

# Progress in Observation-Based Ionospheric Modeling

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Models for the ionospheric component of space weather are needed for a wide range of applications. For example, any remote sensing techniques that use radio waves traveling through the ionosphere, looking up from the ground or down from space, must correct for the retarding, refractive, and scintillation effects of the ionospheric plasma. Two types of models are used for this purpose: theoretical, physics-based models and empirical, observation-based models. Status and progress regarding the latter were reviewed during a workshop in Prague, Czech Republic, from 10 to 14 July 2007.

The workshop, entitled “Ionosphere—Modelling, Forcing and Telecommunications,” was organized jointly by the prime international and European cooperatives in observation-based ionospheric modeling: IRI and COST/MIERS. IRI, the International Reference Ionosphere (<http://iri.gsfc.nasa.gov/>), a project of the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), has the goal of developing and improving an international standard for the specification of ionospheric densities, temperatures, and velocities. COST/MIERS, the European Cooperation in the Field of Scientific and Technical Research project for the Mitigation of Ionospheric Effects on Radio Systems (<http://www.cost296.rl.ac.uk>), is a 5-year Europe-wide effort to improve data-based models for the European sector with special emphasis on Global Navigation Satellite System (GNSS) and telecommunications applications.

The IRI model is currently undergoing registration with the International Organization for Standardization (ISO) as a technical specification (TS16457), and it is the ionospheric model recommended by the European Cooperation for Space Standardization (ECCS).

Annual IRI meetings are the prime forum for discussions of model shortcomings, improvements, new model additions, applications, and other IRI-related topics. For its 2007 workshop, the IRI team joined forces with the European COST 296 project, which deals with similar modeling and application issues but is confined primarily to the European sector. The workshop was locally organized by the Czech Republic’s In-

stitute of Atmospheric Physics and attracted 103 scientists from 27 countries from North and South America, Europe, Asia, and Africa. The meeting was financially supported by COSPAR, URSI, the International Association of Geomagnetism and Aeronomy (IAGA), the European Office of Aerospace Research and Development (EOARD) of the U.S. Air Force, the U.S. Office of Naval Research (ONR), and the Czech Academy of Sciences.

Workshop presentations were grouped into sessions on ionospheric effects on radio systems, Global Positioning Systems (GPS) and total electron content (TEC), modeling of the topside and bottomside ionosphere, ionospheric storm effects, ionospheric sounding, and mapping the ionospheric  $F$  region. Closing sessions included a summary discussion and a management meeting for COST 296. All presentations are available on the workshop Web site at <http://www.ufa.cas.cz/html/conferences/IRICOST2007/>. Papers and posters from the meeting will be considered for a special issue of COSPAR’s *Advances in Space Research*.

The  $F$  layer, which extends from roughly 150 to 600 kilometer altitude, contains the  $F$  peak, typically at an altitude between 300 and 500 kilometers. The  $F$  peak is of special importance because it monitors the point of highest electron density and therefore the point of strongest impact on transionospheric radio waves. Increased accuracy of models for the  $F$  peak parameters is an important goal of both IRI and COST. COST is primarily focused on the European sector, while IRI deals with the whole globe. The International Radio Consultative Committee (CCIR) and URSI models for these parameters, often at the core of operational ionospheric models, date from the late 1960s and mid-1980s, respectively, and are urgently in need of an update. Several new modeling approaches were presented at this meeting, including neural networks (NN), genetic algorithms, eigenmode analysis, and others. The most advanced and prime candidates for inclusion in a future version of IRI are the NN peak models developed by Lee-Anne McKinnell and colleagues (Rhodes University, Grahamstown, South Africa) based on a large volume

of worldwide ionosonde data. Comparisons with data not used in the NN training process show significant improvements versus the older CCIR and URSI models. As a first step, their  $F$  peak height related model (using the propagation factor  $M(3000)F_2$  that is routinely monitored by ionosondes) will be included in the next version of IRI to get a better representation of diurnal structures currently not well represented in IRI, like the very sharp evening peak that indicates an uplift of the  $F$  layer. Also not fully reproduced in IRI is the longitudinal structure in the equatorial  $F$  peak density, including four distinct longitudinal maxima, caused by tidal forcing from below, that were first reported by Benkova and colleagues (Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation (IZMIRAN), Moscow) during the 1988 COSPAR IRI session based on Intercosmos 19 topside sounder data and recently rediscovered with IMAGE far ultraviolet imager (FUV) data.

An important outcome of the Prague meeting is the forming of a special task group on mapping  $F$  peak parameters to bring together data providers and modelers and to facilitate inclusion of the improved models in IRI and in operational programs. The task group includes members from IRI and COST and is led by Dieter Bilitza (George Mason University, Fairfax, Va.). A first task is to interact with the International Telecommunication Union's Radiocommunication (ITU-R) Group, who are debating an approach that would digitize the existing CCIR maps on a  $2.5^\circ$  latitude/longitude grid and publish new maps every 5 years. An important goal of this team effort is to pull together all available ionosonde and topside sounder data as a foundation for the modeling project.

Many of the GNSS-related presentations discussed how to deduce peak and profile information from the GPS's slant path phase and amplitude measurements using either simple assumptions about the profile or a more sophisticated tomographic approach. Difficulties remain in areas of large ionospheric gradients and/or of scarce ground station coverage. Further, there is still insufficient knowledge of the plasmaspheric contribution to the TEC. The new Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) satellites carrying GPS receivers into space help to overcome some of the coverage problems but have to deal with the inherent limitations of the radio occultation technique; for example, it requires a priori knowledge about horizontal gradients and topside as well as the plasmasphere's TEC. Several presentations showed how using IRI as an a priori source of information can lead to improvements in the tomographic construction of three-dimensional maps from GNSS measurements. Good progress is made in accounting for higher-order ionospheric effects on the GPS signal, and significant improvements are expected from the additional (third) frequency channel that will be standard with Europe's planned Galileo GNSS mission.

GNSS data are an important input for the current gener-

ation of global assimilation ionosphere models (GAIMs) that are now being considered for operational use by the U.S. Air Force. In comparisons with Jicamarca incoherent scatter radar and ionosonde measurements, Fred Rich et al. (Air Force Geophysics Laboratory, Hanscom, Mass.) found that assimilating COSMIC and GPS data into the Jet Propulsion Laboratory/Global Assimilation Ionosphere Model (JPL/GAIM) led to improvements in the topside ionosphere but made results worse in the  $F$  layer. They attribute this to the difficulty in adjusting simultaneously the  $F$  peak density and the topside profile with TEC as a constraint and on a GAIM  $F$  layer that is too thick because only oxygen ions are considered.

In the ionosphere's bottomside, comparisons of ionosonde and incoherent scatter radar data with IRI illustrated the shortcomings of the current tabular form of the representation of annual and global variations of several bottomside profile parameters in IRI. The spherical harmonics approach by David Altadill and coworkers (Ebro Observatory, Roquetes, Spain) showed much better results and will be included in the next version of IRI.

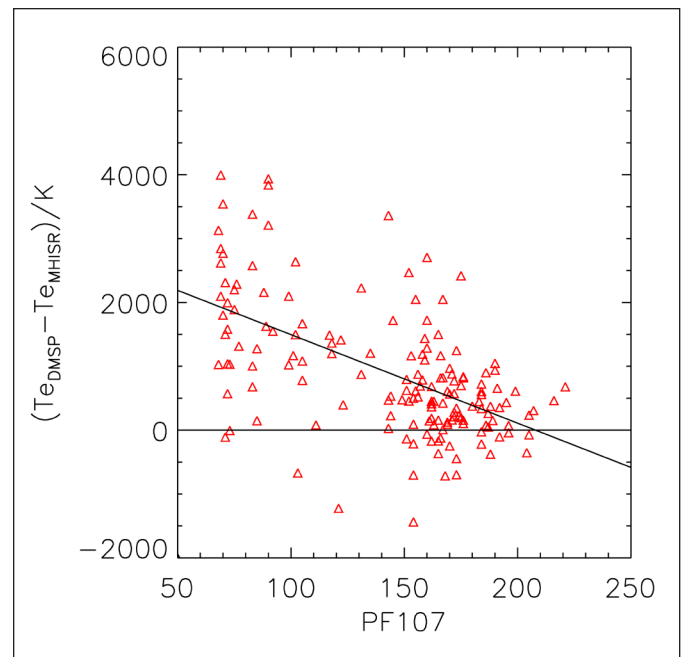


Fig. 1. Difference between the electron temperatures measured simultaneously with the Millstone Hill radar from the ground ( $T_{e\_MHISR}$ ) and the DMSP satellite overhead ( $T_{e\_DMSP}$ ) plotted versus solar activity during daytime. Also shown is a linear fit to the difference data. The commonly used solar INDEX  $PF_{107}$  is defined as  $PF_{107} = (F_{10.7} + F_{10.7A})/2$ , where  $F_{10.7}$  is the daily solar 10.7-centimeter radio flux and  $F_{10.7A}$  is the 81-day average (three solar rotations). Note the large discrepancies between satellite and ground-based data at low solar activities, which correspond to low electron densities.

The representation of ionospheric storm effects in IRI is currently limited to the  $F$  peak density and represents quite well negative storm effects (density depletions) during mid-latitude summer. Inclusion of the storm-induced uplift of the  $F$  layer is a high-priority goal for future versions of IRI. A new effort by Chris Mertens and coworkers (NASA Langley Research Center, Hampton, Va.) is aimed toward an IRI model description of  $E$  region (typically at 90–120 kilometer altitude) storm effects based on more than 6 years of volume emission rate (VER) data from the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite Sounding of the Atmosphere Using Broadband Emission Radiometry instrument (TIMED/SABER).

Regarding plasma temperatures, an accurate representation of solar cycle effects is the top priority. When combining incoherent scatter radar and Defense Meteorological Satellite Program (DMSP) satellite data toward this goal, significant discrepancies were found between the ground and space measurements at low solar activities (see Figure 1), likely due to the low electron densities that make accurate electron temperature determination difficult for both techniques. At lower altitudes, a large database of satellite in situ measurements is being used to establish the average variation patterns of electron temperature over the solar cycle for different local time, season, and latitude (Vladimir Truhlik and coworkers, Institute for Atmospheric Physics, Prague, Czech Republic).

The new equatorial zonal drift model of Bela Fejer and colleagues (Utah State University, Logan), based on Jicamarca incoherent scatter radar measurements, was proposed for IRI and will be included in the next version, complementing the already included vertical drift models by the same authors. The model includes dependencies with solar activity and season and reproduces the observed westward daytime drifts and eastward nighttime drifts.

A series of presentations reviewed the status and progress of COST-296-specific activities, which include studies of the detrimental effects of the ionosphere on high-frequency (HF) communications used for military and commercial airplane and ship communications and ionospheric impacts on HF radar usage, circuit diagnostics, and radio frequency allocations. Other topics discussed in this series were ionospheric scintillations and ionospheric influence on the performance of various GNSS-based systems. The objective in all cases is

to mitigate the effects of the ionosphere on systems involved (e.g., loss of lock of GNSS receivers). COST efforts to establish a good perturbation index have focused on squared TEC rates and latitudinal TEC gradients.

Bringing together the international IRI community with the European COST membership, the meeting offered a unique view of the current status of observation-based ionospheric modeling. It also stimulated a host of new collaborations with the goal of achieving further improvements of the IRI and COST models. The presentations showed that observation-based models like IRI have reached a high degree of maturity representing quite reliably the main altitudinal, latitudinal, diurnal, seasonal, and solar activity variations of ionospheric parameters. These models describe average conditions, climatology, but can be updated with real-time data (e.g.,  $F$  peak parameters or TEC) to provide real-time snapshots of the ionosphere for operational use. An IRI session during the 2008 COSPAR assembly has updating of ionospheric models with ground and space data as its particular focus, and a special real-time IRI workshop is planned for early 2009.

The most important next steps are statistical studies of the variation patterns of the characteristic features in the low- and high-latitude ionosphere that are not yet included in the IRI and COST models. At low latitudes, studies are focused on the amplitude and width of the “equatorial anomaly,” which consists of ionization crests on both sides of the magnetic equator and an equatorial minimum. At high latitudes, the focus is on the inclusion of auroral boundaries and the subauroral density trough and temperature peak. These tasks require satellite data since both regions are poorly served with ground-based equipment (ionosondes). TIMED and GNSS data will help but provide only indirect measurements of the electron density. The best instrument for measuring the  $F$  peak and topside density is a satellite topside sounder, and workshop participants expressed their support for such a satellite mission.

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