Regularized Estimation of TEC from GPS Data (Reg-Est)

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Outline

- Introduction
- Regularized Estimation Technique (Reg-Est)
- Preprocessing of GPS Data
- Computation of TEC
  - Determination of Reg-Est Parameters
  - Comparisons with IRI, JPL, CODE, ESA and UPC
- Conclusion

Introduction

- Total Electron Content (TEC) is defined as number of free electrons in a unit area along ray path.
- Using TEC values, short and long term variations in the ionosphere and ionospheric disturbances can be analyzed.
- Global Positioning System (GPS) satellites transmit two simultaneous PRN signals in L-band whose carrier frequencies are 1575.42 MHz and 1227.60 MHz, respectively.
- Earth based GPS receivers record these signals as Pseudo Range and Relative Phase.
- Global TEC values can be estimated using either the Pseudo Range or Relative Phase or a combination of these two recordings.

Introduction (cont.)

- **The GPS constellation is constituted by a network of 24 satellites orbiting at 20.200 km with respect to the Earth surface. The satellites are evenly distributed within 6 orbitals planes inclined 55° with respect to the Earth's equator and equally spaced at 60°. Each satellite has a period of 12 hours.**

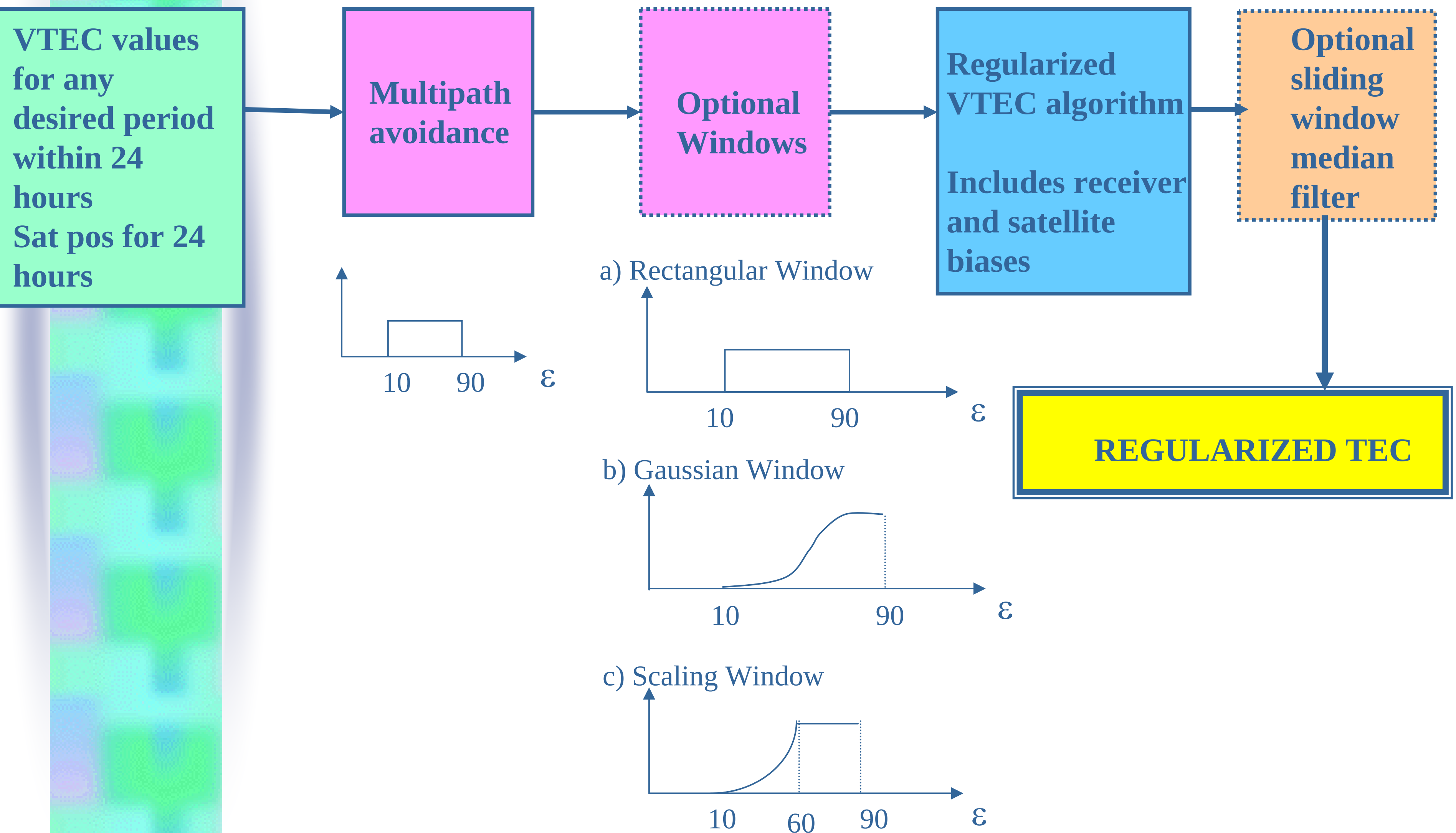
Introduction (cont.)

- In various studies in the literature, vertical TEC (VTEC) values are estimated assuming that
  - Ionosphere is distributed homogeneously around local zenith of the receiver
  - Ionosphere is stable during at least 5 to 15 minutes
  - The satellite which is closest to the local zenith is chosen.
- Regularized VTEC Estimation technique (Reg-Est) incorporates all the available GPS signals recorded by the receiver for the 24 hours from all the satellites.
- VTEC values, computed from a desired time period within 24 hour period and from all satellites, are combined using the Least Squares method and the estimation is performed using a two-step regularization method.

Introduction (cont.)

- When the regularized estimation results are compared with those from IRI-2000, JPL, CODE, UPC and ESA, best accordance is observed with JPL and CODE estimates.
- IRI computations usually provide a better fit for the night values.
- IRI estimates are highly dependent on Sunspot Number (SSN).
- Results from the Reg-Est are highly accurate in detecting disturbances and irregularities for various time scales and stations.

Regularized Estimation Technique (Reg-Est)



Reg-Est (cont.)

A set of measurements obtained from ith satellite:

$$\mathbf{x}_i = [x_i(0) \; \ldots \; x_i(n) \; \ldots \; x_i(N-1)]^T$$

$1 \leq i \leq M$ (total number of satellites); $0 \leq n \leq N-1$ (N =2x60x24=2880)

An optional weighting function $\mathbf{w}_i$ can also be defined as

$$\mathbf{w}_i = [0 \; \ldots \; 0 \;\; w_i(1) \; \ldots \; w_i(N_{i,m}) \;\; 0 \; \ldots \; 0]^T$$

$N_{i,m}$= the number of non-zero measurements from the ith satellite within the 24 hour period.

Reg-Est (cont.)

The cost function which includes $\mathcal{L}_2$ norm between the estimated and computed VTEC values summed over all satellites plus a detrended high pass penalty filter multiplied by a regularization parameter μ:

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

where $\mathbf{W}_m$=diag($\mathbf{w}_m$), and $\mathbf{H}(k_c)$ is the high pass penalty function. $\mathbf{H}(k_c)$ is designed to pass all signals up to a cutoff frequency, k_c.

$(\mathbf{x}-a\mathbf{t})$ = detrend operator

Reg-Est (cont.)

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 $\nabla_{\mathbf{x}} J_{\mu,k_c}(\mathbf{x}) = \mathbf{0}$ and $\partial J/\partial a = 0$.

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

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

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

Reg-Est (cont.)

The estimate of x, $\tilde{\mathbf{x}}$, is obtained by

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

The high pass penalty filter is Toeplitz for a 24 hour period.

The success of the estimation depends on optimum choices of the estimation parameters, μ and k_c.

The optional sliding window median filter follows the data structure and further smooths irregularities due to processing. The sliding window median filter length, N_f.

Reg-Est (cont.)

- **F. Arikan, C.B. Erol and O. Arikan,`Regularized estimation of vertical total electron content from Global Positioning System data´, *Journal of Geophysical Research-Space Physics*, 108(A12), 1469 - 1480, 2003.**
- **F. Arikan, C.B. Erol, and O. Arikan, `Regularized estimation of VTEC from GPS data for a desired time period´, *Radio Science*, 39(6), RS6012, 2004.**
- **F. Arikan, O. Arikan, and C. B. Erol (2007), Regularized estimation of TEC from GPS data for certain mid-latitude stations and comparison with the IRI model, *Adv. in Space Res*., 39, 867–874, doi:10.1016/j.asr.2007.01.082**
- **C.B. Erol and F. Arikan, `Statistical analysis of the ionosphere using GPS signals´, *Journal of Electromagnetic Waves and Applications, JEMWA*, 19(3), 373 - 387, 2005.**
- **H. Nayir, Ionospheric Total Electron Content Estimation Using GPS Signals, (in Turkish) *Master's Thesis, Hacettepe University*, Ankara, Turkey, 2007.**

Preprocessing of GPS Data

SAT-1 → P2, P1 → STEC → VTEC

SAT-2 → P2, P1 → STEC → VTEC

STEC computation from pseudorange (PR) only

STEC computation from carrier phase corrected (PR)

$A = 40.3 \text{ m}^3/\text{s}^2;\ f_1 = 1575.42 \text{ MHz};\ f_2 = 1227.60 \text{ MHz}$

$$\text{VTEC} = \text{STEC}/M(\epsilon)$$

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

$\epsilon =$ elevation angle; $R =$ effective earth radius; $h = 428.8$ km

SAT-12 → P2, P1 → STEC → VTEC

- ✓Compute VTEC for desired time period (24 hours : 2880 samples)
- ✓Obtain satellite positions and biases for 24 hours
- ✓Interpolate satellite positions for every 30 second data
- ✓Convert to local coordinates

Computation of TEC

Stations:

For October, 2003 : 10-11 (Quiet), 27-31 (Disturbed)

- **Zelenchukskaya, Russia (43.17°N, 41.33°E)**
- **Trabzon, Turkey (40.59°N, 39.46°E)**
- **Ankara, Turkey (39.53°N, 32.45°E)**
- **Istanbul, Turkey (41.06°N, 29.01°E)**
- **Gebze, Turkey (40.47°N, 29.27°E)**
- **Ohrid, Macedonia (41.07°N, 20.47°E)**
- **Sofia, Bulgaria (42.33°N, 23.23°E)**
- **Nicosia, Cyprus (35.08°N, 33.23°E)**

For April, 2001 : 25 (Quiet), 23, 25 (Disturbed)

- **Kiruna, Norway (67.32°N, 20.09°E)**
- **Kiev, Ukraine (50.22°N, 30.30°E)**
- **Ankara, Turkey (39.53°N, 32.45°E)**
- **M. Dragot, Israel (31.35°N, 35.23°E)**

Determination of Estimation Parameters

- For optimum choice of μ and k_c, define an error function:

$$e(\mu, k_c) = \sum_{i=1}^{M} ||\mathbf{W}_i(\tilde{\mathbf{x}} - \mathbf{x}_i)||^2$$

- Larger $\mu \rightarrow$ more regularization $\Rightarrow$ smoother estimates BUT may not follow the desired features in the data!

- Smaller $\mu \rightarrow$ and Larger $k_c \rightarrow$ less regularization $\Rightarrow$ jagged estimates BUT follows the local trends in the data!

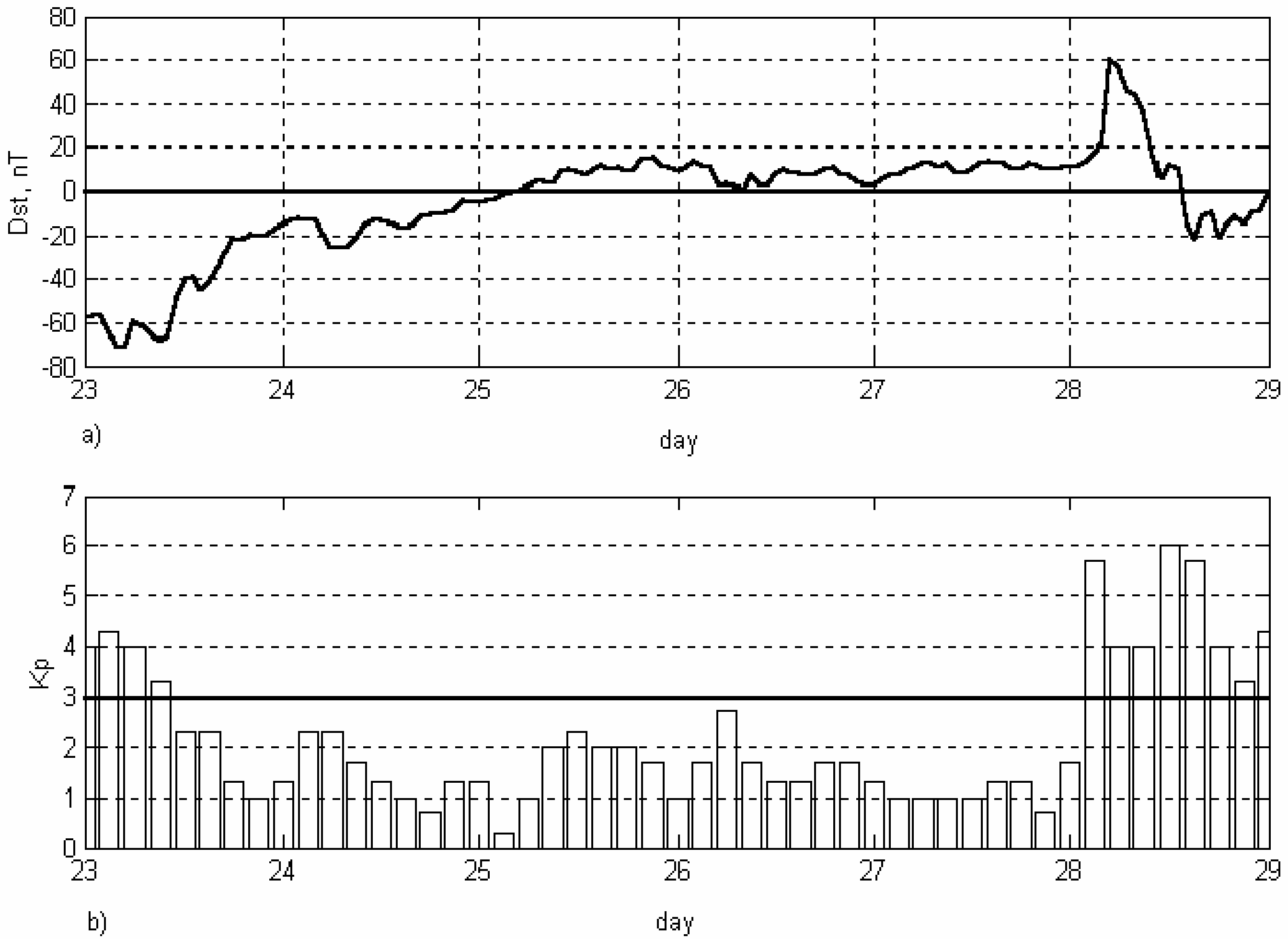
Determination of Estimation Parameters

- Reduce the jagged estimates with undesired jumps using an optional sliding window median filter. For optimum length of median filter, N_f define error function:

$$\text{med error}(N_f) = ||\tilde{\mathbf{x}} - \tilde{\mathbf{x}}_{N_f})||^2$$

Computation of TEC (cont.)

D_{st} and K_p Variation During April 23 – 28, 2001 Period



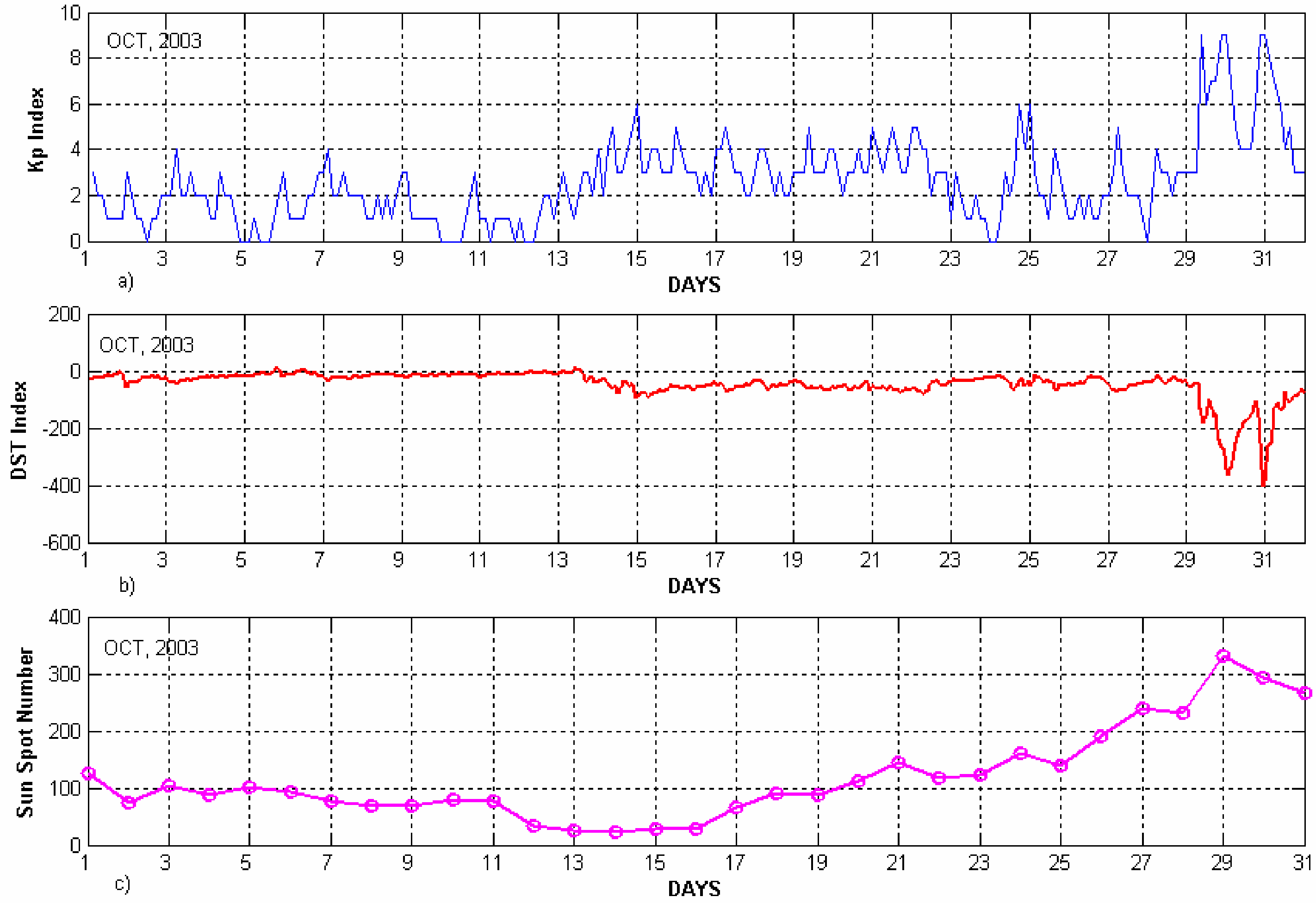
Computation of TEC (cont.)

- **April 23, 2001**
  Negatively Disturbed
- **April 25, 2001**
  Quiet Day
- **April 28, 2001**
  Positively Disturbed

- Ionospheric Dispatch Center (IDCE)
  www.cbk.waw.pl/rwc/idce.html

Computation of TEC (cont.)

D_{st} , K_p and Sunspot Number Variation During October 2003



Computation of TEC (cont.)

- **October 10, 11 2003**
  Quiet Day
- **October 27, 28, 29 2003**
  Positively Disturbed
- **October 30, 31 2003**
  Negatively Disturbed

- Ionospheric Dispatch Center (IDCE)
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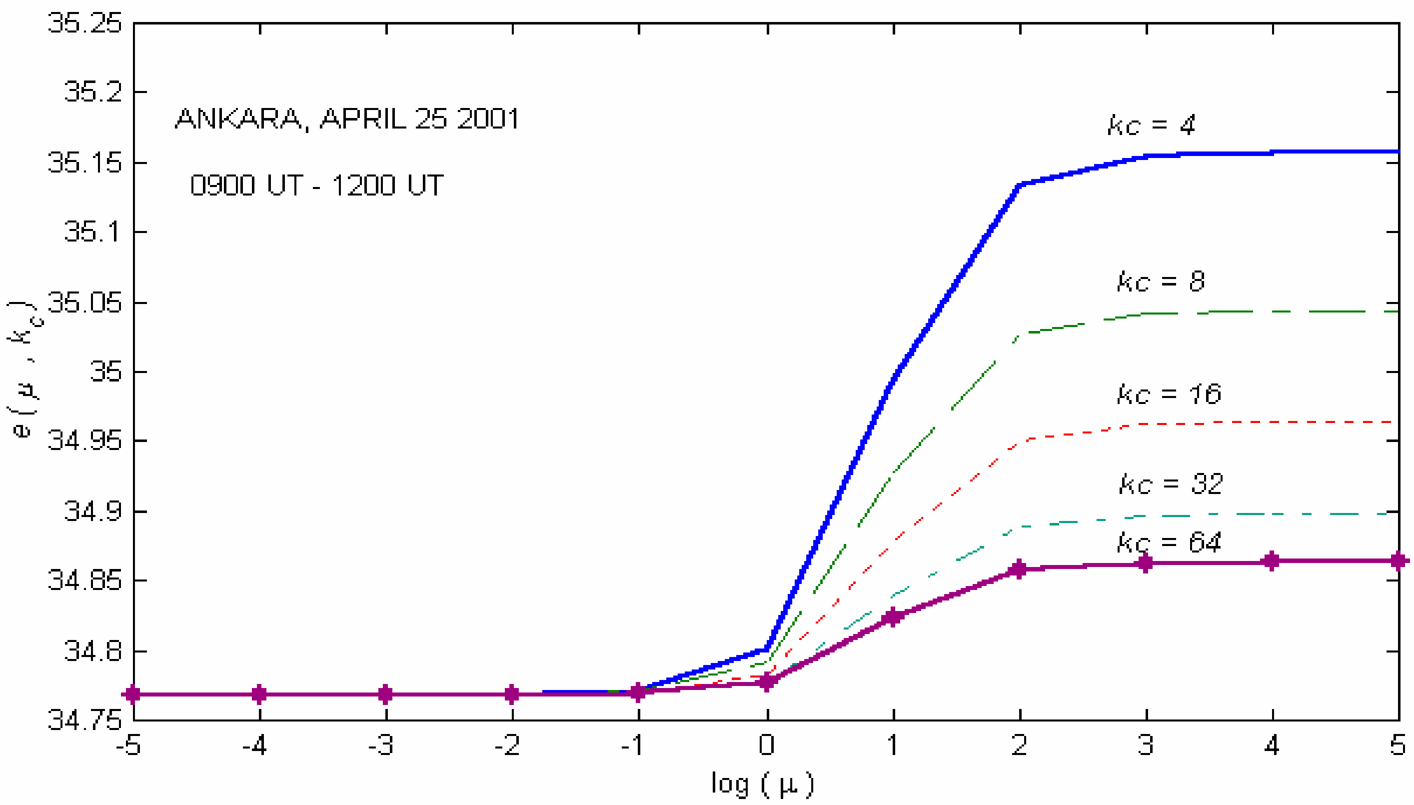
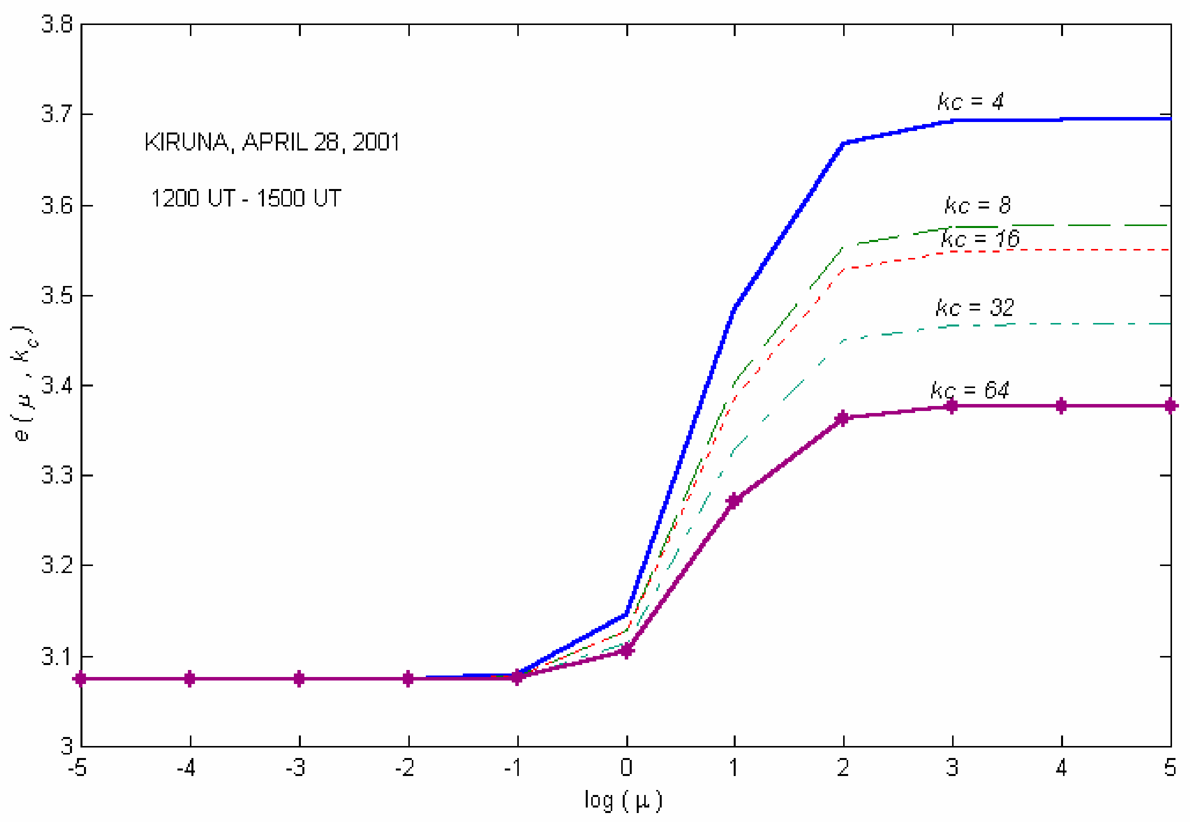
Determination of Estimation Parameters



Best choice: $\mu = 0.1$ and $k_c = 8$

Determination of Estimation Parameters



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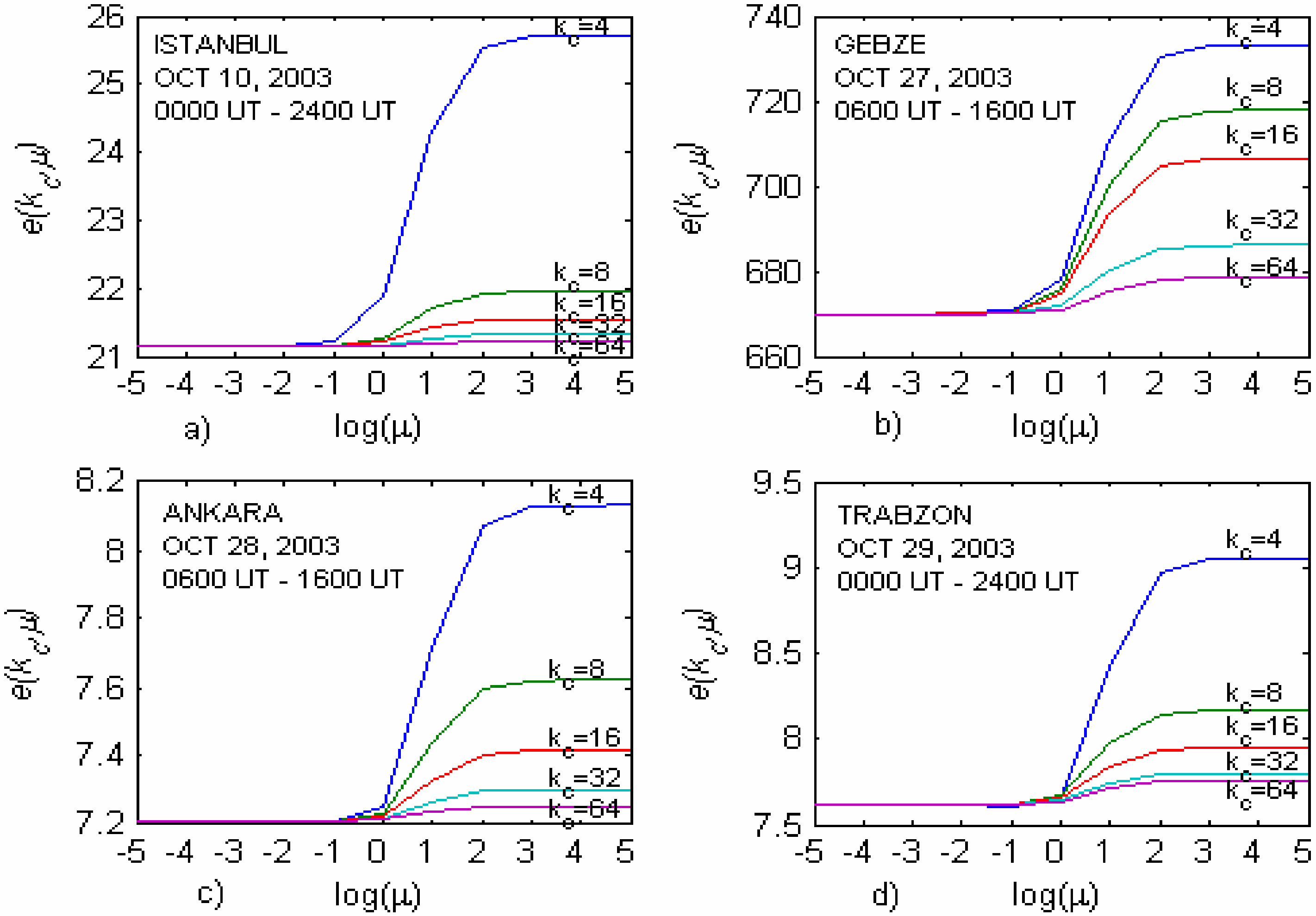

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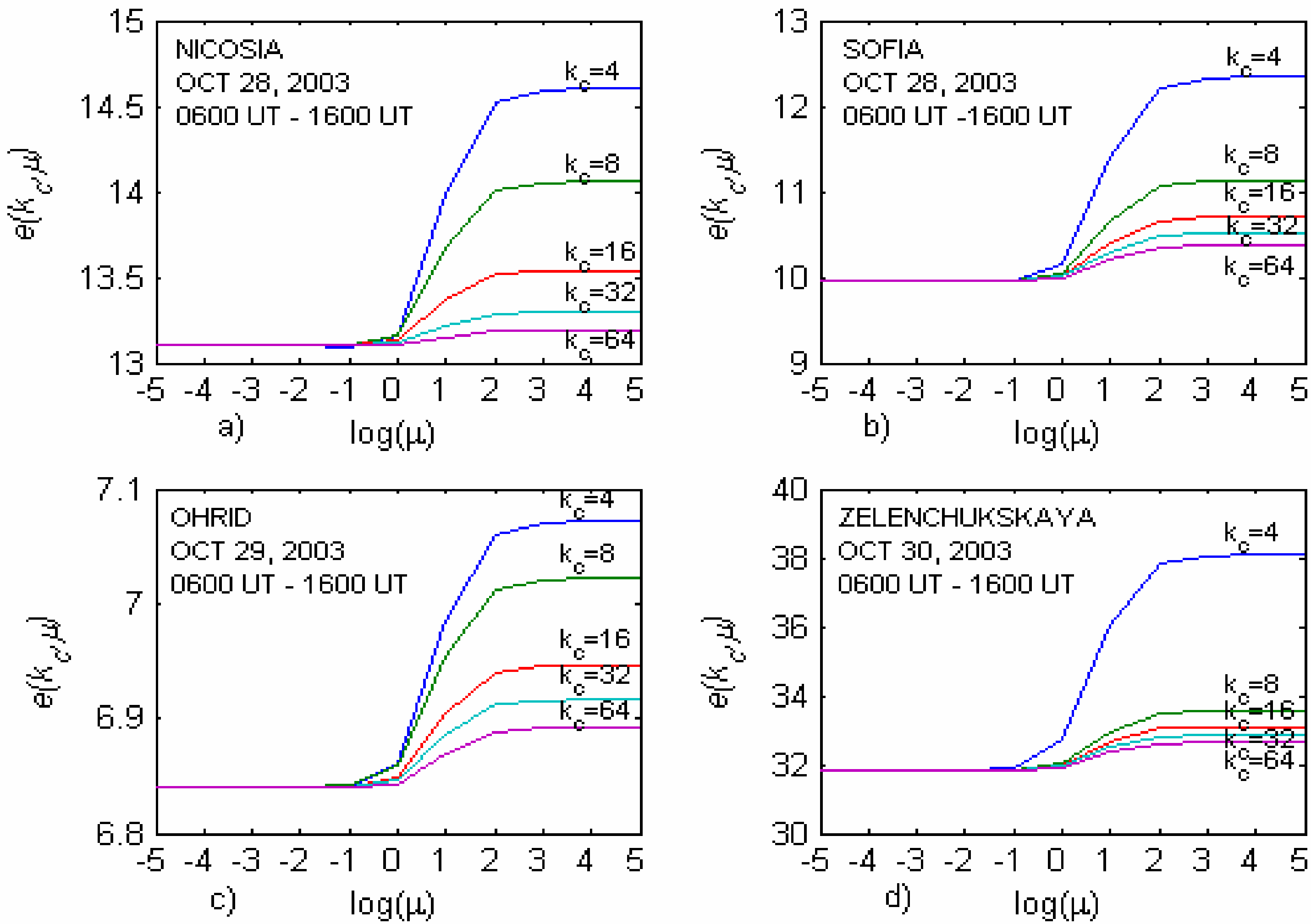

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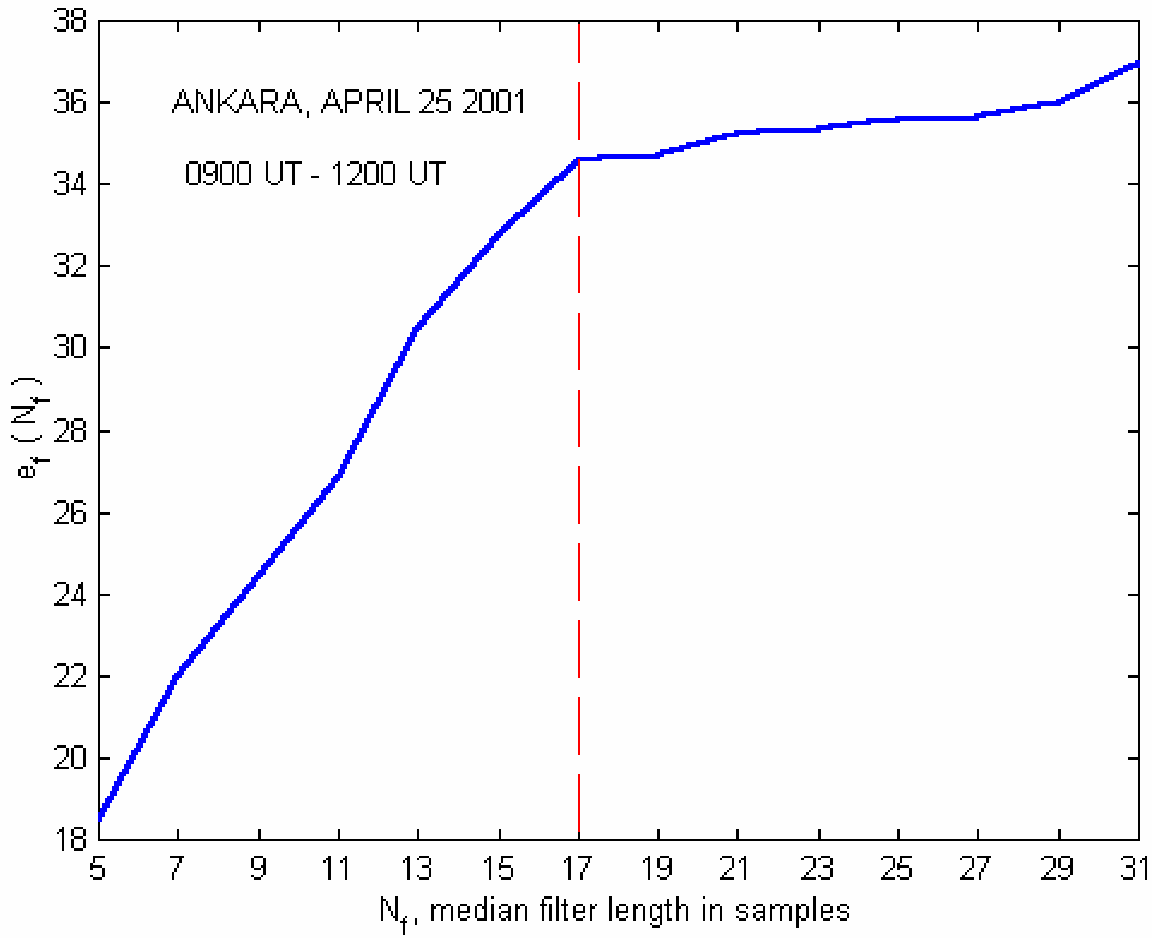

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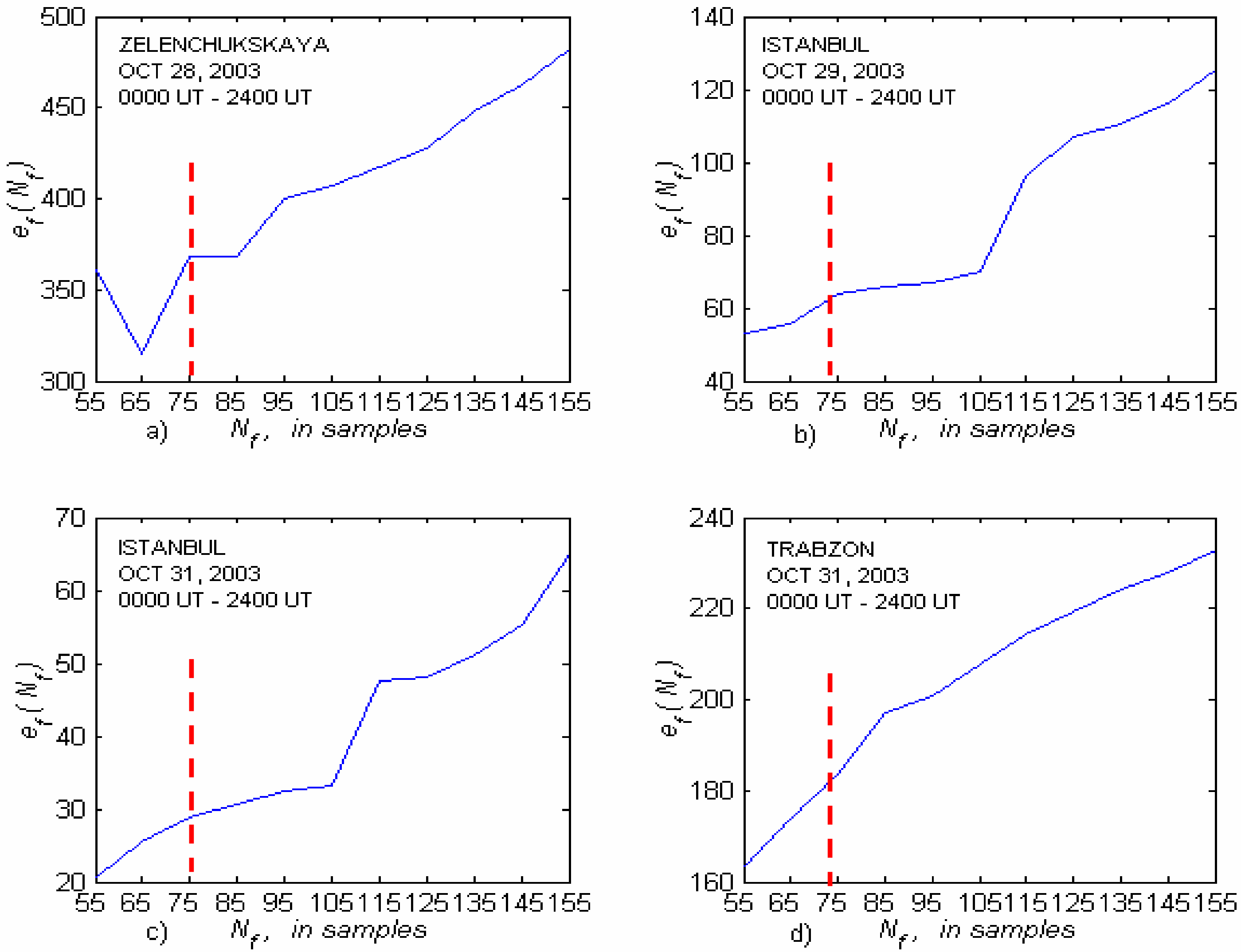

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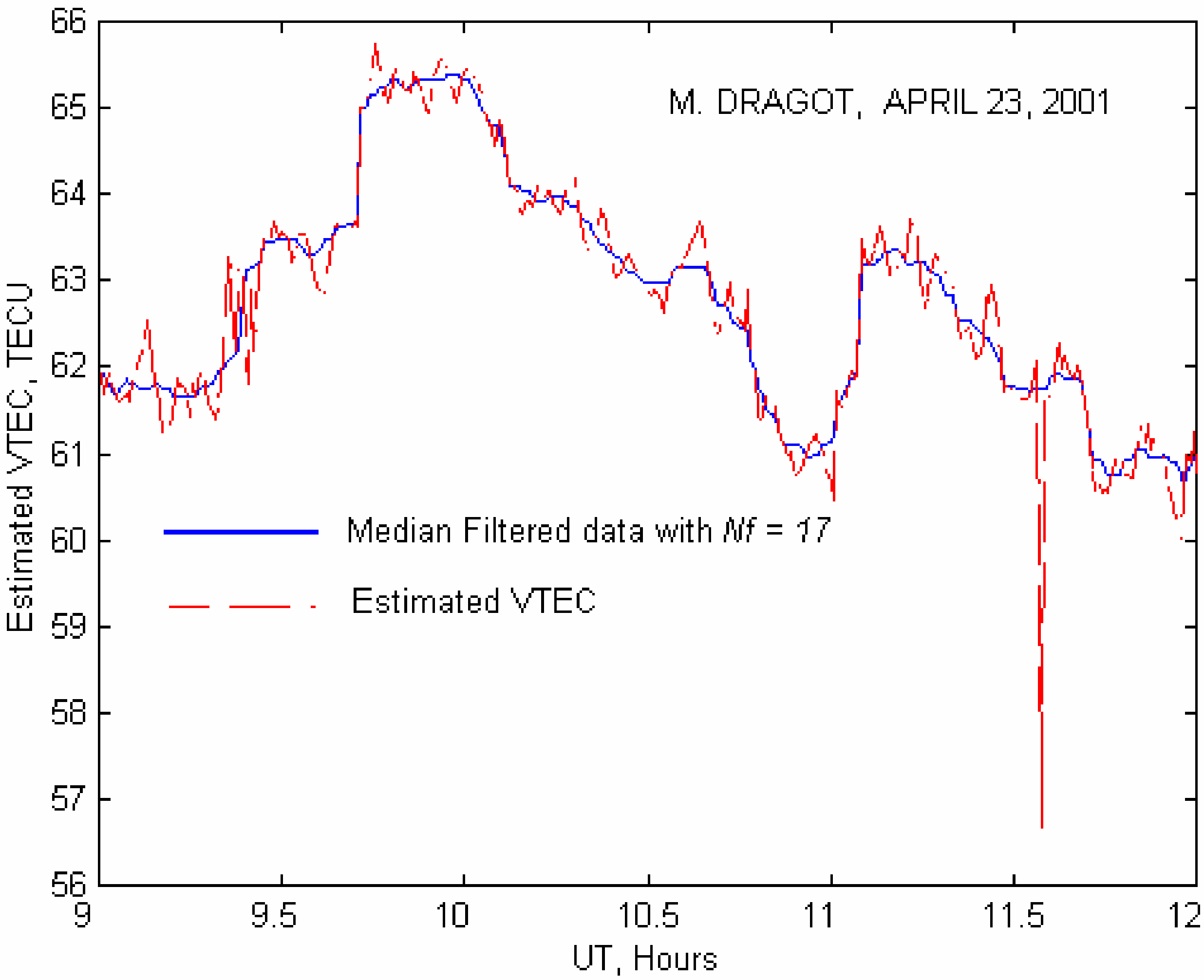


Comparisons with IRI, JPL, CODE, ESA and UPC

- **JPL-GNISD** provides global ionospheric maps generated on an hourly and daily basis at Jet Propulsion Laboratory (JPL) Pasadena, California, USA using data from up to 100 GPS sites of the IGS and other institutions (http://iono.jpl.nasa.gov)
- **CODE,** Center for Orbit Determination in Europe, University of Berne, Switzerland derives 12 2-hour sets of 149 ionosphere parameters per day from GPS data of IGS network.

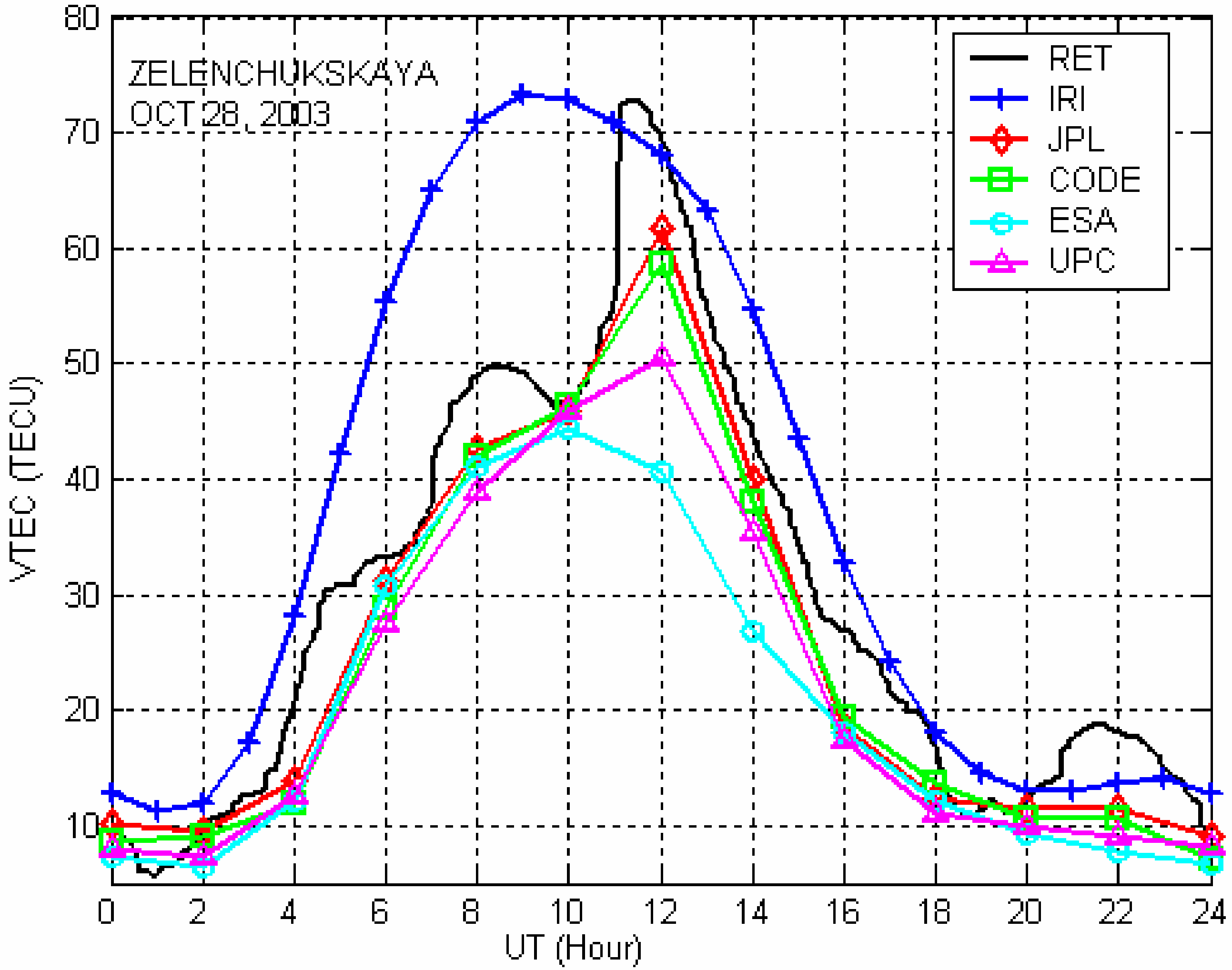
  (http://www.aiub.unibe.ch/ionosphere.html)
- **ESA/ESOC** model contains 2-dimensional TEC maps from the European Space Operations Center (ESOC) of European Space Agency (ESA), Darmstadt, Germany

  (http://nng.esoc.esa.de/gps/ionmon.html)
- **gAGE/UPC** global ionospheric maps are generated by Polytechnical University of Catalonia, Barcelona, Spain (UPC)

  (http://maite152.upc.es/~ionex/gAGE_dip/gAGE_dip.html)
- **IRI – 2001** is obtained from

  (http://nssdc.gsfc.nasa.gov/space/model/models/iri.html)

Comparisons with IRI, JPL, CODE, ESA and UPC



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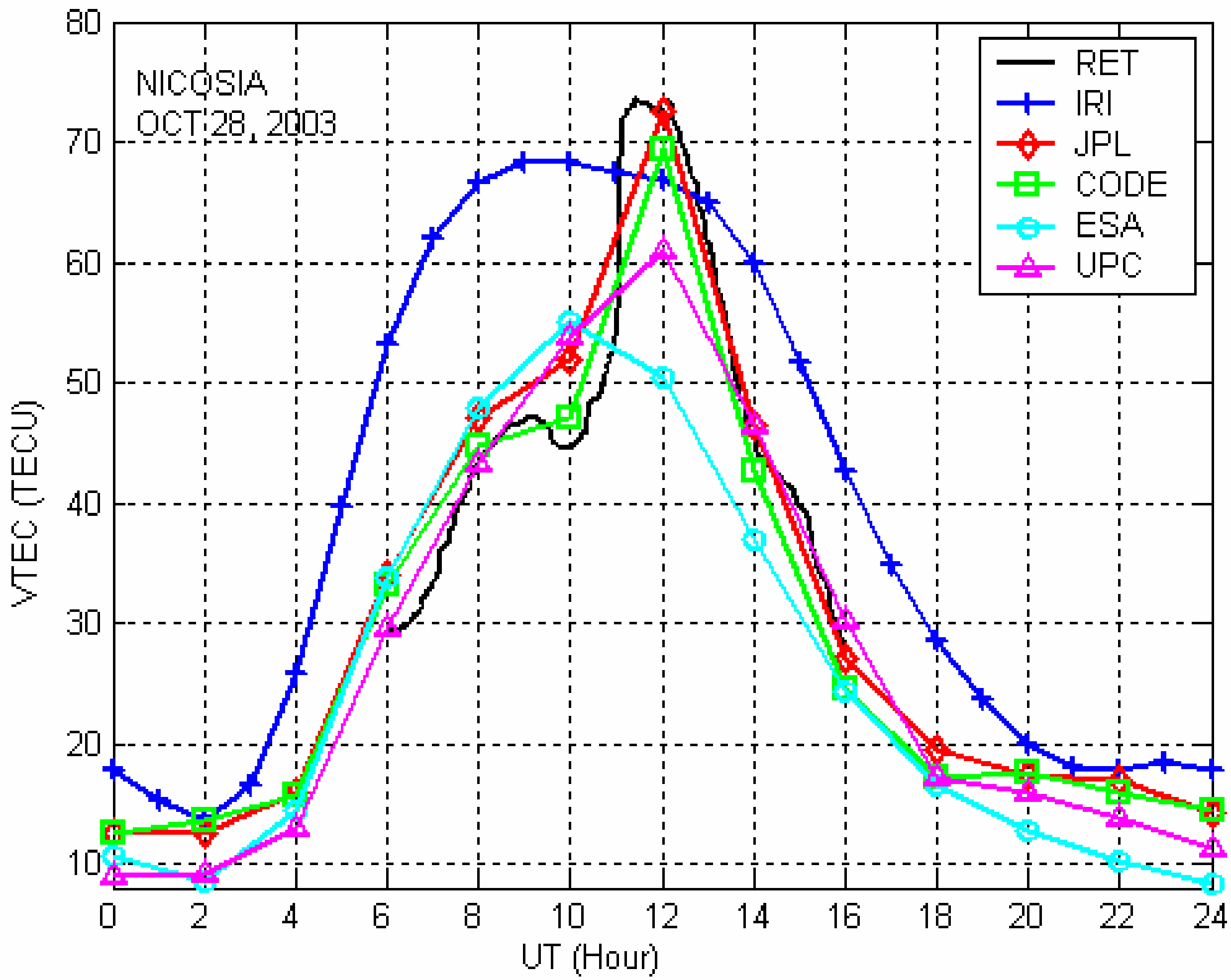

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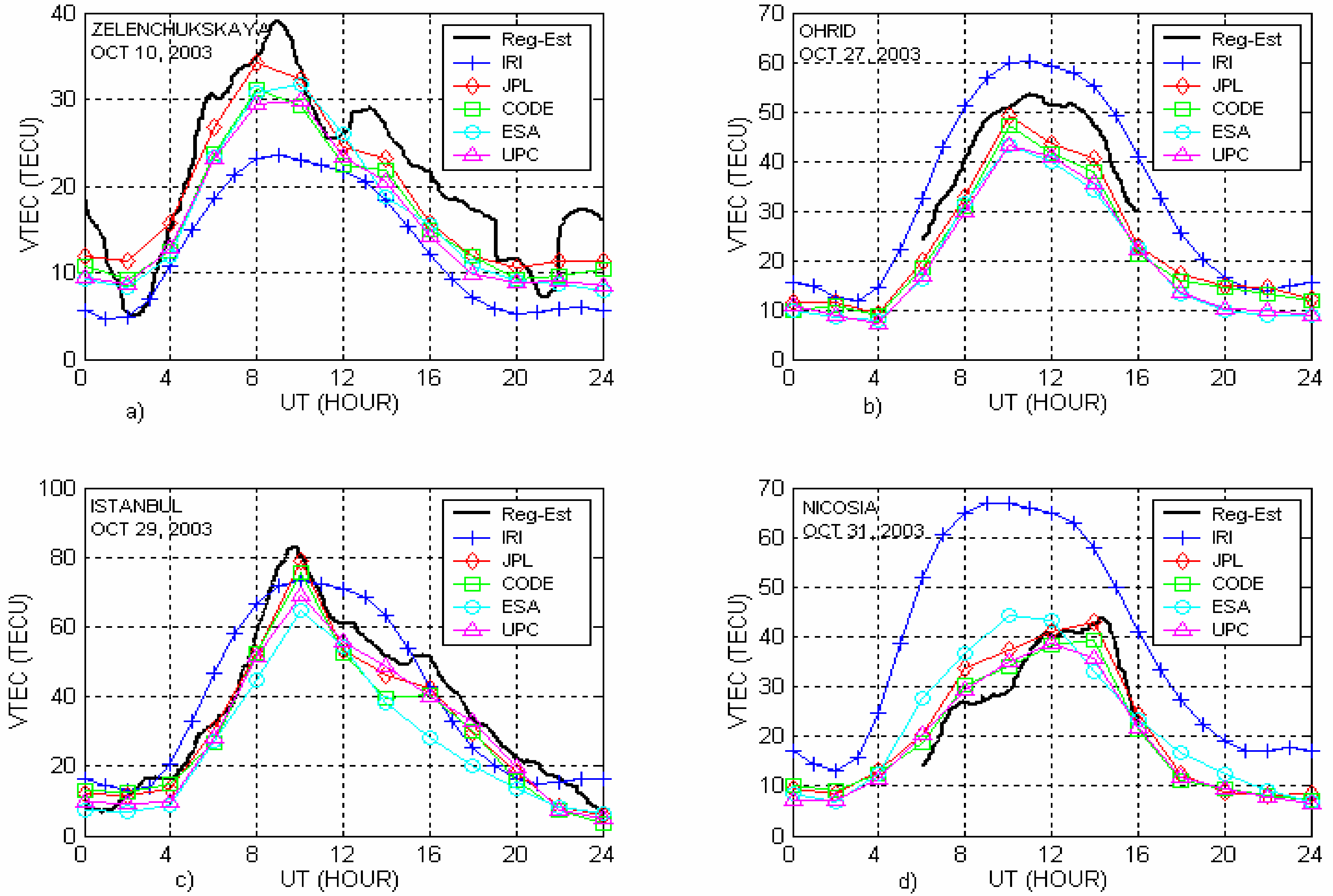

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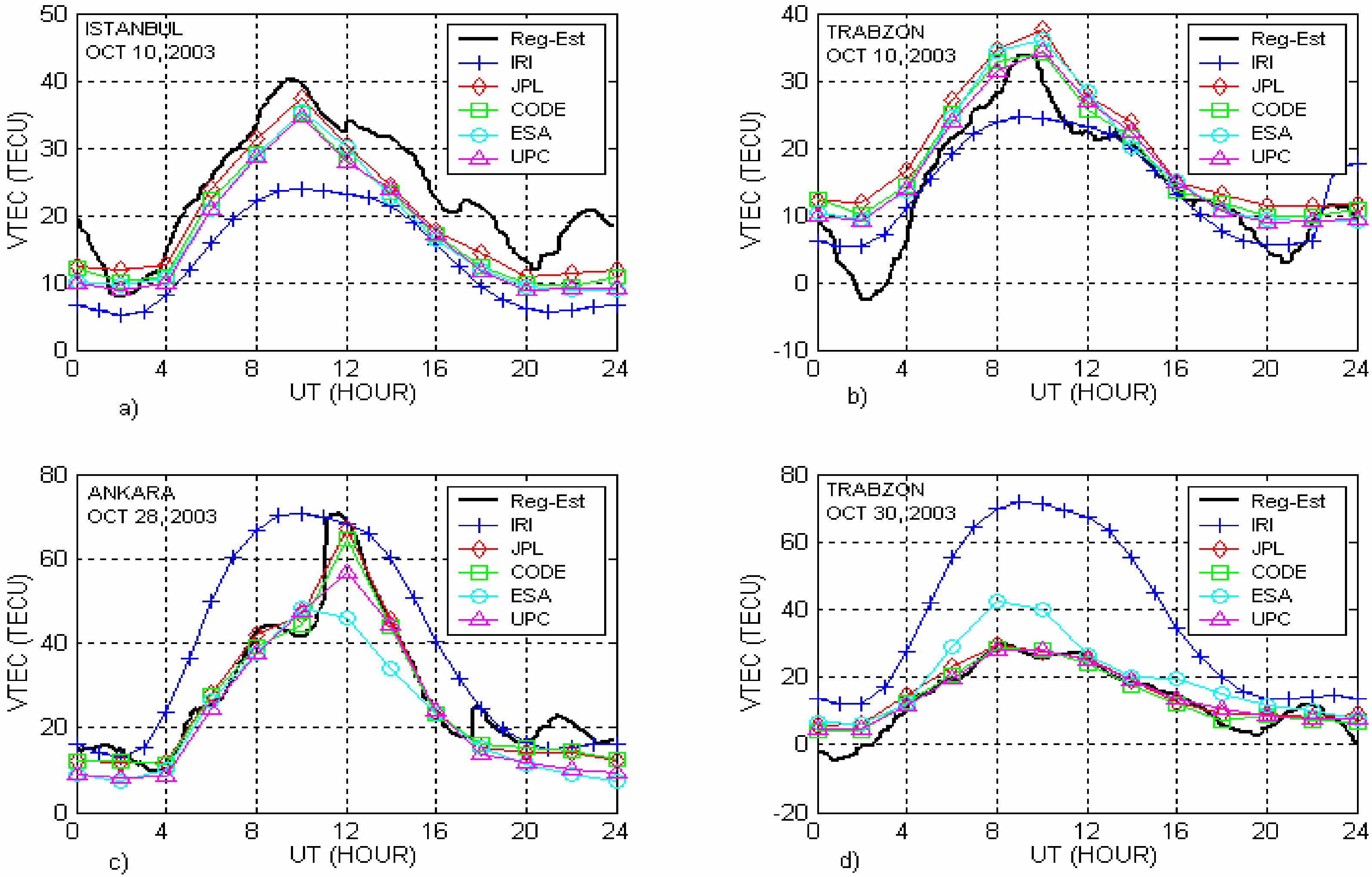
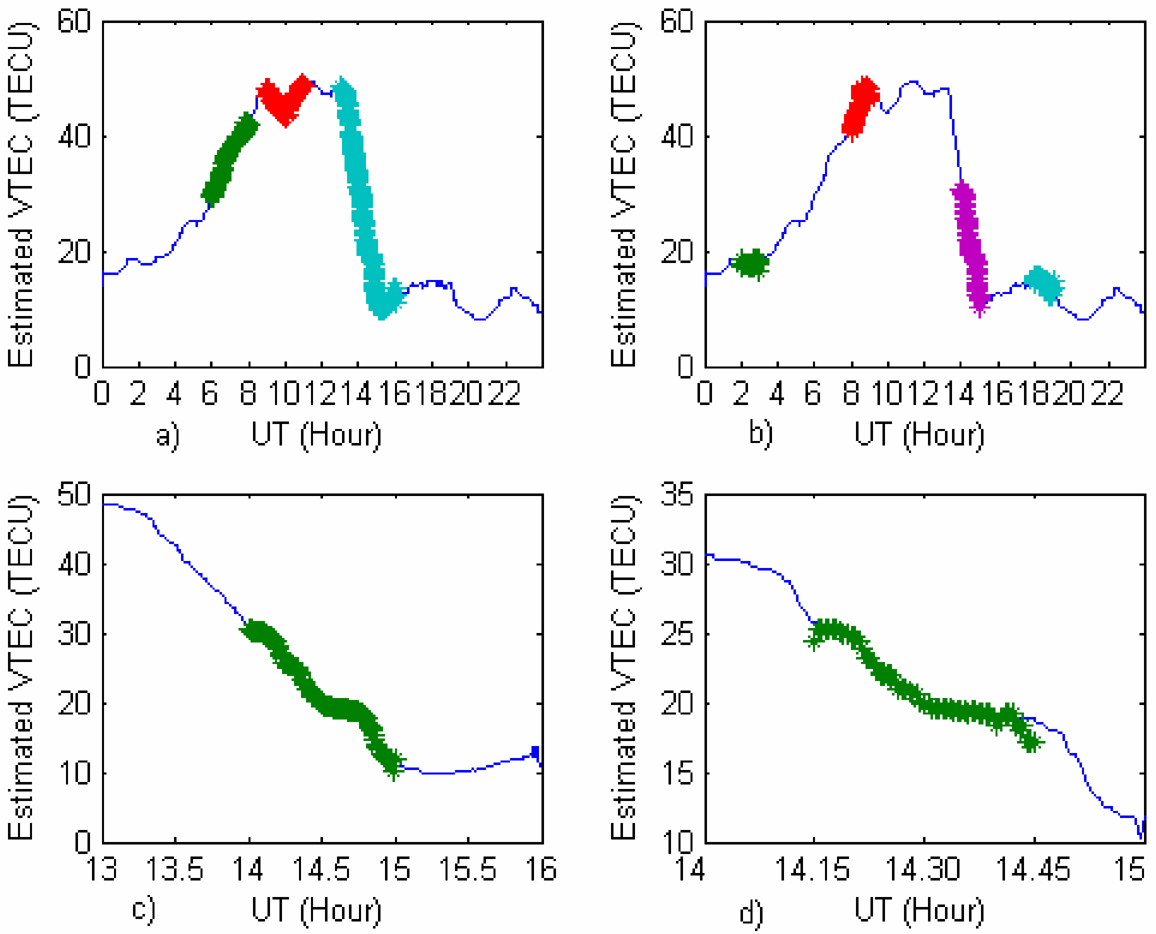


Comparisons with IRI, JPL, CODE, ESA and UPC

Kiruna, April 28, 2001



Conclusion

- **Reg-Est estimates VTEC with 30 s time resolution using all satellites in the vicinity of the receiver.**
- **Reg-Est is easy to implement and has no computational complexity. Reg-Est can estimate VTEC near real time with very high accuracy.**
- **Estimation parameters are very robust and same set can be used with any station (high or midlatitude) and with any ionospheric state (quiet or disturbed).**
- **Small scale time variations and disturbances can be observed very accurately.**
- **Regularized VTEC values are in accordance with other GIM-VTEC data and better agreement with JPL and CODE is observed.**
- **Consistent with IRI model.**

IONOLAB-TEC

- **Reg-Est is programmed in JAVA so that it can be accessed from internet without the need to download any program.**
- **IONOLAB-TEC is the Java version of Reg-Est.**
- **For details:**
- **O. Ugurlu, Web Based Computation and Presentation of Total Electron Content (TEC) Using the IONOLAB Method, (in Turkish) *Master's Thesis, Hacettepe University*, Ankara, Turkey 2007.**