The USU-GAIM Data Assimilation Models for Ionospheric Specifications and Forecasts

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Abstract

Physics-based data assimilation models have been used in meteorology and oceanography for several decades and are now becoming prevalent for specifications and forecasts of the ionosphere. This increased use of ionospheric data assimilation models coincides with the increase in data suitable for assimilation. At USU we have developed several different data assimilation models, including the Global Assimilation on Ionospheric Measurements Gauss-Markov (GAIM-GM) and Full Physics (GAIM-FP) models. Both models assimilate a variety of different data types, including ground-based GPS/TEC, occultation, bottomside electron density profiles from ionosondes, in-situ electron densities, and space-based UV radiance measurements and provide specifications and forecasts on a spatial grid that can be global, regional, or local. The GAIM-GM model is a simpler model that uses the physics-based Ionosphere Forecast Model (IFM) as a background model but uses a statistical process in the Kalman filter. This model is currently in operational use at the Air Force Weather Agency (AFWA) in Omaha, NE. The GAIM-FP model is a more sophisticated model that uses a physics-based ionosphere-plasmasphere model (IPM) and an Ensemble Kalman filter. The primary GAIM-FP output is in the form of 3-dimensional electron density distributions from 90 km to near geosynchronous altitude but also provides auxiliary information about the global distributions of the self-consistent ionospheric drivers (neutral winds and densities, electric fields). The GAIM-FP model has recently been updated and extended to include the ionospheric D-region and to incorporate bubble information obtained from the SSUSI instruments.

Introduction

At Utah State University, two physics-based Kalman-filter data assimilation models for the Earth's ionosphere have been developed. These models are the Gauss-Markov Kalman Filter Model (GAIM-GM) and the Full Physics-Based Kalman Filter Model (GAIM-FP) [*Scherliess et al.,* 2006, 2009]. Both models are part of the Global Assimilation of Ionospheric Measurements (GAIM) project [*Schunk et al.,* 2004a,b, 2005a,b, 2011; *Scherliess et al.,* 2004, 2006, 2009, 2011; *Jee et al.,* 2007, 2008; *Sojka et al.,* 2007; *Thompson et al.,* 2006, 2009; *Zhu et al.,* 2006].

Some of the data that have previously been assimilated by these models include phase-leveled ground-based Global Positioning Satellite (GPS) slant total electron content (TEC); bottomside electorn density profiles from ionosonde/digisonde in Standard Archiving Output (SAO) data files; radio occultation (RO) slant total electron content data from the

Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) Precision Omni-directional Dipole (POD) antennas; topside ionospheric plasma electron density measurements from the Defense Meteorological Satellite Program (DMSP) in situ sensors; and DMSP Special Sensor Ultraviolet Spectrographic Imager (SSUSI) and Special Sensor Ultraviolet Limb Imager (SSULI) nighttime UV radiances. Data reduction utilities are used to reduce the raw data files and provide data in an appropriate form for the GAIM models to assimilate. The reduction utilities can be adapted for both historical and real-time executions of the GAIM models. In order to increase the use of latent data, both models accept in its real-time mode (nowcast) the data with a latency of 3 hours.

Recently, GAIM-FP has been updated to include a Data Driven D-region (DDDR) model [*Eccles et al.,* 2005]. The D region plays an important role in radio propagation due to the very high ion-neutral and electron-neutral collision rates in the lower atmosphere. Most importantly the electron-neutral collision rate becomes comparable to the frequency of radio waves used for regional and long-distant communications. When High-Frequency (HF) radio signals propagate (3-30MHz) through the D region, the electron response to the radio wave is interrupted by the collisions with the neutrals. This efficiently causes loss to the radio signal strength. For High-Frequency skywaves bouncing off the F region bottomside, the daytime D region is the largest loss of signal strength for the lower HF range (<10MHz). Furthermore, the D region also defines the ionospheric boundary of the earth-ionosphere waveguide for Very Low Frequency (VLF) wave propagation. The ionospheric boundary for VLF propagation rises and descends with the D region day-night variation and descends dramatically during large solar flares.

GAIM-GM

The GAIM-GM model [*Scherliess et al.,* 2004, 2006; *Schunk et al.,* 2004b] is based on a physics-based model of the ionosphere and a Kalman filter data assimilation technique. The model is currently in operational use at the Air Force Weather Agency (AFWA) in Omaha, NE. The accuracy of the model for global and regional specifications has been shown by *Scherliess et al.* [2006], *Thompson et al.* [2006], *Sojka et al.* [2007], and independently by *Decker and McNamara* [2007], *McNamara et al.* [2007, 2008, 2010], and by *McDonald et al.* [2006].

Using a Kalman filter techniques, GAIM-GM assimilates various ionospheric measurements to solve for deviations from a physics-based Ionospheric Forecast Model (IFM), which covers the E region, F region, and the topside ionosphere up to 1400 km altitude [*Schunk et al.,* 1997]. To reduce the computational requirements, these deviations and the associated error covariances evolve over time with a statistical model (Gauss-Markov process). To further reduce the computational requirements, the error covariances are constructed from 1107 2-day IFM runs, which substantially reduces the computation times. The background ionospheric densities, however, evolve with the full physical model. As a result, the USU Gauss-Markov Kalman filter can be executed on a single CPU workstation.

GAIM-GM is a global model that can support regional, higher definition assimilation windows within the model specification. The high-definition assimilation window in the regional mode can be used to provide higher resolution for regions of large data coverage, allowing the model grid resolution to be adjusted to that density. In both the global and regional modes, the latitudinal and longitudinal resolutions are adjustable. However, the resolution adopted depends on the data coverage and the computational environment, and consequently, the model is typically executed with a 15° longitudinal resolution and a 4.6° latitudinal resolution in the global mode. In the regional mode, the spatial resolution can be 3.75° in longitude and 1° in latitude if there are sufficient data to warrant such a resolution. With regard to altitude, GAIM-GM extends from 92 to 1400 km, which covers the E region, F region, and topside ionosphere. The spatial resolution of the output is 4 km in the E region and 20 km in the F region and above.

GAIM-FP

The GAIM-FP model is based on an ensemble Kalman filter approach [*Evensen*, 2003] and rigorously evolves the ionosphere and plasmasphere electron density field and its associated errors using a physics-based Ionosphere-Plasmasphere model (IPM) [*Scherliess et al.,* 2004; *Schunk et al.,* 2004a]. The IPM is based on a numerical solution of the ion and electron continuity and momentum equations and covers the low and mid-latitudes from 90 to 30,000 km altitude (a description of this physics-based model is given in *Schunk et al.,* 2003). The equations are solved along magnetic field lines for individual flux tubes of plasma, and the 3-D nature of the model is obtained by following a large number of plasma flux tubes. The 3-D distribution is obtained by mapping the results on a geographic grid. The IPM model uses the International Geomagnetic Reference Field (IGRF) [*Finlay et al.,* 2010], which properly accounts for the displacement between the geomagnetic and geographic equators and the bending of the magnetic field lines with latitude. In its current version, the model does not assimilate data in the regions poleward of ~ ±60° geomagnetic latitude due to the vastly different physical processes that govern the high-latitude ionosphere, e.g., convection electric fields, particle precipitation.

GAIM-FP provides specifications of the 3-dimensional electron and ion (NO^+, O_2^+, N^+, O^+, H^+, He^+) density distributions from 90 km to near-geosynchronous altitude (~30,000 km). In addition, the model can provide the global distribution of the ionospheric drivers (electric field, neutral wind and composition) that are consistent with the ionospheric observations. It is important to note that the estimation of the ionospheric drivers is an integral part of our ensemble Kalman filter and is achieved by using the internal physics-based model sensitivities to the various driving forces. In this procedure, the ionospheric data are used to adjust the plasma densities and its drivers so that a consistency between the observations (within their errors) and the physical model is achieved. As a result, the assimilation procedure produces the optimal model-data combination of the ionosphere-plasmasphere system together with the set of drivers (electric fields, neutral winds, and composition) consistent with the ionospheric observations [*Scherliess et al.,* 2009, 2011].

D-Region Extension

Recently, GAIM-FP has been extended to include a Data-Driven D-region model (DDDR) [*Eccles et al.,* 2005] that extends the lower boundary of the model down to 34 km altitude. Within the DDDR, the solar x-rays are modeled as hard x-rays (0.1 Å < l < 10 Å) and soft x-rays (10 Å < l, 100 Å). The GOES x-ray instruments observe hard x-rays in two integrated bands; 0.5-4 Å and 1-8 Å. These are overlapping bands of x-rays that have a modest influence on D region densities. It is the soft x-rays that have significant impact on ionization in the 60 to 90 km altitudes. Within the DDDR, the flux and ratio of the GOES x-ray bands are used to populate hard and soft x-ray energy-flux bins. The absorption cross sections for the hard and soft x-rays are from *Banks and Kocharts* [1973] with updates from *Pavlov* [2013]. The x-ray ionization creates energetic secondary electrons or Compton photons that have sufficient energy for further ionization. It is assumed all secondary ionization occurs locally in the lower E region and D region with an ion-electron pair created for each 35 eV available in the energetic photon [*Banks and Kockarts*, 1973]. The DDDR also includes Lyman Alpha ionization of Nitric Oxide as an important source of D-Region ionization.

The DDDR nighttime ionization is created from geocorona resonant emissions, interplanetary gas scatter (He II, He I, Lyman Alpha) and starlight [*Strobel et al.,* 1980; *Titheridge*, 2001]. The ionization rates within the DDDR are dependent on F10.7 and (nighttime) solar angle. The absorption cross-sections and ionization cross-sections for Lyman Alpha are from *Pavlov* [2013].

Energetic electron precipitation from the auroral region is determined from the oval model of *Hardy et al.* [1985, 1987]. The calculation of ionization due to energetic electrons uses the average energy and flux provided by the climatological Hardy oval model to create an electron energy distribution at the top of the ionosphere [*Robinson et al.*, 1986]. The topside electron energy fluxes are then used to calculate an ionization profile using primary fluxes and secondary electron production. Finally, average ionization profiles are used to model Solar Proton Events using the GOES energetic proton flux observations and cutoff rigidity formulae [Smart and Shea, 2005].

Figure 1 shows an example of the GAIM-FP electron density in the D region and lower E region. The log of the electron density is shown for day 2013/059 from 40 km to 120 km altitude in 10 km altitude steps. The left panel corresponds to 00:00 UT and the right panel corresponds to 12:00, respectively. One can see the elevated electron densities at D region altitudes (65-95km) in the sunlit regions (Figure 1). There is a low level Solar Proton Event in progress at the time, which elevates the electron densities in the polar caps below 80 km altitude.

Bubble Incorporation

Although neither GAIM-GM, nor GAIM-FP includes the physical processes that drive ionospheric plasma instabilities and bubbles, information about the location and extend of ionospheric bubbles has recently been incorporated into the GAIM models. The bubble information is obtained from the HiRes SSUSI 3-D ionosphere product and consists of the plasma-depletion centroid location (longitude, latitude, altitude) and the median depth of the plasma depletion.

The GAIM bubble incorporation is designed, first, to interpolate the electron density field from either GAIM-GM or GAIM-FP, and, second, to produce a new output file containing a high-resolution specification of the electron densities with field-aligned density depletions based on the HiRes SSUSI observations. The HiRes SSUSI NetCDF files are currently used in the program. This Bubble Mapping program uses the depletion region characteristics to initiate the field-line plasma bubble definition.

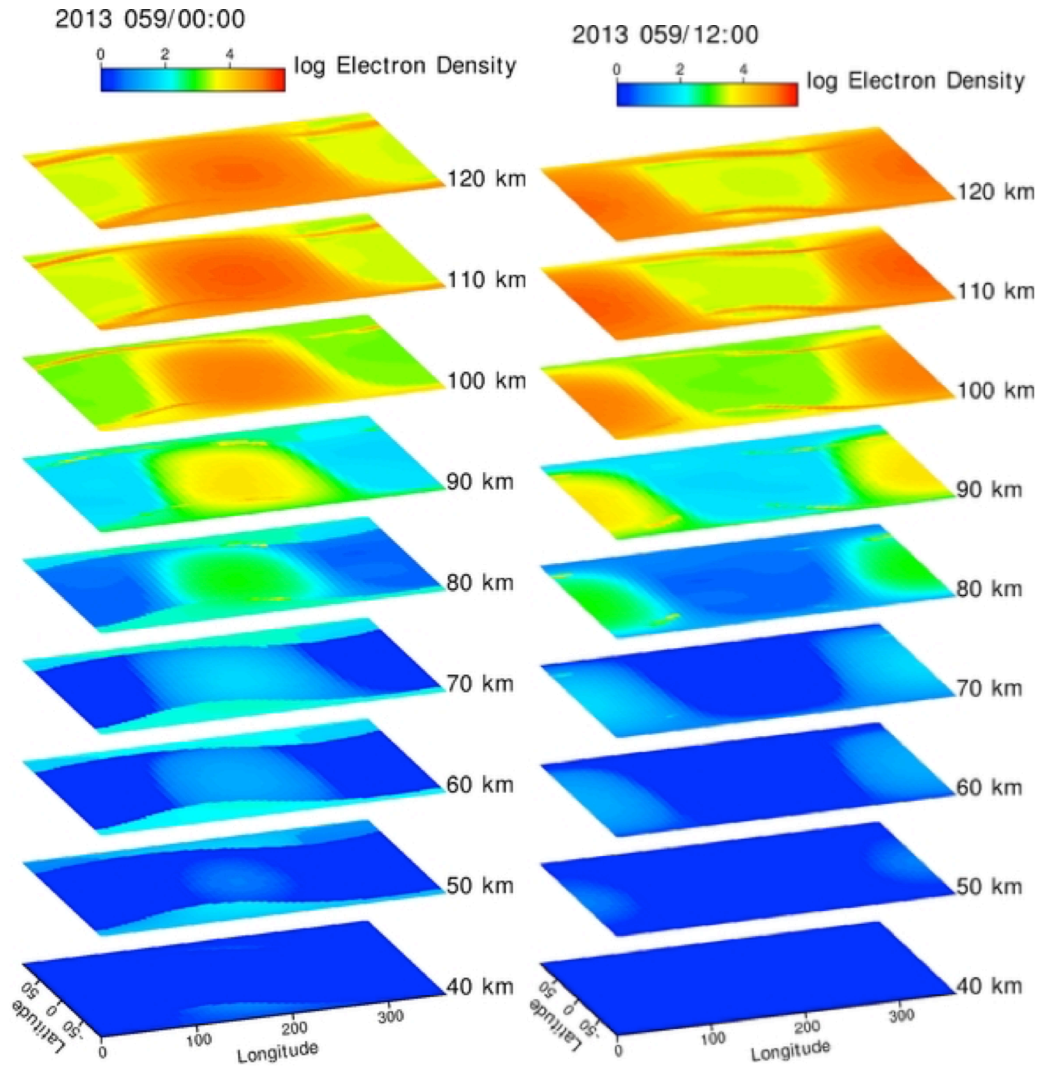

Figure 1. GAIM-FP electron densities in the D region and lower E region. The log of the electron density for day 2013/059 is shown from 40 km to 120 km altitude in 10 km altitude steps. The left panel corresponds to 00:00 UT and the right panel corresponds to 12:00, respectively.

For each time of GAIM output, the mapping program examines all depletions found within the SSUSI data files for the current and previous UT day. Only depletions that reside in the current nighttime regions are retained for the specification. These observed depletions are assumed to extend along magnetic field-lines. This assumption is well founded on observations and theory of the low-latitude ionosphere structure. Each plasma depletion (bubble) in the final electron density output is generated by, first, numerically tracing along the field line that pierces the observed centroid of the depletion. This properly extends the plasma depletion through the low-latitude F region beyond the SSUSI observation. Figure 2 shows an example of the GAIM-GM electron densities at 1500 UT for day 078/2013. The top panel shows a longitude/altitude slice through the 3-dimensional electron density field as provided by GAIM-GM at the geographic equator. The bottom panel shows the interpolated density field together with the superposed plasma depletions. These interpolated output files with superposed plasma bubbles can be useful for user applications that need higher resolution input with medium-scale plasma structures. For example, sensitive mathematical procedures, such as ray-tracing programs, benefit from the higher resolution and the communications breakups generated by irregularity structures in the background ionosphere.

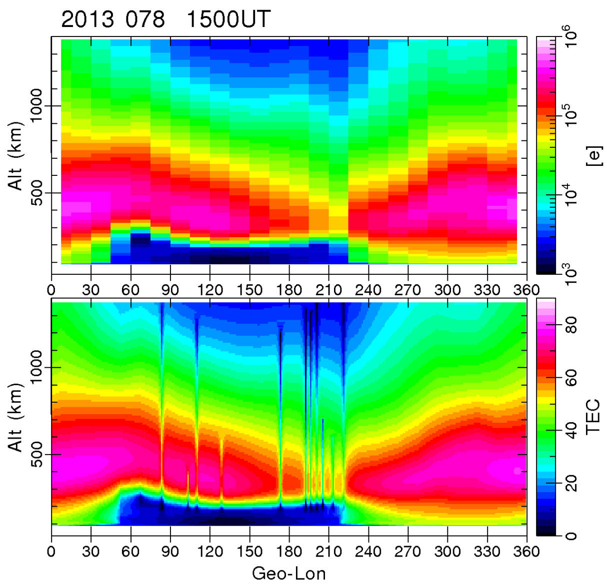

Figure 2. GAIM-GM results in top panel. Interpolated & bubble results in bottom panel. Both are a longitude slice at the geographic equator.

Summary and Conclusions

Two ionospheric data assimilation models with different sophistication and complexity have been developed at USU. Both models assimilate measurements from various ionospheric observing systems and allow for data latencies of up to 3 hours. Recently, the GAIM-FP model has been updated to include ionospheric bubble information and a data-driven D-region model. The D-region model extents the altitude range of GAIM-FP down to 34 km altitude.

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