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Estimation of 3D Electron Density in the Ionosphere By Using Fusion of GPS Satellite-Receiver Network Measurements and IRI-Plas Model

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***Abstract*—GPS systems can give a good approximation of the Slant Total Electron Content in a cylindrical path between the GPS satellite and the receiver. International Reference Ionosphere extended to Plasmasphere (IRI-Plas) model can also give an estimation of the vertical electron density profile in the ionosphere for any given location and time, in the altitude range from about 50 km to 20000 km. This information can be utilized to obtain total electron content between any given receiver and satellite locations based on the IRI-Plas model. This paper explains how the fusion of measurements obtained from a GPS satellite-receiver network can be utilized together with the IRI-Plas model in order to obtain a robust 3D electron density model of the ionosphere.**

I. Introduction

The ionosphere is a layer in the upper atmosphere ranging from about 60 km to nearly 20000 km. Technically, it is not an atmospheric layer but it is different from other layers because it is ionized by solar radiation. It has a crucial importance in radio wave propagation because of its electromagnetic properties.

Ionosphere is mainly affected by solar zenith angle and solar activity. In the daytime, ionization in the ionosphere is at the highest level, and the ionospheric effects are stronger. In the night, ionization decreases, and the effects of ionosphere gets weaker. In the solar active days, ionization patterns in the ionosphere can be very chaotic and reach enormous values. The ionization values in the ionosphere can be briefly explained by two physical processes, which are called as ionization and recombination. When a photon strikes a molecule in the air, and if the emergent energy is high enough, it can dislodge an electron from it. This process creates negatively charged free electrons and positively charged ions, and is called as ionization. If a positively charged molecule captures a free electron, it is called as recombination. At the lower parts of the ionosphere, the atmosphere is very dense, molecules are very close to each other, and any ionization is followed by a recombination process. At higher altitudes, atmosphere gets thinner and electrons can roam free in the atmosphere longer before a recombination process. Therefore electron density in the atmosphere increases as the altitude increases. However, as the altitude rises further, atmosphere gets too thin, and the density of the molecules decreases to very low values. Hence, after a certain point, electron density starts decreasing. The electron density profile in the ionosphere is basically determined by these two processes, however, in reality it has a very complex characteristic. It depends on lots of parameters such as the density of atmospheric gases and their interaction with different wavelengths of sunlight. Together with geomagnetic field effects and other secondary effects, these properties constitute an electron density profile with different layers in the atmosphere.

The most important parameter for modeling the ionosphere is the electron density profile. Electron density profile is a direct way to investigate the structure and variability of the ionosphere as well as the ionospheric disturbances on radio waves. Radio waves are reflected and/or refracted as they travel through ionosphere with an amount based on the electron density values in the layers of the ionosphere. It makes long range telecommunication possible by reflecting some wavelengths and it causes delays in the satellite signals by refracting some wavelengths. Ionosphere is the main error source for GPS systems. Without calculating ionospheric effects, GPS systems cannot obtain good resolution values.

International Reference Ionosphere (IRI) is a physical and empirical 3D model of the ionosphere, constructed by using the physical relations and all available past measured ionospheric data [1]. It is sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). IRI model is updated every year, and it has been continuously developed for more than 40 years. For any given location and time, IRI model can give the 3D model of the electron density, electron temperature, ion temperature, and ion composition estimates in the ionosphere, in the altitude range from about 50 km to about 2000 km. International Reference Ionosphere extended to Plasmasphere (IRI-Plas) is an extended version of IRI. It increased the height coverage to the extent of 20000 km and has an updated scale parameter set for scaling electron density profile in the topside ionosphere [2].

GPS systems can also give a good approximation of the Total Electron Content (TEC) in the transmission path between the GPS satellite and the receiver. Although, they are not intended to calculate ionospheric properties, GPS data can be used for calculating total electron content values. Furthermore,

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GPS systems provide continuous measurement data. GPS based TEC estimation is an inexpensive method and has been widely used to estimate both regional and global TEC values.

The main purpose of this paper is to introduce a novel method for reconstructing 3D electron density profile in the ionosphere by employing both the IRI-Plas model and the GPS measurement data together. IRI-Plas model input parameters are modeled as 2D parametric surfaces and these surface parameters are optimized in a way that the obtained 3D electron density model fits measurement data obtained from GPS systems. A stochastic optimization approach known as Particle Swarm Optimization is used for this optimization problem. Results show significant success in obtaining a robust 3D electron density profile which is in compliance with the both GPS measurement data and the IRI-Plas model.

II. Estimation of Slant Total Electron Content by using GPS measurements

Ionosphere introduces delays on the signals transmitted from GPS satellites. This delay in the transmitted GPS signals severely degrades the performance of GPS based positioning systems. In order to compensate this error, GPS satellites use two different frequency bands at 1575.42 MHz (L1 band) and 1227.60 MHz (L2 band). GPS signals at each frequency band are delayed with different amounts based on the total electron content in the propagation path between the GPS satellite and the receiver, and the frequency of the signals. The delay difference between two signals can be calculated in GPS receivers and by using this value, overall delay can be estimated. Since this overall delay is directly related with the total electron content in the transmission path, Total Electron Content (TEC) between the satellite and the receiver can be estimated [3]. TEC is defined as the total number of free electrons in a cylinder with 1 m^2 cross section area, between the GPS satellite and the GPS receiver. It is expressed in terms of TECU which corresponds to 10^{16} electrons. Since the total electron content between the satellite and receiver is the total number of free electrons along a slant path, it is generally called as Slant Total Electron Content (STEC). If the Total Electron Content is calculated on a vertical path, it is called Vertical Total Electron Content (VTEC).

Turkish National Permanent GPS Network (TNPGN) contains 147 settled GPS stations spread all over Turkey and North Cyprus, and it provides a perfect tool for analyzing ionospheric properties over Turkey. TNPGN stations are continuously collecting data and the collected data are sent to IONOLAB at Hacettepe University for ionosphere studies. TNPGN data contains pseudo range (P_1,P_2) and phase (L_1,L_2) data for two different frequency bands transmitted from GPS satellites (L1 and L2 bands) and for each satellite and receiver pair, provided that the satellite is in the line of sight of the corresponding receiver. By using the pseudo range data, delay difference between these two bands, and therefore STEC values between the receiver and the satellite can be estimated. Phase data contains additional information and can be used for fine-tuning these STEC estimation values.

In this study, IONOLAB-STEC data, which is obtained from TNPGN stations, is used as GPS STEC measurements. IONOLAB-STEC data has a time resolution of 30 seconds and calculates GPS receiver biases based on IONOLAB-BIAS and satellite biases for obtaining more precise measurements [3].

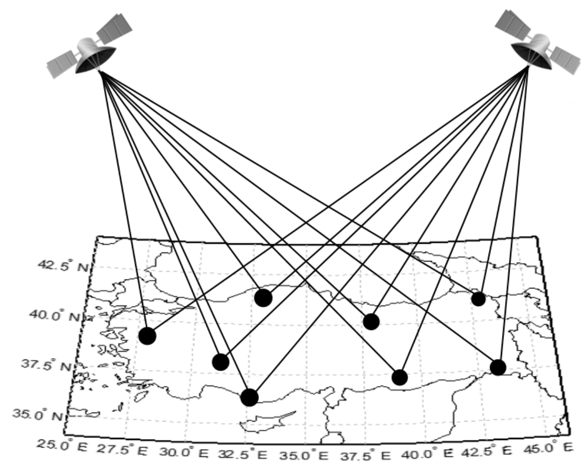


Fig. 1. An illustration of Total Electron Content measurements by using a GPS satellite-receiver network

There are some proposed techniques in the literature for obtaining 3D model of the electron content in the ionosphere by using GPS measurements [4][5]. However, obtaining a 3D model of the electron density in the ionosphere from these measurements is not a simple task. The measurement data is not uniform and the number of measurements is not sufficient for employing known tomography methods. A physical/empirical model together with these measurements has to be employed in order to have a robust solution method. The measurements should be considered as whole rather than individual values in order to decrease the effect of the noise caused by individual receiver and satellite pairs in the measurements.

III. Estimation of 3D Electron Density Profile with IRI-Plas

IRI-Plas is a parametric model of the ionosphere. By default, IRI-Plas uses a recorded parameter set for given time and location, however, some of the ionospheric parameters can be provided by user to IRI-Plas. For given time, location and optional ionospheric parameters, IRI-Plas can give the vertical electron density profile from about 50 km to 20000 km. By using these electron density profiles obtained from IRI-Plas model and some geodetic calculations, IRI-Plas based synthetic STEC values between any given satellite and receiver coordinates can be calculated.

A. STEC calculation from IRI-Plas

In order to calculate the STEC value precisely along a given slant path s, the electron density values and the normal angle values along this slant path s have to be obtained. The electron density values can be estimated by IRI-Plas model, provided that the coordinates of these points are given. Suppose that every slant path s is defined with three parameters u, v and t, which represent receiver, satellite and time, respectively.

TABLE I. INPUT PARAMETERS FOR CALCULATING THE SLANT PATH COORDINATES

Symbol	Definition
$\phi(u)$	Latitude of Receiver u
$\lambda(u)$	Longitude of Receiver u
α^s	Satellite Elevation Angle The angle between the surface plane at the receiver u location and the slant path s
β^s	Satellite Azimuth Angle The clockwise angle between the local north vector at the receiver u location and the projection of the slant path s, onto the surface plane which is tangential to earth at the receiver u location

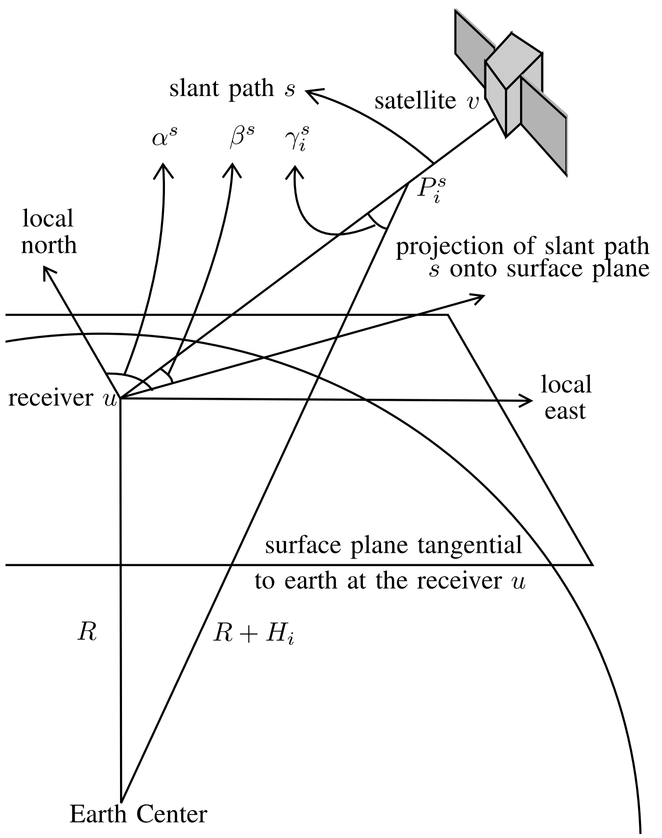


Fig. 3. Parameters used in STEC calculation

The coordinates of the slant path s and the normal angle values along this slant path s are calculated for discrete height values contained in array $\underline{H}$ in increasing order. In following calculations H_i represents the i^{th} height level in array $\underline{H}$, and P_i^s represents the point, where slant line s reaches height H_i. The earth is considered as a sphere with a radius of 6378 km, which will be denoted as R. Before beginning calculations, suppose that, the parameters listed in Table I are given as input parameters. A sample drawing is given in Figure 3 for depicting these parameters.

Let γ_i^s represent the angle between the slant path s and the surface normal, which intersects s at point P_i^s, and let D_i^s represent the distance between the receiver u and the point P_i^s. By using the law of sines, γ_i^s and D_i^s can be calculated as follows.

$$\gamma_i^s = \sin^{-1}\left(\frac{R}{R+H_i}\sin\left(\frac{\pi}{2}+\alpha^s\right)\right) \tag{1}$$

$$D_i^s = \left|\frac{\sin\left(\frac{\pi}{2}-\alpha^s-\gamma_i^s\right)}{\sin(\gamma_i^s)}R\right| \tag{2}$$

After D_i^s is calculated, the local east, north, up (ENU) coordinates of the point P_i^s can be calculated by using (3).

$$\begin{bmatrix} E(P_i^s) \\ N(P_i^s) \\ U(P_i^s) \end{bmatrix} = \begin{bmatrix} D_i^s \cos(\alpha^s)\cos\left(\frac{\pi}{2}-\beta^s\right) \\ D_i^s \cos(\alpha^s)\sin\left(\frac{\pi}{2}-\beta^s\right) \\ D_i^s \sin(\alpha^s) \end{bmatrix} \tag{3}$$

where $E(P_i^s)$, $N(P_i^s)$ and $U(P_i^s)$ represent the local east, north and up coordinates of point P_i^s, respectively, in ENU coordinate system. These ENU coordinates are transformed to Earth Centered Earth Fixed (ECEF) coordinates by using (4), (5) and (6)

$$\underline{\underline{T}}^u = \begin{bmatrix} -\sin(\lambda(u)) & \sin(\phi(u))\cos(\lambda(u)) & \cos(\phi(u))\cos(\lambda(u)) \\ -\cos(\lambda(u)) & \sin(\phi(u))\sin(\lambda(u)) & \cos(\phi(u))\sin(\lambda(u)) \\ 0 & \cos(\phi(u)) & \sin(\phi(u)) \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} X(u) \\ Y(u) \\ Z(u) \end{bmatrix} = \begin{bmatrix} R\cos(\phi(u))\cos(\lambda(u)) \\ R\cos(\phi(u))\sin(\lambda(u)) \\ R\sin(\phi(u)) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} X(P_i^s) \\ Y(P_i^s) \\ Z(P_i^s) \end{bmatrix} = \underline{\underline{T}}^u \begin{bmatrix} E(P_i^s) \\ N(P_i^s) \\ U(P_i^s) \end{bmatrix} + \begin{bmatrix} X(u) \\ Y(u) \\ Z(u) \end{bmatrix} \tag{6}$$

In equations (4), (5) and (6), $\underline{\underline{T}}^u$ represents the transformation matrix; $X(u)$, $Y(u)$ and $Z(u)$ represent the x, y, z coordinates of receiver u; $X(P_i^s)$, $Y(P_i^s)$ and $Z(P_i^s)$ represent the x, y, z coordinates of point P_i^s, respectively, all in ECEF coordinate system.

After the ECEF coordinates of point P_i^s are obtained, spherical latitude (ϕ) and spherical longitude (λ) of P_i^s, which will be used as inputs to IRI-Plas, are calculated as follows.

$$\phi(P_i^s) = \frac{180}{\pi}\tan^{-1}\left(\frac{Z(P_i^s)}{\sqrt{(X(P_i^s)^2+Y(P_i^s)^2)}}\right) \tag{7}$$

$$\lambda(P_i^s) = \frac{180}{\pi}\tan^{-1}\left(\frac{Y(P_i^s)}{X(P_i^s)}\right) \tag{8}$$

Note that, for unambiguous determination of $\phi(P_i^s)$ and $\lambda(P_i^s)$, inverse tangent functions shall be used together with the quadrant information.

Suppose that ΔH_i is the height step value used at height level H_i. In order to find the electron density contribution at each height level, the length of the slant path s within the height step ΔH_i, which will be denoted as ΔH_i^s, must be calculated. ΔH_i^s can be found by the trigonometric relation given in equation (9).

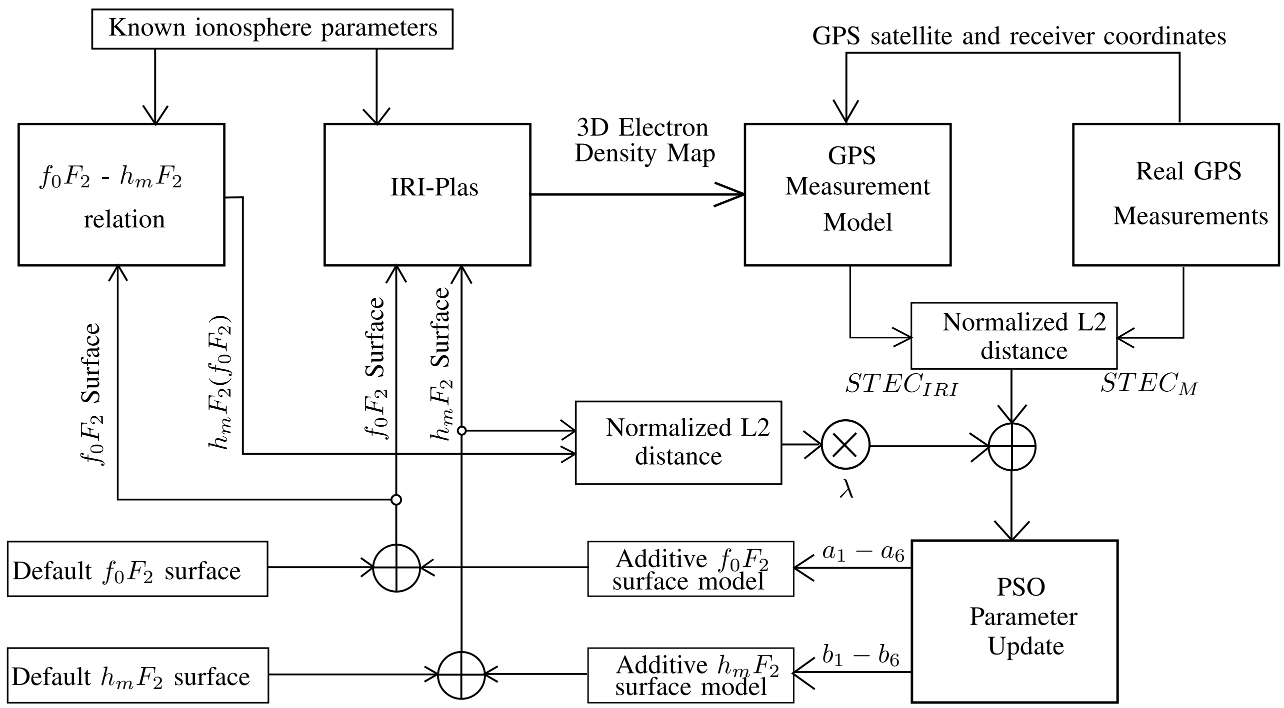


Fig. 2. Block diagram of model based data fusion technique that utilizes GPS satellite-receiver network measurements to reconstruct 3D electron density model of the ionosphere

$$\Delta H_i^s = \frac{\Delta H_i}{\cos(\gamma_i^s)} \quad (9)$$

Finally, IRI-Plas model based STEC value along the slant path s, which will be denoted as $STEC^s$, can be calculated by integrating the electron density contributions from each height level along the slant path s.

$$STEC^s = \sum_{i=1}^{I} Ne(\phi(P_i^s), \lambda(P_i^s), H_i)\Delta H_i^s \quad (10)$$

where $Ne(\phi(P_i^s), \lambda(P_i^s), H_i)$ represents the electron density value obtained from IRI-Plas model for given latitude $\phi(P_i^s)$, longitude $\lambda(P_i^s)$ and height H_i parameters, and I is the length of array $\underline{H}$.

Selection of the height parameter array $\underline{H}$ depends on the computational cost and precision requirements of the system. A larger array with denser height levels will give more precise results while increasing computational intensity of the calculations. It is convenient to use denser height levels at high electron density regions, and sparse height levels at low electron density regions. In this paper, 1 km height step sizes are used between 100 km and 600 km, 10 km step sizes are used between 600 km and 1300 km, and 50 km step sizes are used between 1300 km and 20000 km.

IV. 3D Electron Density Estimation Model

Proposed 3D electron density estimation model employs both GPS measurements and the IRI-Plas model together. IRI-Plas parameters are adjusted in a way that resultant ionosphere model matches with the GPS measurements. The parameters used for adjusting the model are f_0F_2 (critical frequency of the F2 layer which has the highest electron density) and h_mF_2 parameter (height of the peak electron density region). Those are the most important parameters for modeling the electron density profile in the ionosphere. Their variation depends mostly on the solar activity, and also long term geomagnetic activities [8].

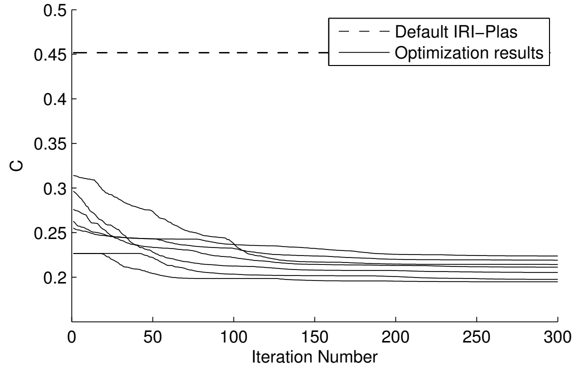
By using f_0F_2 and h_mF_2 parameters, IRI-Plas model can be fit to any feasible measured VTEC data at a location on earth. However, in order to fit IRI-Plas model to a group of measurements obtained in a region, the spatial properties of f_0F_2 and h_mF_2 have to be considered together with their correlation with each other. These parameters vary very smoothly over the region; i.e. they cannot change rapidly. This property also leads to another result, if the spatial variability of these parameters is very low, then their values over a region can be expressed with fewer parameters.

For a low order parameterization of f_0F_2 and h_mF_2 values over a spatially limited area such as Turkey, these values can be represented by summation of their default values over Turkey obtained from IRI-Plas model, and a 2-dimensional 2nd degree polynomial surface models. Such surface models can generate spatially smooth and slowly varying surfaces, which are desired features of synthetically generated f_0F_2 and h_mF_2 surfaces.

Suppose that the coordinates of the region of interest is defined as

$$R = \{(\lambda, \phi) | \lambda_{max} > \lambda > \lambda_{min}, \phi_{max} > \phi > \phi_{min}\} \quad (11)$$

where λ and ϕ are geodetic latitude and longitude values, respectively. Suppose that $f_0F_2(\lambda, \phi)$ and $h_mF_2(\lambda, \phi)$ are used



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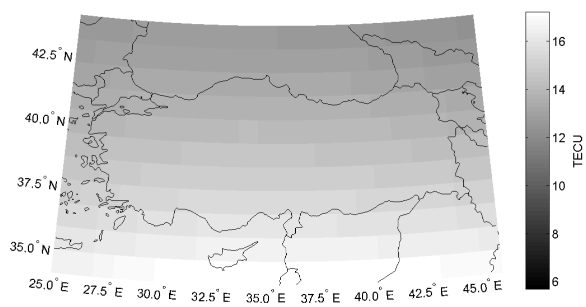

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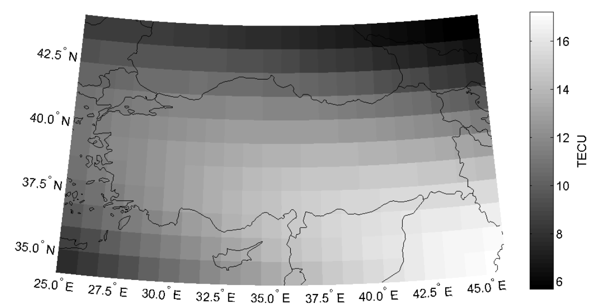


(c)

Fig. 4. Simulation results obtained for 21 June 2009. a) Cost function with respect to iteration number, b) Default VTEC map obtained from IRI-Plas, c) Optimized VTEC map obtained after PSO.

for representing the IRI-Plas input values f_0F_2 and h_mF_2 for latitude λ and longitude ϕ. These values are calculated as

$$f_0F_2(\lambda,\phi) = f\left(\frac{2\lambda-\lambda_{max}-\lambda_{min}}{\lambda_{max}-\lambda_{min}}, \frac{2\phi-\phi_{max}-\phi_{min}}{\phi_{max}-\phi_{min}}\right) + f_0F_2(\lambda,\phi)_{IRI-Plas} \quad (12)$$

$$h_mF_2(\lambda,\phi) = h\left(\frac{2\lambda-\lambda_{max}-\lambda_{min}}{\lambda_{max}-\lambda_{min}}, \frac{2\phi-\phi_{max}-\phi_{min}}{\phi_{max}-\phi_{min}}\right) + h_mF_2(\lambda,\phi)_{IRI-Plas} \quad (13)$$

$f_0F_2(\lambda,\phi)_{IRI-Plas}$ and $h_mF_2(\lambda,\phi)_{IRI-Plas}$ are used for representing the default f_0F_2 and h_mF_2 values obtained from IRI-Plas for given latitude λ and longitude ϕ values. f and h functions are defined as

$$f(x,y) = S_f(a_1x^2 + a_2x + a_3 + a_4y^2 + a_5y + a_6xy) \quad (14)$$

$$h(x,y) = S_h(b_1x^2 + b_2x + b_3 + b_4y^2 + b_5y + b_6xy) \quad (15)$$

S_f and S_h functions are basically sigmoid functions for limiting the outcome of f and h functions in certain feasible limits.

For given 12 parameters, f_0F_2 and h_mF_2 values over the region of interest can be calculated by using above equations. By using these f_0F_2 and h_mF_2 values, 3D electron density profile over the region of interest can be obtained from IRI-Plas model. On the other hand, GPS measurements also contain important data about the 3D electron density profile. Therefore, problem can be defined as an optimization problem where the main goal is to tune these 12 parameters in a way that the resultant 3D electron density profile is in compliance with the measurements. While doing this, another issue is to reduce the deviation of the f_0F_2 and h_mF_2 values from their physical relationship. Therefore, the main goal of this optimization problem can be defined as to minimize a cost function as follows

$$C = \frac{||STEC_M - STEC_{IRI}||_2}{||STEC_M||_2} + \lambda\frac{||h_mF_{2IRI} - h_mF_2(f_0F_{2IRI})||_2}{||h_mF_{2IRI}||_2} \quad (16)$$

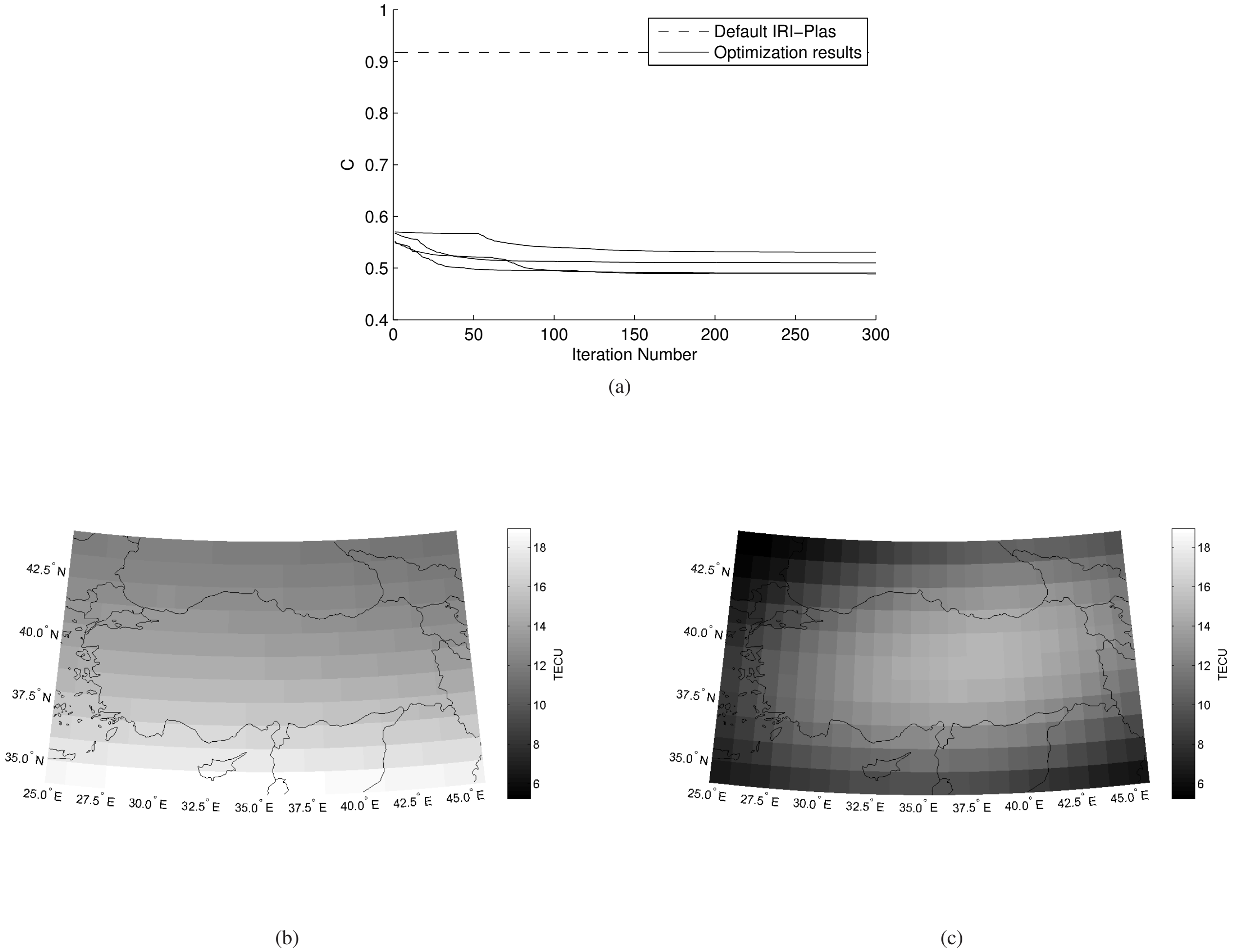


Fig. 5. Simulation results obtained for 18 September 2009. a) Cost function with respect to iteration number, b) Default VTEC map obtained from IRI-Plas, c) Optimized VTEC map obtained after PSO.

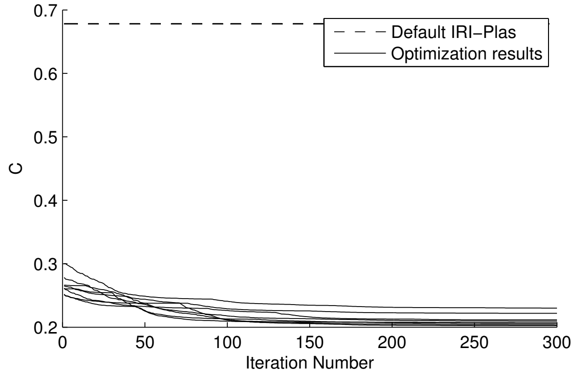
where $STEC_M$ represents the array of measured STEC values obtained from IONOLAB-STEC data, $STEC_{IRI}$ represents the array of calculated STEC values obtained from optimized IRI-Plas 3D electron density profile, f_0F_{2IRI} and h_mF_{2IRI} represent the arrays of f_0F_2 and h_mF_2 input values given to IRI-Plas, respectively, $h_mF_2(f_0F_{2IRI})$ represents the array of default h_mF_2 values obtained from IRI-Plas for given f_0F_{2IRI} values, and λ is an adjustable weight parameter.

For optimization approach, Particle Swarm Optimization (PSO) algorithm is employed. PSO is a stochastic and iterative optimization technique which mimics the behavior of bird flocking or fish schooling. It was developed in 1995 and drew a lot of interest because of its simplicity and superior performance [6].

PSO uses particles in order to search for the optimum solution in the search space. These particles are randomly placed into the problem space. Each particle calculates and knows how good position it has. Each particle has also memory of the best position it has been. And each particle communicates with the rest of the swarm and knows the best position found so far. PSO does not use gradient of the problem, nor does it follow a deterministic way. Each particle is accelerated randomly towards the personal best position and the global best position. After each iteration, memory of the swarm is updated. In this way, particles follow a path similar to bird flocking or fish schooling in the search space. PSO has been successfully applied in many areas. The challenge here is to model the problem with minimum number of parameters, and construct a problem space suitable for particle swarm optimization technique. Number of parameters determines the number of dimensions of the search space. As the number of parameters increase, particle swarm optimization technique becomes less feasible, because the number of particles and the number of iterations should be increased accordingly, and the probability of finding the global optima decreases.

An important parameter in PSO technique is the communication topology between particles. Global communication between the particles is the original and the widely used method. However, it has been shown that some topologies leads better results than global communication model in well-known problems [7]. In this paper, global communication topology is used in the obtained results. The particle itself did not contribute to the calculation of the global best position. This way a particle reaching the best position among the swarm continued to accelerate towards the second best position.

Other important parameters that have to be considered care-



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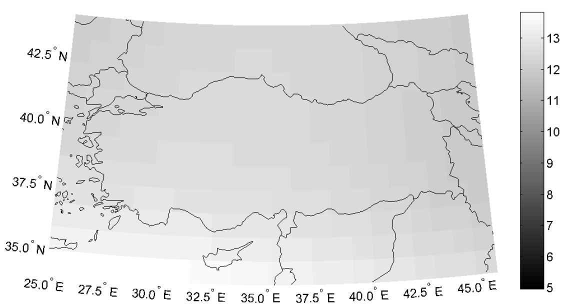

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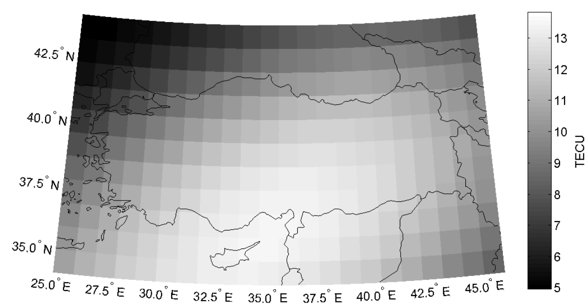

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Fig. 6. Simulation results obtained for 15 December 2009. a) Cost function with respect to iteration number, b) Default VTEC map obtained from IRI-Plas, c) Optimized VTEC map obtained after PSO.

fully are the acceleration and the velocity update coefficients of the particles. Acceleration vector of the particles are calculated as the summation of acceleration vectors towards global and personal best positions. Each acceleration vector is calculated as the distance vector towards to the global/personal best point multiplied by the acceleration coefficient and a random number uniformly distributed between 0 and 1. Velocity vectors are updated such that the new velocity vector is equal to the previous velocity vector multiplied with the velocity update coefficient plus total acceleration vector. Since the swarm converges around the solution and the particles get closer, the acceleration and the velocity of the particles will slow down.

The proposed 3D electron density estimation model is depicted in Figure 2. The f_0F_2 and h_mF_2 values over Turkey are constructed by using 12 parameters obtained from PSO particles plus their default values obtained from IRI-Plas. In order to construct the 3D electron density map over the Turkey, input parameters of f_0F_2 and h_mF_2 values are taken from these surfaces and default IRI-Plas values are used for the remaining parameters. As a result, each particle leads to a 3D electron density map over Turkey. After that, these electron density maps are compared with the data obtained from GPS measurements. In order to do that, the synthetic STEC measurement values for corresponding receiver and satellite positions are calculated from the obtained 3D electron density model. The normalized mean L2 distance between STEC values obtained from the electron density map and the real measurement data is calculated and recorded as the STEC cost. The normalized mean L2 distance between the current h_mF_2 values and the default h_mF_2 values corresponding to the current f_0F_2 values are calculated and recorded as the h_mF_2 cost. The total cost is calculated as the sum of STEC cost and h_mF_2 cost multiplied with a weight parameter λ. This value is assigned to the corresponding PSO particle as its fitness value. PSO moves the particles according to these fitness values and the system iterates again until the iteration number reaches its maximum value. The global best solution which has been achieved until the last iteration is selected as the final solution.

V. Results

Proposed 3D electron density estimation method is run several times by using IONOLAB-STEC measurement data over Turkey and IRI-Plas model. Three dates are selected for PSO runs, which are 21 June 2009 10:00 GMT, 18 September 2009 10:00 GMT and 15 December 2009 10:00 GMT. The ionosphere is assumed to be highly correlated within 15 minutes. IONOLAB-STEC data provides 2339 number of measurements for 21 June 2009 10:00 GMT, 2166 measurements for 18 September 2009 10:00 GMT and 1239 measurements for 15 December 2009 10:00 GMT, within this 15 minute interval. Number of PSO particles is selected as 100 and the maximum number of iterations is selected as 300. The weight parameter λ is 1. Velocity update coefficient for each particle is 0.5, and the acceleration coefficient for each particle is 0.05. Obtained results are presented in Figures 4, 5 and 6. The default fitness values obtained by using default IRI-Plas parameters are 0.45 for 21 June 2009 10:00 GMT, 0.92 for 18 September 2009 10:00 GMT, and 0.67 for 15 December 2009 10:00 GMT. After PSO runs with 100 particles and 300 iterations, these fitness values are decreased to 0.24 for 21 June 2009 10:00 GMT, 0.49 for 18 September 2009 10:00 GMT, and 0.21 for 15 December 2009 10:00 GMT.

VI. CONCLUSION

A new approach for estimation of 3D electron density profile in the ionosphere by using both the fusion of GPS measurements and IRI-Plas model together is presented. 3D electron density obtained from IRI-Plas model is adjusted by using IRI-Plas input parameters f_0F_2 and h_mF_2 over Turkey in a way that synthetic measurements calculated from the 3D electron density profile is in compliance with GPS measurements. f_0F_2 and h_mF_2 values over Turkey are represented with additive quadratic surface models both with 6 parameters. The problem is reduced to a 12 parameter optimization problem. A stochastic optimization method PSO is used for solving this optimization problem. Results show significant improvement in the conformity between the measurements and the model.

ACKNOWLEDGMENT

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