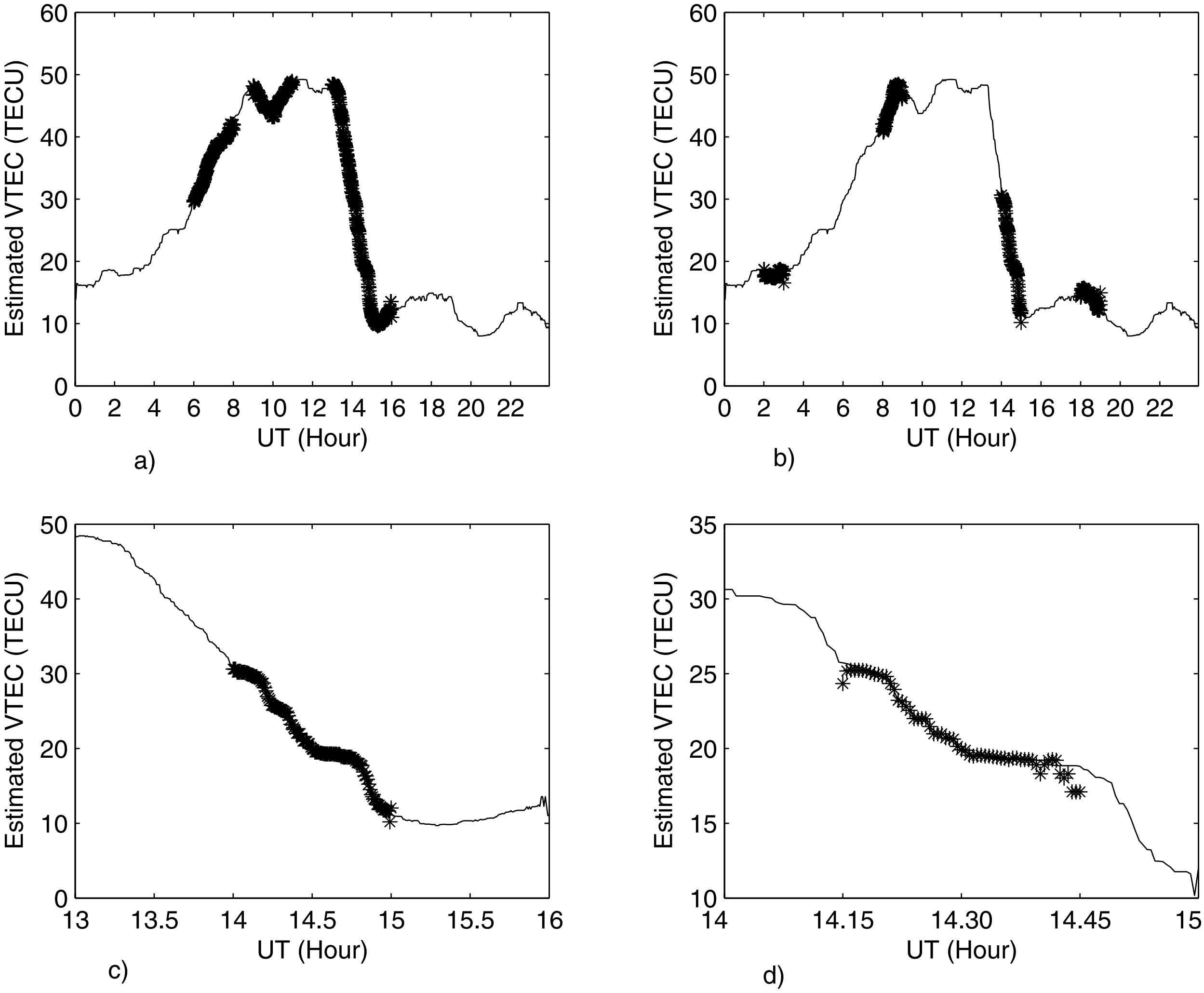

Figure 5. The estimated VTEC values for Kiruna, 28 April 2001: (a) 24 hour period (solid line) and 0600–0800, 0900–1100, and 1300–1600 UT (asterisks); (b) 24 hour period (solid line) and 0200–0300, 0800–0900, 1400–1500, and 1800–1900 UT (asterisks); (c) 1300–1600 UT (solid line) and 1400–1500 UT (asterisks); and (d) 1400–1500 UT (solid line) and 1415–1445 UT (asterisks).

be between 10 and 15 min (Figure 2). Thus the shortest time interval that can be investigated seems to be twice the longest constraint from the median filter 30 min. In Figure 5d, we plotted a half hour interval between 1415 and 1445 UT (asterisk line) where the solid line denotes the VTEC between 1400 and 1500 UT. From this figure and our other investigations on different parts of data set, we observed that edge effects due to smoothing function in half hour estimates cause mismatches to the one hour estimates. Thus we conclude that given the set of parameters for regularization, smoothing cutoff, and median filter length, the optimum robust shortest time period that we can use the regularization algorithm discussed in this paper is one hour.

4. Conclusions

[19] In this paper, a novel regularization technique which combines signals from all GPS satellites within the vicinity of an earth based GPS receiver, is developed to estimate the vertical TEC values for any desired time period without missing any important features in temporal or spatial domain. The algorithm is based on the minimization of a cost function including a high pass

penalty filter and detrend processing. The developed algorithm is applied to GPS data for four GPS receiver stations in the same time zone located from north to south for the solar maximum week of 23–28 April 2001. It is observed that the new method is very successful in estimating TEC for both quiet and disturbed days and for any desired time frame. The robust parameter set required by the regularization and smoothing procedure, can be used for all GPS station locations, for all days both quiet and disturbed. The minimum time period that the algorithm can run reliably is found to be one hour. It is observed that the developed estimation algorithm is very accurate in representing the sharp and sudden temporal variations in the ionosphere due to its 30 s time resolution and capability to focus in any desired time frame.

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