Global Assimilation of Ionospheric Measurements (GAIM)

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LONG-TERM GOALS

Our primary goal is to construct a real-time data assimilation model for the ionosphere-plasmasphere system that will provide reliable specifications and forecasts. A secondary goal is to validate the model for a wide range of geophysical conditions, including different solar cycle, seasonal, storm, and substorm conditions.

OBJECTIVES

We propose to develop a software program that will provide for a *Global Assimilation of Ionospheric Measurements (GAIM)*. GAIM will use a physics-based ionosphere-plasmasphere model as a basis for assimilating a diverse set of real-time (or near real-time) measurements. The program will provide specifications and forecasts on a specified spatial grid that can be global, regional, or local (50 km x 50 km). The specifications/forecasts will be in the form of 3-dimensional electron density distributions from 90 km to geosynchronous altitudes (35,000 km). Auxiliary plasma parameters will also be provided, such as N_mF_2, h_mF_2, N_mE, h_mE, and slant and vertical TEC. In its *specification mode*, GAIM will provide *quantitative estimates* for the accuracy of the reconstructed ionospheric densities. The measurements GAIM will assimilate include: (1) Slant path TECs between 80-90 ground receivers and the Global Positioning System (GPS) satellites; (2) Occultation data from a satellite constellation such as COSMIC; (3) TECs associated with the CIT network; (4) Bottomside N_e profiles from digisondes associated with the Air Force DISS network; (5) In situ plasma parameters from the SSIES instrument package on the DMSP satellites; and (6) Line-of-sight UV emissions and deduced plasma parameters from the Naval Research Laboratory's SSUSI and SSULI instruments. GAIM will have a *modular construction*, so that new data types can be readily assimilated when they become available.

APPROACH

Our approach is to use a *two-step process* to obtain a 3-D ionospheric reconstruction. First, *certain* data sets will be assimilated so that the *inputs* (neutral parameters, electric fields, precipitation) to the physics-based ionosphere-plasmasphere model *can be adjusted*, within expected errors, to match observations, and then the physics-based model will be run in order to obtain a 3-D N_e distribution that is consistent with the measured inputs. This first step should result in realistic ionospheric density features. Next, this simulated ionosphere-plasmasphere system will be used as a *starting point* for an *electron density reconstruction* using all of the different data types that pertain to N_e and a Kalman filter assimilation technique. The use of a simulated ionosphere-plasmasphere system will provide

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14. ABSTRACT
Our primary goal is to construct a real-time data assimilation model for the ionosphere-plasmasphere system that will provide reliable specifications and forecasts. A secondary goal is to validate the model for a wide range of geophysical conditions, including different solar cycle, seasonal, storm, and substorm conditions.

15. SUBJECT TERMS

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important constraints on the N_e reconstruction, and hence, should yield more reliable reconstructions. Additional parameters that will be available as a result of the N_e reconstruction include the neutral densities, temperatures and winds, the equatorial plasma drifts, and the high-latitude convection and precipitation patterns. Also, forecasts are possible *(step 3),* because the inputs to the physics-based model will be known along with the ionosphere-plasmasphere reconstruction. Starting from this reconstruction and the *initial* model inputs, a forecast can be made for the variations of the inputs and then the physics-based model can be run forward in time with these forecast inputs. Our approach requires the following general tasks: (1) Model construction; (2) Algorithm development for real-time data quality assessment; (3) Construction of the Kalman filter data assimilation algorithms; (4) Construction of an executive system to control the data flow and models; and (5) A validation program.

The GAIM model is being developed by a team of scientists from Utah State University (USU), the University of Colorado at Boulder (CU), the University of Texas at Dallas (UTD), and the University of Washington (UW). R. W. Schunk has overall responsibility for the project and has responsibility for the data assimilation connected with the high-latitude model drivers. J. J. Sojka (USU) is responsible for the data quality assessment algorithms and the data assimilation connected with the mid-latitude drivers. D. C. Thompson (USU) is responsible for constructing the executive system. L. Scherliess (USU) is responsible for the Kalman filter N_e reconstruction algorithms. D. N. Anderson (CU) is responsible for the data assimilation connected with the low-latitude model drivers. T. J. Fuller-Rowell (CU) is responsible for the data assimilation connected with the neutral atmosphere. M. Codrescu (CU) is responsible for the GPS-TEC and occultation data. R. A. Heelis (UTD) is responsible for the DMSP satellite data. B. M. Howe (UW) is responsible for guiding the construction of the Kalman filter algorithms.

WORK COMPLETED

There are three variants of GAIM models under development. All three models incorporate state-of-the-art data assimilation techniques at different levels of sophistication and maturity. The least complex, but most mature, is the Gauss-Markov Kalman Filter model, which covers the E-region, F-region, and topside ionosphere up to 3000 km, and takes account of six ion species (NO^+, O_2^+, N_2^+, O^+, He^+, H^+). With this model, the Ionosphere Forecast Model (IFM) provides background ionospheric density fields and then density perturbations are superimposed on the background densities based on the available data. This model has both global and high-resolution regional capabilities.

The Limited Physics-Based Kalman Filter incorporates the next level of complexity in the suite of USU models. Similar to the Gauss-Markov Kalman filter, the USU Limited Physics-Based Kalman Filter is based on the IFM and covers the E-region, F-region and topside ionosphere to 3000 km and takes account of six ion species (NO^+, O_2^+, N_2^+, O^+, He^+, H^+). However, the output of the model is a 3-dimensional electron density distribution at user specified times. In addition, auxiliary parameters are also provided, including N_mF_2 h_mF_2, N_mE, H_mE, slant and vertical TEC. In the USU Limited Physics-Based Kalman Filter, the ionospheric densities obtained from the IFM constitute the background ionospheric density field on which perturbations are superimposed based on the available data and their errors. However, contrary to what is done in the Gauss-Markov Kalman Filter, the perturbations evolve over time using the IFM model. For the evolution of the errors, a statistical model (Gauss-Markov process) is incorporated. This allows for a better representation of the electron density field near steep gradients without introducing the computational load of a rigorous error propagation.

The most sophisticated of the USU models is the Full Physics-Based Kalman Filter. This model rigorously evolves the ionospheric (and plasmaspheric) electron density field and its associated errors using the full physical model. Advantages of this rigorous approach are expected to be most significant in data-sparse regions and during times of "severe weather." Necessary approximations to make the model computationally tractable capitalize on the newest developments in oceanographic data assimilation. The model is based on a new physics-based model that is composed of an Ionosphere-Plasmasphere Model (IPM) that covers low and mid-latitudes and an Ionosphere-Polar Wind Model (IPWM) that covers high latitudes. These new physics-based models are state-of-the-art and include six ion species (NO^+, O_2^+, N_2^+, O^+, He^+, H^+), ion and electron temperatures, and plasma drifts parallel and perpendicular to the geomagnetic field. These models are based on the International Geomagnetic Reference Field, which accurately describes the relative positions of the geographic and geomagnetic equators and the declination of the magnetic field lines. The physics-based models cover the altitude range from 90 to 35,000 km, which includes the E-region, F-region, topside ionosphere, plasmasphere, and polar wind. The different real-time data sources are assimilated via a Kalman filter technique and quality control algorithms are provided as an integral part of the full Kalman filter model.

With the above descriptions in mind, the following work was accomplished during the reporting period:

- We purchased an additional 18 CPUs with matching money from USU and expanded our GAIM computer cluster to 40 CPUs.

- We conducted an evaluation of statistical convection patterns for possible use in real-time specifications and forecasts (*Bekerat et al., 2003*).

- We conducted a preliminary analysis of ionospheric assimilation techniques for LORAAS tomographically reconstructed equatorial N_e profiles obtained from the ARGOS satellite (*Sojka et al., 2002*).

- We conducted an analysis of ten years of TEC data obtained from the TOPEX/Poseidon satellite mission so that we could acquire information of ionospheric behavior over the oceans (*Jee et al., 2003*).

- We studied various data assimilation techniques for the neutral thermospheric species during geomagnetic storms (*Fuller-Rowell et al, 2002*).

- We developed an algorithm to extract TEC from the NOAA CORS data.

- Previously, we constructed a physics-based Kalman filter model for the global ionosphere-plasmasphere system, but in the initial application only synthetic (model generated) data were used. During the last year, we have implemented four real data types, including ground-based GPS-TEC data from 170 sites, occultation data from 3 satellites, digisonde data from several sites, and in situ N_e from 2 DMSP satellites.

- Our regional Gauss-Markov Kalman filter model has been running continuously and autonomously since January, 2003, at USU, which assimilates ground-based TEC from more than 300 GPS receivers in the continental US (the NOAA CORS network).

- Our global Gauss-Markov Kalman Filter model has been running continuously and autonomously since July, 2003, assimilating occultation data, GPS-TEC data from 190 ground receivers, DMSP satellite data, and digisonde data.

- Beta versions of our regional Gauss-Markov Kalman Filter model have been given to NRL, AFRL, and NOAA/SEC for initial validation purposes.

RESULTS

Our physics-based, Kalman filter, data assimilation model has been run for a four-day period (March 20-23, 2002) using four different data types. The model assimilated in situ electron densities from 2 DMSP satellites (F13, F15), bottomside electron density profiles from 6 globally distributed DISS sounders, occultation data from 3 satellites (IOX, SAC-C, CHAMP), and slant TEC from a network of 167 GPS ground receivers (Figure 1). The data were continuously assimilated throughout the 4-day period and the physics-based Kalman filter model produced a 3-dimensional reconstruction of the ionosphere and plasmasphere. The reconstruction covered all longitudes, magnetic latitudes between 60° S and 60° N, and altitudes from 90 to 20,000 km.
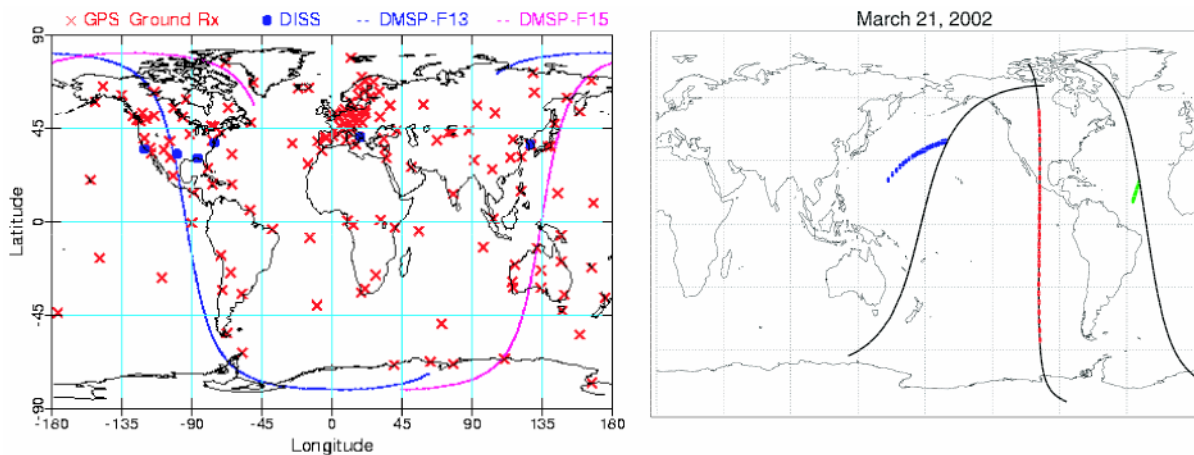

Figure 1. The spatial distribution of ground and space observing platforms. The figure shows 6 digisondes (blue dots), 167 ground GPS receivers (red crosses), two DMSP satellite tracks for a 1-hour duration (blue and purple solid curves), and sample orbits for the IOX, CHAMP, and SAC-C satellites (right panel).

Figure 2 shows a snapshot of the TEC distribution as a function of latitude and longitude at a selected universal time during the 4-day period. The figure shows vertical total electron content (TEC) versus latitude and longitude, with red corresponding to high TEC values and blue to low TEC values. The vertical TEC was obtained by integrating through the 3-D ionosphere-plasmasphere from 90 km to the upper boundary. The upper-left plot shows a snapshot at 02:45 UT of the Kalman filter reconstruction and the lower-left plot shows the corresponding result obtained from the Ionosphere Forecast Model (IFM), which amounts to time-dependent climatology. The lower-right plot shows the ratio of the Kalman/climate TEC values and the upper-right plot shows the Kalman TEC minus the climate TEC. A comparison of the physics-based, Kalman filter, electron density reconstruction with measurements not included in the data assimilation scheme indicates that the physics-based Kalman filter model is

able to satisfactorily reproduce the global N_e distribution. The model also calculates the self-consistent ionospheric drivers and it provides a quantitative estimate of the accuracy of the N_e reconstruction.
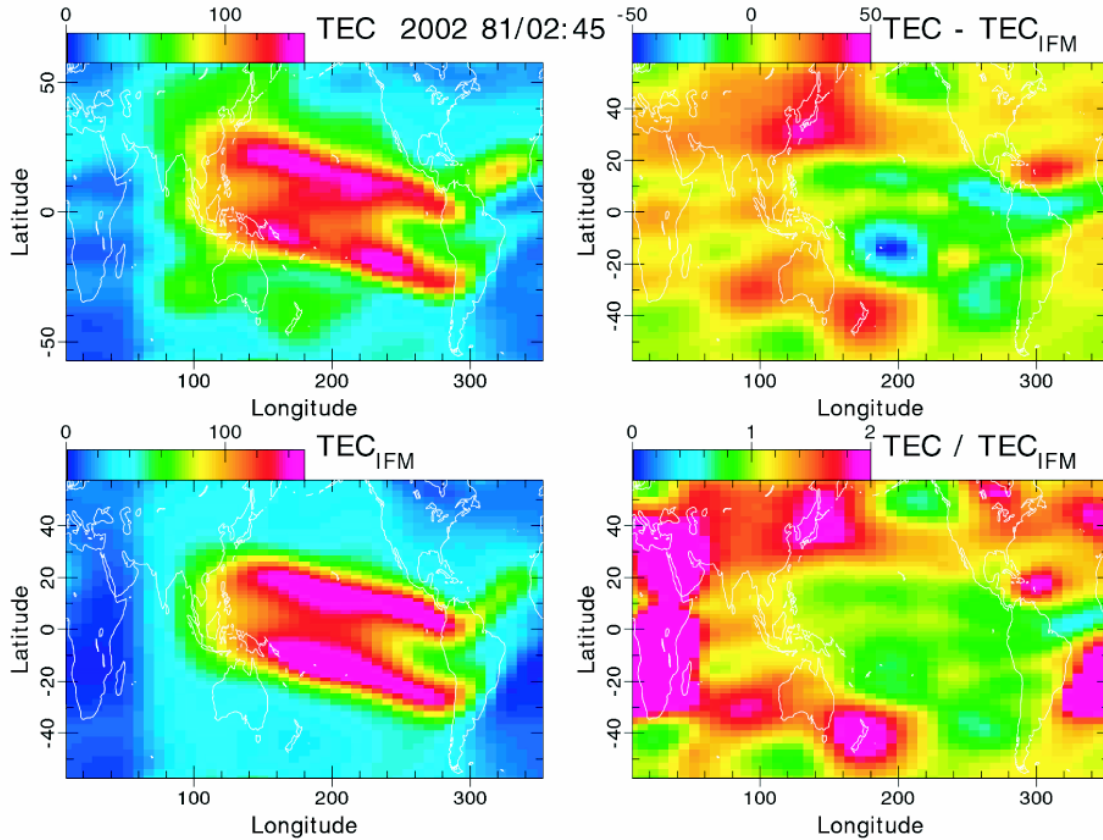

Figure 2. Vertical TEC plots at a selected time during a 4-day physics-based Kalman filter reconstruction of the ionosphere-plasmasphere system. The panels show the Kalman filter reconstruction (upper-left), the corresponding IFM result (lower-left), a plot of the (Kalman-IFM) TEC (upper right), and the TEC ratio of Kalman/IFM (lower-right). The color code is in TECU (1 TECU = 10^{16} TEC /los/m^2).

IMPACT/APPLICATIONS

GAIM will provide ionospheric specifications and forecasts on a global grid with a user specified spatial resolution. GAIM can be run at a central and distributed locations, including ships. The ionospheric specifications and forecasts are applicable to HF communications and geolocations, over-the-horizon (OTH) radars, surveillance, as well as surveying and navigation systems that use GPS data.

TRANSITIONS

GAIM will be used by NOAA, the Air Force, and the National Reconnaissance Office (NRO) to obtain a wide range of ionospheric products. In June, the NRO (via the Naval Research Laboratory) began testing our regional Gauss-Markov data assimilation model of the ionosphere for possible implementation at NRO. In September, the Air Force Weather Agency (AFWA) decided to fast-track the implementation of our global Gauss-Markov data assimilation model of the ionosphere so that it could be used for all of its ionospheric products. The goal is to deliver the model to the Air Force in January, 2004, for validation and then have it operational in January, 2005.

RELATED PROJECTS

Chunming Wang at the University of Southern California (USC) is the PI of a project entitled 'Global Assimilative Ionospheric Model.' This project is complementary to ours and we are collaborating on several aspects concerning modeling and data assimilation techniques. Both our program and his are funded through the same MURI initiative.

PUBLICATIONS

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Minter, C. F., Fuller-Rowell, T. J., and Codrescu, M. V., 2003: Estimating the state of the thermospheric composition using Kalman filtering, *Space Weather Journal*, submitted.

HONORS/AWARDS/PRIZES

R. W. Schunk, Utah State University, Nicolet Lecture, American Geophysical Union, 2002.

J. J. Sojka, Utah State University, "2002 Carnegie Foundation for the Advancement of Teaching Utah Professor of the Year."