Real-Time Ionospheric Characterization and Modeling

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ABSTRACT

Complete descriptions of spatial and temporal distributions of the ionosphere are obtained using a real-time ionospheric characterization (RTIC) system developed at CRS (and described by Ganguly and Brown, 2001). The system accepts data from various sources, regions, and times, then assimilates these data within the framework of physical ionospheric models, providing a 4-D description of the ionosphere anywhere in the world.

A framework for data-fusion using an ionospheric model was demonstrated by Ganguly (1990, 1991). Most recently, this technique has been extended to incorporate a variety of data, including total electron content (TEC) observation from ground- or satellite-borne receivers and beacons, oblique and vertical sounders, radar, radio propagation, incoherent scatter, optical observations, and in situ measurements.

Currently, the RTIC system is being integrated with internet services in order to access a variety of data and user applications. We describe the salient features of the system.

INTRODUCTION

Accurate and global description of electron density distribution in the ionosphere is needed for various operational, technical, and scientific purposes. Demands on the accuracy, spatial and temporal resolution, and time scale of predictions (e.g., "forecasting" versus "nowcasting") vary across a wide range of applications. Currently, these different demands are met using relatively uncoordinated data sets in a rather piecemeal fashion. A coordinated and coherent effort has been missing.

Several types of ionospheric data are collected by different users and communities. Each data set provides a limited view of the ionosphere.

Interpretation of these data in terms of ionospherically useful parameters such as the electron density distribution and their variations of height, time and space may not always be straight- forward. Ionogram inversion involves uncertainty arising through "valley" and "underlying ionization" problems. Tomography inversion (using only ground based receivers) is highly uncertain in terms of ionospheric height, shape and plasmaspheric contributions and the inversion of optical and ultraviolet (UV) data are appropriate only over limited regions and involve complexities arising through neutral atmosphere, related chemistry and background radiation.

The different aspects of ionospheric diagnostics are treated separately by different user communities. It is intuitively obvious that a coordinated effort to "fuse" these different information would allow superior estimation of the complete ionospheric description. Use of data assimilation using nonlinear mapping functions derived from almost any user supplied model has been demonstrated by Ganguly and Brown (1996). A real-time ionospheric characterization system (RTIC) has been fully developed and released by the Center for Remote Sensing, Inc. This RTIC system allows assimilation of a variety of ionospheric data into any global ionospheric model provided by the users. Several standard models such as IRI, PIM (Parametric Ionospheric Model), Chapman etc. are built in and the user can choose any portion of the world (region of interest), select the data sources and the RTIC provides a 4-D description of the ionosphere which is self-consistent with the data and constrained by the models. Various types of data can be assimilated in the present form.

SYNTHESIS OF THE IONOSPHERE

Various data sets cover different regions of the ionospheric profile and also provide very different spatial, temporal sampling. Uncertainties and reliability's of these data also vary widely and the availability cannot be entirely relied upon. Fusion of such diverse data-sets into a self-consistent picture is a formidable task and requires thorough understanding and appreciation of the data sets, their spatial and temporal correlation's, their zone of influence. All of these must be performed within the framework of underlying physics.

The "true-height profile" obtained from ionogram, oblique sounders, topside sounders etc. provide a reasonable description of the electron density distribution over limited regions of the ionosphere. Conventional ionosondes use broad beam antennas and the ionospheric description obtained from a vertical sounder could be representative of the average ionosphere over 50 to 100 km region (horizontally), it could also be representative of some combination of ionospheric distribution from anywhere in the region. If more accurate representation is desired, one must use direction of arrival (DOA) information available from modern ionosondes. Spatial distribution and gradients are caused by horizontal pressure gradients, electric fields, traveling ionospheric disturbances, tides and gravity waves, plasma bubbles and instabilities, meteorological warming, seismic activities etc. DOA information is generally not available from ionosondes and the effects of spatial unhomogenities should be borne in mind while performing the reconstruction.

One of the most abundant data-set is the TEC type data available through ground based and satellite borne receivers, altimeters etc. By observing the delay between two radio-frequencies emitted from a satellite, the integrated column density is derived. Inversion of the total electron density distribution can be performed using (i) some assumption about the ionospheric distribution (ii) tomographic inversion using multiple receivers and satellites.

One of the major difficulties in ionospheric tomography is incomplete information resulting from limited viewing geometry. Various approaches are used to circumvent these deficiencies. One simple approach is to use some ionospheric model shape as an initial guess and adaptively modify it to obtain the best match with observed data. In model-less algorithms, a Monte-Carlo or pyramid based approach may be used for reconstruction. Another approach is to use some a prior knowledge such as homogeneity or smoothness factor. Ganguly and Brown (1996, 2001) developed both model-based and model-less algorithms and have performed thorough investigations about their accuracy limits under different situations. In general, the model-less algorithms demand superior experimental data.

Integration of various types of ionospheric models within the framework of observational data has been developed using the RTIC. Both physical and empirical models can be chosen and a self consistent model output is provided. The self-consistency is achieved in terms of model prediction as well as with the observational data. The assimilation process is performed through an expert system.

Tomographic reconstruction using slant TEC's from ground based and/or space borne receivers has been fully developed at CRS. The Real Time Ionospheric Characterization (RTIC) system developed at CRS allows integration of many disparate types of data in the characterization of a fully 4-dimentional time dependent ionosphere over any portion of the Earth. The location and size are fully adjustable by the user in real time. The program accepts a wide variety of data including: TEC data from GPS, NNSS, or other beacon satellites; ionosonde data; radio beacon data; and propagation data. All of these data are assimilated and self-consistent ionospheric profiles are generated. The system utilizes various theoretical and physical models to supplement incomplete data sets, and in the absence of any data only the theoretical models. Ionospheric parameters, propagation, and prediction and TEC values can also be obtained from the 4-dimensional ionospheric characterizations.

The software is divided into two programs. The first is a simulation program, used to generate a model ionosphere and calculate TEC values based on user defined receiver arrays and satellite constellations. The second program uses the TEC output from the first, and performs four-dimensional ionospheric reconstruction. Each allows native visualization of electron density in contour, three-dimensional, and false color plots, as well as contours of peak density and peak height. TEC values can be displayed versus time for all receivers and satellites, and a three dimensional interactive plot of the geometry is included. The current four-dimensional ionospheric tomography software may also be used for the purpose of simulating and investigating the effect of satellite based receivers on the tomography problem. The software includes the ability to place any number of both ground and satellite based receivers using any possible orbit for the purposes of simulating various arrangements. Satellite based receivers may optionally be equipped with their own beacons, thereby increasing the overall amount of TEC data coming in. In addition, the actual GPS constellation, or any other satellites, may be loaded into the software.

The reconstruction software will use these simulated TEC values in its reconstruction. In addition support for input other than TEC is available to improve overall reconstruction. Tomographic techniques provide a key element in the model and several novel techniques have been incorporated to obtain:

a) independent estimate of ionospheric height (without model assumption)
b) improved reconstruction of bottomside profile
c) use of GPS data for real time specification
d) space-time mapping using models
e) incorporation of ancillary data
f) flexible and robust operation applicable to any region, any sets of receivers (ground based, satellite borne), any number of satellites, any number of ancillary data etc.
g) excellent user interface and visualization
h) interface to ancillary programs such as:

- ray tracing
- critical frequency plots
- M-factor plots
- Propagation plots

RTIC system is a fully functional data assimilation program with excellent user interfaces and is ready for operational status. Examples of the user interface for RTIC are shown in Figures 1 and 2. Figure 1 shows the geometry and ray-paths between ground receivers and satellite-borne transmitters (GPS and LEO). Figure 2 shows an example of the ionospheric electron density distribution (against height and latitude) obtained from RTIC. Various other representations, including variations with time, are built in. Some of the major features are described in Table 1.

Currently we are in the process of making the RTIC system available through the internet. Users' could access various data sets over the internet, interactively operate the RTIC through web based server and obtain the desired outputs through internet. The client-server architecture will allow several users throughout the world to feed different regional and/or global data sets and obtain a self-consistent description of the regional and/or global ionospheric descriptions at will. For details see www.cfrsi.com.

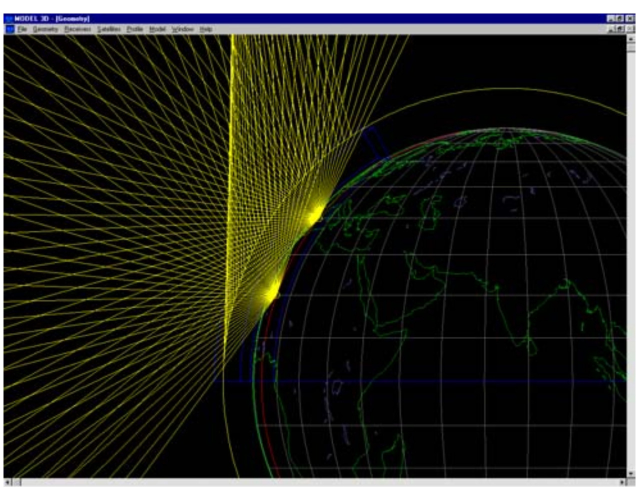

Figure 1. Graphical User Interface of RTIC showing the geometry and ray paths for two ground receivers and with GPS and LEO beacons.

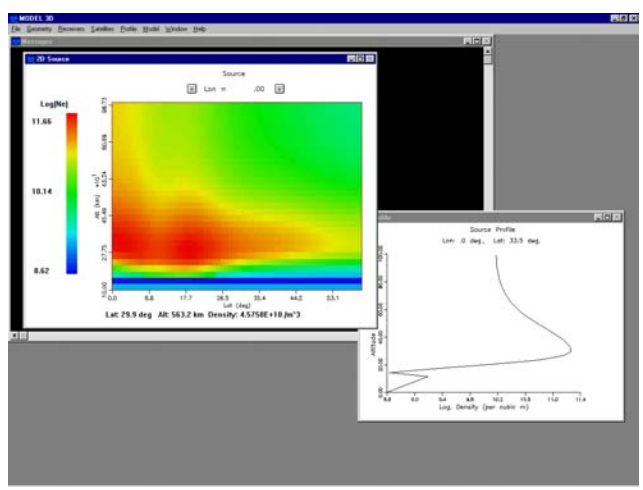

Figure 2. Example of electron density distributions obtained from RTIC. 3-D and 4-D (in height, latitude, longitude and time) are obtained.

CONCLUSION

Ionosphere characterization requires data-assimilation. Accurate ionospheric description for useful and practical uses cannot be achieved using theoretical or empirical models alone. Various types of ionospherically relevant data can be used for ionospheric characterization. One must be careful about the accuracies, limitations, utility, reliability etc. of these data sets. Practically none of these data sets provide complete spatio-temporal description of the ionospheric structures and the fusion of these incomplete data-sets needs to be performed under the framework of physical processes.

Table 1. Key Features of CRS's RTIC System

1.	Provides real-time descriptions of the ionospheric density distribution over height, latitude, longitude and time over any region of interest.
2.	It incorporates various techniques and approaches and allows the user to configure the system for his specific application.
3.	It allows user-defined configuration of region of interest (anywhere in the world), satellite locations (GPS, NNSS, GLONASS, CICADA, or other), and receiver locations (anywhere in the world and up to a maximum of 30), including both ground-based and satellite-based.
4.	It can accept various types of observables (data), such as TEC, vertical and oblique ionosondes, WISBY, transponders, known emitters, etc. It allows the user to choose any of these data sets.
5.	Acceptance of these data sets is performed in a hierarchical manner, i.e., the system will function in the absence of most of these data. Availability of these data will result in refined output.
6.	It allows "objective" determination of ionospheric heights using a "pre-tomography" module. An integral-based approach is used as opposed to difference-based approaches of tomographic algorithms.
7.	It incorporates various tomographic techniques which are used for further improvements of density distributions.
8.	Several initial guesses can be used to assure confidence in the reconstructed profiles. An expert system helps determine the initial guess.
9.	Plasmaspheric model allows efficient utilization of GPS data.
10.	Plasma Flow Modeling maintains self-consistency of the density distributions.
11.	Simple menu-driven operation allows user specification of the overall system.
12.	It can be used as a test bed for complex simulations as well as for operational applications under various circumstances.

A comprehensive data-assimilation system (RTIC) has been developed and released by CRS. The software along with the user interfaces and data input-output elements are being implemented using client-server computing techniques. This will make the self consistent description of the ionosphere available at anytime and anywhere.

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