An Operational Data Assimilation Model of the Global Ionosphere


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Abstract

Physics-based data assimilation models of the ionosphere were developed at Utah State University as part of a DoD Multidisciplinary University Research Initiative (MURI) program. The USU effort was called Global Assimilation of Ionospheric Measurements (GAIM). One of the USU data assimilation models has been selected for operational use at the Air Force Weather Agency (AFWA) in Omaha, Nebraska. This model is a Gauss-Markov Kalman Filter model, and it uses a physics-based model of the global ionosphere and a Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) measurements. The model has been designed to be modular and flexible. It can assimilate four different data types from an arbitrary number of stations. Quality control algorithms are an integral part of the model and latent data of up to three hours can be taken into account. The Gauss-Markov model can also be applied to just a region (e.g., North America or Europe) with a simple change to the setup file. The configuration of the model and its current status are presented.

1. Introduction

The ionosphere has been probed and modeled for more than five decades and it is now well known that the ionosphere exhibits both a background state (climatology) and a disturbed state (weather). Because of the Earth’s strong magnetic field, the ionosphere’s background state displays different characteristic features at high, middle, and low latitudes. The high-latitude ionosphere is characterized by tongues of ionization that extend across the polar cap, plasma troughs, and auroral density enhancements. At mid-latitudes, the ionosphere exhibits a fairly smooth variation during the day and at night, but the variation is large at sunrise and sunset. At low latitudes, the most prominent feature is the equatorial anomaly, which is a term used to describe the electron density enhancements that form on both sides of the magnetic equator at about 10 degrees from the equator. These characteristic features have been successfully modeled, as has their variations with season and solar activity. However, superimposed on this background state is a myriad of weather disturbances, and consequently, the ionosphere can vary appreciably from hour to hour and from day to day. Unfortunately, the weather disturbances can have detrimental effects on human systems and operations. They can adversely affect over-the-horizon radars, HF communications, GPS navigation systems, surveillance, power grids, pipelines, and the FAA’s Wide-Area Augmentation System (WAAS). In an effort to mitigate the adverse effects of the ionosphere on civilian and military operations, specification and forecast models are under development. These models will be used to correct for ionospheric effects and to predict weather disturbances.

Recently, Utah State University (USU) has developed two physics-based data assimilation models for ionospheric specifications and forecasts as part of the DoD Multidisciplinary University Research Initiative (MURI) program (Schunk et. al., 2004a, 2004b; Scherliess et. al., 2004, 2005). The USU effort was called Global Assimilation of Ionospheric Measurements (GAIM). The USU-GAIM models have been selected for operational use by the Air Force
Weather Agency (AFWA) in Omaha, Nebraska, and one of them (the Gauss-Markov Kalman Filter model) is currently being implemented at AFWA. This model is also being validated at the Naval Research Laboratory in Washington, DC, and at the Air Force Research Laboratory in Bedford, MA. The characteristic features of the operational Gauss-Markov Kalman Filter model are briefly described in this paper.

2. Gauss-Markov Kalman Filter Model

The Gauss-Markov model contains a physics-based model of the ionosphere, a Kalman filter data assimilation algorithm, several data sources, an executive system to control the real-time operation of the model, as well as several other important features listed in Table 1. The physics-based model is the Ionosphere Forecast Model (IFM), which is global and covers the E-region, F-region, and topside from 90 to 1400 km. It takes account of five ion species (NO⁺, O₂⁺, N₂⁺, O⁺, H⁺), electron and ion temperatures, and fluid drifts both parallel and perpendicular to B (Schunk et al., 1997). The main output of the model is a 3-dimensional electron density distribution at user specified times. In addition, auxiliary parameters are also provided, including Nₑ, hₑ, NₑF₂, hₑF₂, Nₑ (800 km), and slant and vertical TEC. The operational version of the model assimilates four data types, including bottom-side Nₑ profiles from a variable number of ionosondes, slant TEC from a variable number of ground GPS/TEC stations, in situ Nₑ from a variable number of DMSP satellites, and line-of-sight UV emissions measured by satellites. Quality control algorithms for all of the data types are included and the model takes account of latent data (up to 3 hours). Also, an algorithm is included that provides a 24-hour forecast.

With the Gauss-Markov model, the ionospheric densities obtained from the IFM constitute a background ionospheric density field on which perturbations are superimposed based on the available data sources and their errors (cf. Scherliess et al., 2005). The density perturbations are assimilated via a Kalman filter (Daley, 1991), and the density perturbations and the associated errors evolve over time via a statistical Gauss-Markov process. The IFM variability is calculated a priori and 1107 2-day runs of the global ionosphere are stored in a database, from which the covariance matrix is calculated during the operation of the model.

<table>
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<tr>
<th>Table 1. Operational Gauss-Markov Kalman Filter Model</th>
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<td>• Physics-Based Model is an Updated IFM</td>
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<td>• Variable Number of Ground GPS/TEC Sites</td>
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<td>• Variable Number of DISS Stations</td>
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<td>• DMSP in situ Nₑ</td>
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<td>• UV Radiances (SSULI)</td>
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<td>• Quality Control Algorithms</td>
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<td>• Data Latency (up to 3 hours)</td>
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<td>• Real-Time GPS Leveling</td>
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<td>• Altitude Resolution is 4 km in E-Region &amp; 20 km in F-Region</td>
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3. Operational Status

Global and regional modes of the Gauss-Markov model are running simultaneously at USU on separate CPUs. The regional mode has been running continuously and automatically since 1 January 2003. The global mode has been running continuously and automatically since 1 July 2003. The operational version of the model was delivered to NRL on 15 July 2004, and subsequently, to AFRL, to the Space and Missile Command (SMC), and to Northrop Grumman for implementation at AFWA for military applications. The Gauss-Markov model will also be delivered to the Community Coordinated Modeling Center (CCMC) in the near future for scientific purposes, and it being considered for operational use at NOAA’s National Weather Service for civilian applications.

4. Operational Runs

In an operational setting, the Gauss-Markov Kalman Filter model runs continuously and reconstructs the global electron density distribution as a function of time. The model automatically acquires the relevant data on the web, quality controls the data, inputs the data into the Kalman filter, and outputs a variety of ionospheric parameters at a 15-minute cadence. The data assimilated can include slant TEC from up to 1000 ground GPS receivers, bottom-side electron density profiles from 20 digisondes, in situ electron densities from several DMSP satellites, and integrated UV emissions from satellites. In practice, however, different amounts of data are assimilated, depending on the data availability. In general, occultation data can also be assimilated, but that capability is not included in the version that was delivered for operational use.

Figures 1-3 show some of the standard output parameters of the Gauss-Markov model from an example 1-month ‘equinoct’ that was delivered with the operational model (days 80 - 110 in 2004). For this period, the assimilated data included slant TEC from 162 GPS ground receivers, bottom-side $N_e$ profiles from 17 digisondes, and in situ $N_e$ from DMSP satellites F13, F14, and F15. Figure 1 shows snapshots (at 00:30 UT on day 80) of vertical TEC obtained by integrating through the $N_e$ distribution from 90-1400 km (top-left panel), $N_mF_2$ (bottom-left panel), and contours of $N_e$ at selected altitudes (right panel). Clearly evident in both $N_mF_2$ and TEC are the equatorial anomaly peaks. Figure 2 shows snapshots (at 00:15 UT on day 80) of $N_mE$, $N_mF_2$, and $N_e$ at 840 km. Output of these parameters is routinely tracked to make sure that the E-region, F-region, and topside behave properly after the various data types are assimilated. Finally, Figure 3 shows snapshots of $N_e$ profiles at selected locations (high, middle and low latitudes) along longitudes relevant to the North American and European/African sectors. Note that at high latitudes, the peak in $N_e$ can occur in the E-region due to auroral particle precipitation.

The Gauss-Markov model was designed to be flexible and, as noted earlier, it can also be applied to just one region. Figure 4 shows the change in the set-up file that is needed to run a regional mode instead of a global mode, and Figure 5 shows a sample of the output. For this case, a three-dimensional ionospheric reconstruction across North America was considered and the simulated period was November 20-21, 2003, which was when a large geomagnetic storm occurred. The data included TEC measurements from more than 300 GPS receivers and bottom-side electron density profiles from ionosondes at the Dyess (Texas) and Eglin (Florida) stations. During the reconstruction, about 2000 slant TEC values were assimilated every 15 minutes. The bottom panel in Figure 5 shows the data (slant TEC converted to the vertical with an angle factor) at a given instant of time. The top panel shows the vertical TEC obtained from the
physics-based Ionospheric Forecast Model (no data assimilation), and the middle panel shows the Gauss-Markov Kalman Filter TEC obtained from the ionospheric reconstruction when the data are assimilated into the physics-based model. Clearly, the data make a significant contribution to the reconstruction.

5. References


![Figure 1](image_url)  
Figure 1. Sample output from the operational Gauss-Markov Kalman filter model. Shown in the figure are vertical TEC (upper-left panel), $N_mF_2$ (lower-left panel), and contours of $N_e$ at selected altitudes (right panel). The results are for day 80, 2004, at 00:30 UT, and they are displayed in a geographic latitude-longitude coordinate system.
Figure 2. Snapshots of $N_mE$ (bottom), $N_mE_F$ (middle), and $N_e$ at 840 km (top) for day 80, 2004, at 00:15 UT. The parameters are displayed in a geographic coordinate system.
Figure 3. Altitude profiles of $N_e$ at high, middle, and low altitudes along longitudes that pass through North America and Africa. The profiles are for day 80, 2004, at 00:15 UT. The middle panel shows $N_mF_2$.

The Set-Up File for Global Mode

```bash
#!/bin/csh

echo YEAR= YYYY > gm.set
echo START DAY= $DDD >> gm.set
echo START UT= $HH >> gm.set
echo GMODE= GLOBAL >> gm.set
echo ASSI TSTEP= 15 >> gm.set
echo SUN_FIXED= 0 >> gm.set
echo TIME CONSTANT = 5 >> gm.set
echo RUNLOOPS= 2000000 >> gm.set
echo HEIGHT CORR= 500 >> gm.set
echo LAT CORR= 10 >> gm.set
echo LON CORR= 0.001 >> gm.set
echo OUTPUT = 1 >> gm.set

./kalmanrt >& run.log
```

Set-Up File for Regional Mode

```bash
#!/bin/csh

echo YEAR= YYYY > gm.set
echo START DAY= $DDD >> gm.set
echo START UT= $HH >> gm.set
echo GMODE= REGIONAL >> gm.set
echo LatRange= $LAT1, $LAT2 >> gm.set
echo LonRange= $LON1, $LON2 >> gm.set
echo ASSI TSTEP= 15 >> gm.set
echo SUN FIXED= 0 >> gm.set
echo TIME CONSTANT = 5 >> gm.set
echo RUNLOOPS= 2000000 >> gm.set
echo HEIGHT CORR= 500 >> gm.set
echo LAT CORR= 10 >> gm.set
echo LON CORR= 0.001 >> gm.set
echo OUTPUT = 1 >> gm.set

./kalmanrt >& run.log
```

Figure 4.
Figure 5. Sample output from a regional ionospheric reconstruction using the Gauss-Markov Kalman Filter model. The output corresponds to 16:15 UT on day 324, 2003.