Development of a Physics-Based Kalman Filter for the Ionosphere in GAIM

L. Scherliess, R. W. Schunk, J. J. Sojka, and D. C. Thompson

Center for Atmospheric and Space Sciences, Utah State University, Logan UT 84322, USA
E-mail: ludger@gaim.cass.usu.edu

ABSTRACT

We are developing a physics-based data assimilation model of the ionosphere and neutral atmosphere called the Global Assimilation of Ionospheric Measurements (GAIM). GAIM will use a physics-based ionosphere-plasmasphere model and a Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) measurements. Some of the data to be assimilated include in situ density measurements from satellites, ionosonde electron density profiles, occultation data, ground-based GPS TECs, and line-of-sight UV emissions from selected satellites. When completed, GAIM will provide a continuous reconstruction of the 3-dimensional electron density distribution from 90 km to geosynchronous altitude (35,000 km).

INTRODUCTION

Ionospheric weather disturbances can have detrimental effects on numerous human activities and systems. They can adversely affect survey and navigation systems that use Global Positioning System (GPS) satellites, over-the-horizon (OTH) radars, HF communications, surveillance, satellite tracking and lifetimes, power grids, pipelines, and the Federal Aviation Administration's Wide-Area Augmentation System (WAAS). In an effort to mitigate the adverse effects of the ionosphere, specification and forecast models are being used both to correct for ionospheric effects and to predict weather disturbances. Currently, numerous modeling approaches are being used in various space weather applications, including empirical models, analytical and parameterized models, global numerical models that couple different spatial domains and data assimilation models. Also, hybrid models are being used whereby different model types are combined for practical purposes.

The most promising ionospheric weather models are the physics-based data-driven models that use Kalman filter data assimilation techniques [*Schunk et al*., 2002a]. Although such techniques have been successfully used by the meteorologists and oceanographers for several decades, the space physics community has been slow in implementing data assimilation techniques, primarily because of the lack of a sufficient number of measurements. However, this situation is changing rapidly for the ionosphere. Within ten years, it is anticipated that there will be several hundred thousand ionospheric measurements per day from a variety of sources, and these data will be available for assimilation into specification and forecast models.

GAIM MODEL

GAIM uses a time-dependent physics-based model of the global ionosphere/plasmasphere system and a Kalman filter as a basis for assimilating a diverse set of real-time (or near real-time) measurements. When completed, GAIM will provide both specifications and forecasts on a spatial grid that can be global, regional, or local. The primary output of GAIM will be a continuous reconstruction of the 3-dimensional N_e distribution from 90 km to 35,000 km. However, GAIM will also provide a range of auxiliary parameters as well as the main ionospheric drivers. In its specification mode, GAIM will give quantitative estimates for the accuracy of the reconstructed ionospheric densities. Also, GAIM will have a modular construction, so that when new models, observing stations, and data types become available, they can be easily incorporated into the data assimilation scheme. The overall program involves model construction, data quality assessment, data assimilation, the construction of an executive system to automatically run GAIM in real time, and validation. In the subsections that follow, we first describe the GAIM system and then present an illustrative simulation using a recent version of GAIM.

DATA SOURCES

GAIM has the ability to assimilate a wide range of data types from numerous ground-based and space-based platforms. The left panel of Fig. 1 shows a schematic of some of the data sources that are, or could be, available for assimilation in GAIM during the next decade. The data sources include in situ electron densities from NOAA and DoD operational satellites, bottomside electron density profiles from a network of 100 digisondes, line-of-sight Total Electron Content (TEC) measurements between as many as several thousand ground stations and the GPS satellites,

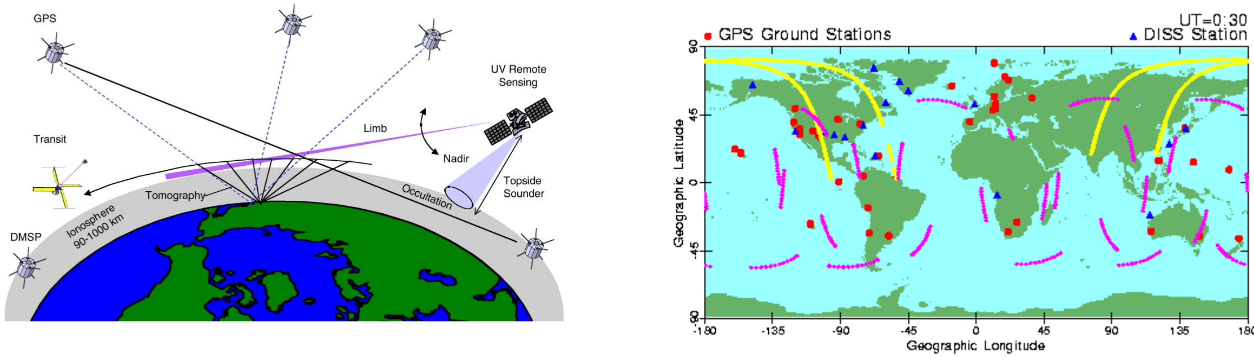

Fig. 1. Left panel: Schematic diagram showing some of the data sources that are available for assimilation into GAIM. Adapted from *McCoy* (2001). Right panel: Data sources used in a typical Kalman filter electron density reconstruction.

TECs between low-altitude satellites with radio beacons and several ground-based tomography chains, TECs via occultations between various low-altitude satellites and between low and high altitude satellites, line-of-sight UV emission data, and magnetometer data from a network of 100 ground stations. To be useful for a model that will provide continuous ionospheric specifications, the data must be in real time or in near real time (within 90 minutes of the specification). Also, the uncertainty in the data must be known, because this is an input to the Kalman filter analysis.

The data sources that are currently being used in our Kalman filter reconstructions are shown in the right panel of Fig. 1. There are 16 digisondes (triangles), 42 ground-based GPS receivers (circles), and 2 DMSP satellites. The short and long curved lines show the GPS and the DMSP satellite tracks during a 1-hour period, respectively. The data are assimilated exactly as they are measured, i.e., bottomside N_e profiles from the digisondes, in situ N_e along the DMSP satellite tracks, and slant TEC from GPS ground-based receivers. Note that the instrument configuration shown in the right panel of Fig. 1 corresponds to a snapshot at 0:30 UT on day 336. As the Earth rotates, the satellite tracks and TEC fields-of-view move around, but this is automatically taken into account in the Kalman filter analysis.

THE IONOSPHERE/PLASMASPHERE MODEL

For GAIM, we have developed a new ionosphere/plasmasphere model (IPM), which is especially tailored for the use in our Kalman filter. The model solves the continuity and momentum equations for the five ions, O^+, NO^+, O_2^+, N_2^+, and H^+, on convecting flux tubes that realistically follow the geomagnetic field. Currently, the IPM extends in magnetic latitude from equatorial to upper mid-latitudes in both hemispheres and extends from 100 km to about 20,000 km altitude, covering the ionospheric E- and F-regions as well as the plasmasphere A detailed description of the model is given in *Schunk et al*. [2002b].

KALMAN FILTER

GAIM uses a Kalman filter technique for the main data assimilation algorithm, which continuously reconstructs the global electron density. This filter provides an efficient means for assimilating different data types into a time-dependent, physics-based, numerical model, taking into account the uncertainties in both the model and data [*Daley*, 1991]. The Kalman filter is a sequential least-squares procedure that finds the best estimate of the state (ionosphere) at time t based on all the information that is available prior to this time. The basic principle is to combine measurements from an observational network with the information obtained from a physics-based ionospheric model, taking into account the corresponding statistical description of uncertainties. Formally, the Kalman filter performs a recursive least-squares inversion of all of the measurements (slant TEC, in situ satellite, digisonde, etc.) for the model variable (electron density) using the physics-based model as a constraint. In practice, a weighted average of the measurements and the model result is taken, using the relative accuracy of the two as the weights. The net result is an improved estimate of the model variable (electron density), where the improvement is in a statistical sense. The improved estimate for N_e has the least expected error given the measurements, model, and error statistics. With this approach, the specification of the error covariances for both the measurements and model is critical. This issue and the mathematical details associated with the Kalman filter are given in *Scherliess et al*. [2002].

APPROXIMATE KALMAN FILTER

Although it is theoretically straight forward to apply the Kalman filter to ionospheric data assimilation, difficulties arise when implementing the system due to the enormous computational requirements, both in storage and CPU time, associated with the propagation of the model error covariance matrix (for a full discussion of this problem see *Fukumori* *and Malanotte-Rizzoli* [1995]). As a practical method, we implemented an approximation of the state error covariance matrix, employing a reduction of the model dimension and a linearization of the physical model for the propagation of the error covariance matrix. These approximations lead to a dramatic reduction in the computational requirements [*Scherliess et al.*, 2002]. Formally, the two approximations could lead to suboptimal estimations, but the uncertainty associated with the observation and model errors may lead to statistically indistinguishable differences between the truly optimal and suboptimal estimates [*Cane et al.*, 1996]. The strength of these approximations, however, lies in the otherwise not possible use of the Kalman filter framework to objectively evaluate the model state error covariances. These errors are typically anisotropic and inhomogeneous and are difficult to specify.

A KALMAN FILTER SIMULATION

To better guide the Kalman filter development in GAIM, we constructed, for our initial application of the technique, a Data Simulation System Experiment (OSSE) for the South-American region. In this simulation we only used a small subset of our typical dataset shown in Fig.1. In particular, we used only two different synthetic (model generated) data types: slant TEC from three ground-based GPS stations and bottomside density profiles from one ionosonde. Fig. 2 shows our model region as well as the locations of the GPS receivers and the ionosonde. The synthetic data were generated from a run of a global ionospheric model by probing the resulting 3-dimensional, time-dependent electron density distribution for a weather (truth) simulation exactly the same way the real instruments probe the real ionosphere. For the ionosondes, observations were taken in 15-minute intervals from 100 km altitude up to the height of the F2-layer, h_mF_2, in 10 km increments. For the GPS receivers, slant TECs were generated only for elevation angles greater than 15°. When the synthetic data were generated, noise was added to each "measurement" in order to mimic a real observation. A 5 TECU level of noise was added to all simulated TEC measurements and a 10% uncertainty to the simulated ionosonde measurements. For the weather simulation, we varied the equatorial vertical drift by superposing on the climatology values a constant offset of 5 m/s in addition to a random component. At each time step a “best-guess” ionosphere (GAIM 1) was also generated [*Schunk et al.*, 2002], which provided ionospheric background densities. For control purposes, a climate run using empirical climatological drivers was also performed.

The Kalman filter assimilation procedure was implemented as follows. At 1200 UT on day 335, the N_e distribution obtained from the climatology run was taken to be the initial distribution at the start of the N_e reconstruction. Every 15 min the evolving weather simulation was probed to obtain the two synthetic data types (with noise), as described above. At these time marks, the ionosphere/plasmasphere model was also integrated forward in time, and the linearized transition matrix and the transition model error covariance matrix were determined. Using the new data and the new transition and error matrices, the Kalman filter reconstructed an updated estimate of the N_e distribution. This update was then used to also improve the estimation of the equatorial vertical plasma drifts, which were fed back into the IPM-background run and the assimilation was repeated at the next 15-min time mark. As time advanced, the Kalman filter produced a 3-dimensional, time-dependent, N_e distribution that got closer and closer to the N_e distribution associated with our weather simulation.

Fig. 3 shows results from our Kalman filter analysis along a geomagnetic meridional plane from 100 km up to 1500 km altitude after 10 hours of assimilation time. The plane is in the middle of our simulation region (Fig.2). The top row shows, from left to right, the weather (truth) case, the climatology (GAIM 0) case, the "best-guess" (GAIM 1) case, and the Kalman filter reconstruction (GAIM 2). In the bottom panel the height profiles at the magnetic equator for the four density fields, "truth", GAIM 0, 1, and 2, are shown (left panel) and the percentage differences between the "truth" case and GAIM 0, 1, and 2, respectively. It is apparent that the Kalman filter was successful in capturing the ionospheric density distribution. In particular, the filter was able to track the equatorial layer height as well as the strength of the equatorial anomaly.

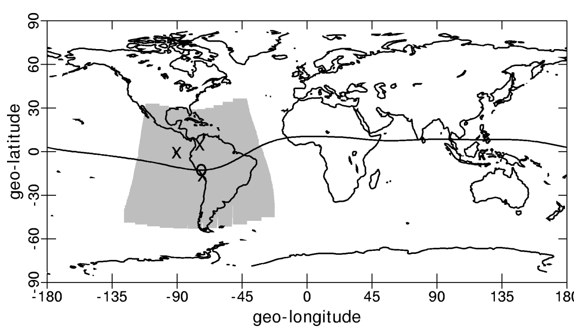

Fig.2. Kalman filter region (shaded area) used in this study. The “x” and “o” represent the locations of the GPS ground receivers and the ionosonde, respectively.

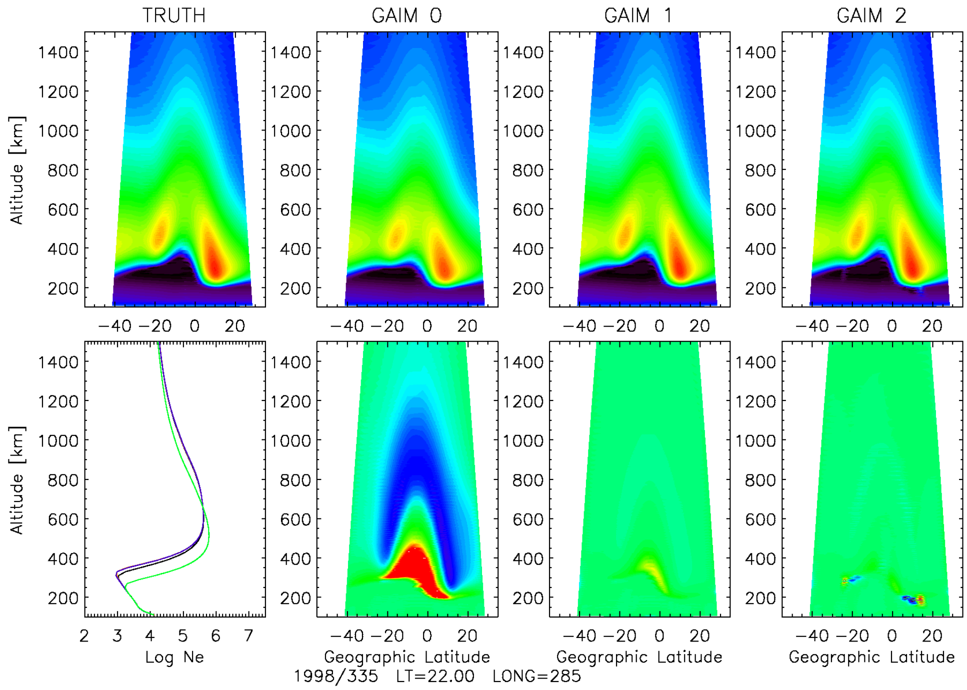

Fig. 3. Top panels from left to right: contour plots of plasma densities corresponding to the weather (truth) simulation, the climate run (GAIM 0), the "best-guess" ionosphere (GAIM 1), and the Kalman filter reconstruction (GAIM 2). The densities are color-coded from $10^3 cm^{-3}$ (blue) to $10^7 cm^{-3}$ (purple).Bottom panel from left to right: Height profiles of the plasma density at the magnetic equator for the four cases shown in the top panel, percentage difference between GAIM 0 and "Truth", GAIM 1 and "Truth", and GAIM 2 and "Truth". The results correspond to the Peruvian sector and 2200 LT on the first day of the assimilation (day 335). A red or blue color in the differences represents an overestimation or underestimation of the "true" densities, respectively.

SUMMARY AND CONCLUSION

A physics-based data assimilation model for the ionosphere is under development as the central part of GAIM. The model is centered on a new model of the ionosphere/plasmasphere system (IPM) and will provide specifications and forecasts from 90 km to geosynchronous altitudes on a global, regional, or local grid, depending on the operational demands and available data sets. The main data assimilation in GAIM is performed by a Kalman filter. We have used a practical method for the implementation of the filter based on a reduced state approximation and a numerical linearization of the physical model. The initial results of this assimilation technique over the South-American region are very encouraging.

REFERENCES

Cane, M. et al., *J. Geophys. Res*., 101, 22,599-22,617, 1996.
Daley, R., *Atmospheric Data Analysis*, Cambridge University Press, Cambridge, 1991.
Fukumori, I., and P. Malanotte-Rizzoli, *J. Geophys, Res., 100*, 6777-6793, 1995.
Howe, B. M., K. Runciman, J. A. Secan, *Radio Sciences, 33,* 109-128, 1998.
McCoy, R. P., *Space Weather, Geophys. Monograph, 125*, 31-37, 2001.
Scherliess, L., R.W. Schunk, J.J. Sojka, and D.C. Thompson, *IES2002 Symposium*, 2002.
Schunk, R.W., L. Scherliess, and J.J. Sojka, *Adv. Space Res*., in press, 2002a.
Schunk, R.W., et al., *IES2002 Symposium*, 2002b.