Global Assimilative Ionospheric Model

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Award Number: N00014-99-1-0743

LONG-TERM GOAL

The long-term goal of our research is to develop a reliable and accurate global ionospheric weather monitoring and forecast system which can serve as a prototype for an operational system. To achieve this goal, we are developing and validating advanced data assimilation techniques to analyze diverse sources of ionospheric measurements. The assimilation of ionospheric measurements into mature first-principle ionospheric models will produce physically consistent, accurate ionospheric analysis, as well as the determination of important ionospheric drivers. As a result, this allows the generation of more accurate ionospheric weather forecasts. Our research activities maximally leverage the development of data assimilation techniques in the meteorological community. The application of general data assimilation techniques to ionospheric data analysis requires us to develop new mathematical techniques for both ionospheric modeling and optimization. This research will also help improve our understanding of the physics of the ionosphere and its response to magnetic storms, leading to a better characterization of severe space weather effects on power grids, communication, navigation, and other applications.

OBJECTIVES

Our research effort is focused upon the development of a global assimilative ionospheric model (GAIM). The model under development is based on first-principle theoretical ionospheric models, and can make use of a variety of data sources for the determination of ion and electron densities as well as the ionospheric driving forces. Our objectives in this phase of development are:

1. Expand the data sources assimilated into the GAIM. In particular, we developed necessary components of GAIM to handle GPS occultation data and the UV limb scanning data from the Low Resolution Airglow and Aurora Spectrograph (LORAAS) on the Advanced Research and Global Observation Satellite (ARGOS).

2. Validate the 4DVAR approach for the estimation of the ionospheric driving forces through both simulation experiments (OSSE) and the use of real data.

3. Improve the computational efficiency of our recursive estimation techniques.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2002**	2. REPORT TYPE	3. DATES COVERED **00-00-2002 to 00-00-2002**

4. TITLE AND SUBTITLE **Global Assimilative Ionospheric Model**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Mathematics,,1042 West 36th Place,Denney Research Building 346,,University of Southern California,,Los Angeles,,CA, 90089**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long-term goal of our research is to develop a reliable and accurate global ionospheric weather monitoring and forecast system which can serve as a prototype for an operational system. To achieve this goal, we are developing and validating advanced data assimilation techniques to analyze diverse sources of ionospheric measurements. The assimilation of ionospheric measurements into mature first-principle ionospheric models will produce physically consistent, accurate ionospheric analysis, as well as the determination of important ionospheric drivers. As a result, this allows the generation of more accurate ionospheric weather forecasts. Our research activities maximally leverage the development of data assimilation techniques in the meteorological community. The application of general data assimilation techniques to ionospheric data analysis requires us to develop new mathematical techniques for both ionospheric modeling and optimization. This research will also help improve our understanding of the physics of the ionosphere and its response to magnetic storms, leading to a better characterization of severe space weather effects on power grids, communication, navigation, and other applications.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

4. Develop tools for the estimation and calibration of the state covariance matrices. This is a critical issue that needs to be resolved before GAIM can be considered “operationally reliable”.

5. Collect and process a wide range of validation data for targeted GAIM validation efforts.

APPROACH

Our approach is to employ several data assimilation techniques to address different aspects of the data analysis problem, namely recursive statistical estimation and nonlinear least square optimization. The recursive estimation techniques used are the Kalman filter and approximate Kalman filter methods, including band-limited Kalman and optimal interpolation. The nonlinear least square optimization method used is the 4-dimensional variational (4DVAR) method with the use of the adjoint equation. Parallel to the development of the optimization components of 4DVAR method, we have developed flexible and efficient parameterization of key driving forces such as the E x B vertical drift, neutral wind, and production terms. The recursive estimation technique is primarily devoted to the determination of electron density with a relatively short data assimilation cycle of around 15 minutes. The 4DVAR technique is currently developed to estimate the ionospheric driving forces with a longer data assimilation cycle of around 2 hours. The optimized ionospheric state variables and driving forces are then used in the forward model to produce new forecasts for ionospheric variables.

The evaluation of the approach is first made through Observation System Simulation Experiments (OSSE) in which simulated measurements derived from forward model output are used. After an appropriate scheme for assimilation is established using synthetic data, real measurements are introduced in the evaluation process. The validation of the system requires the careful assembling and processing of a wide range of independent data sources. These data are compared to the GAIM predicted values for these measurements. When data assimilation model improves the quality of predicted values for these independent measurements that were not assimilated into the model, we have more confidence that the data assimilation model has captured relevant information on ionospheric dynamics.

WORK COMPLETED

Over the past 12 months, we have made significant progress in the following areas:

1. Introduction of Space Data into GAIM

During the last 12 months we have developed data processing tools for the assimilation of the GPS occultation data from several satellites and the UV limb scan data from the LORAAS instrument on the ARGOS satellite. The introduction of these data types marks an important milestone in our development of GAIM. We can for the first time assimilate ionospheric measurements over the entire globe, and we have developed efficient computation approaches to handle the high-rate GPS occultation data and the nonlinear dependence between the electron density and the UV measurements. We are also motivated in our development by the recent availability of the UV data from NRL and the GPS occultation data from the Blackjack GPS receiver on the Challenging Minisatellite Payload (CHAMP) and Satelite de Aplicaciones Cientificas-C (SAC-C), as well as from the Ionospheric Occultation Experiment (IOX) instrument developed by Aerospace Corporation.

In the case of UV data analysis, we have also used a 2D tomographic approach to investigate the quality of UV data and the statistical models necessary for tomographic inversion to obtain the electron density. We have identified the sensitivity of the inversion as a function of the statistical assumptions used in the inversion. A Bayesian approach is formulated for the adjustment of error covariance matrices. The lessons learned in the tomographic inversion approach can be directly applied to the selection of the covariance matrix in the Kalman filter approach.

2. Validation of 4DVAR Approach Through OSSE

Following our development of the 4DVAR approach (with the adjoint equation) for the estimation of the ionospheric driving forces, we have continued our efforts in validating this approach through OSSE. The main issue that we attempted to address is whether or not simultaneous estimation of the equatorial E x B drift and the neutral wind can provide reliable results for these parameters. We have constructed OSSE in which both the E x B drift and the neutral wind are perturbed from the climatological values. The results of our OSSE have demonstrated that through the use of ground GPS/total electron content (TEC) data alone, we can accurately estimate the “truth” values of the perturbed wind. In the table below, the results of an OSSE are shown. We note that the optimization routine seems to adjust the wind velocity first. The drift velocity only begins to converge when the wind velocity is near optimum values.

			Data Assimilation Cycles				
	Truth	Initial	1	2	3	4	5
Drift Parameter 1	-15.0	0.0	-8.15	-1.07	3.13	0.68	0.35
Drift Parameter 2	-167.0	0.0	-7.44	-10.04	-12.80	-48.59	-48.67
Drift Parameter 3	-60.0	0.0	-6.11	-14.00	-18.84	-153.44	-153.03
Drift Parameter 4	-209.0	0.0	-6.56	-27.80	-43.44	-431.30	-428.78
Drift Parameter 5	140.0	0.0	-0.87	5.34	-14.07	-285.58	-282.92
Drift Parameter 6	-160.0	0.0	-1.90	12.10	7.04	-76.38	-76.83
Drift Parameter 7	180.0	0.0	-4.04	0.09	2.68	134.37	133.20
Drift Parameter 8	393.0	0.0	-1.09	8.58	10.21	355.51	361.03
Drift Parameter 9	-225.0	0.0	-18.0	7.93	13.76	45.10	48.22
Wind Parameter 1	-50.	0.00	-185.37	-12.86	-51.55	-38.91	-47.94
Wind Parameter 2	0.	0.00	-127.78	138.67	-12.11	4.41	-0.78
Wind Parameter 3	50.	0.00	320.16	46.56	40.55	55.77	45.56
Wind Parameter 4	100.	0.00	331.78	50.87	92.13	96.75	101.97.

3. Validation of 4DVAR Approach for the Estimation of Equatorial Drift and Neutral Wind

Parallel to the validation efforts of 4DVAR approach through the OSSE, we have established contact with potential data providers for a validation campaign in the South American sector for the 4DVAR approach to the estimation of equatorial drift and neutral wind. The list of independent data sources include:

- Incoherent Scatter Radar (ISR) Measurements: Drifts, Ne, Te, ion composition, etc.
- Co-located instruments: Digisonde, Fabry-Perot Interferometers (FPI) (adjacent)

- On line ISR data: Drifts, power

- Brazil UNIVAP Ionospheric Observation Chain

We are continuing our efforts in data set preparation to be used for the validation of 4DVAR approach.

4. Validation of Kalman Filter Approach

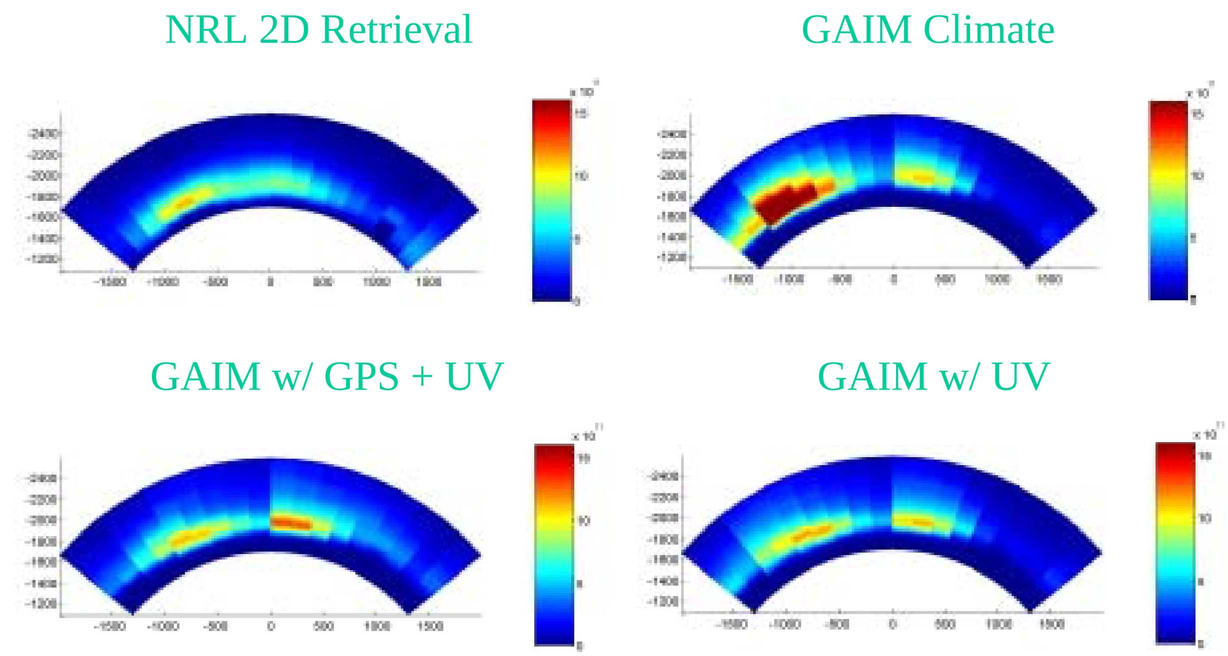
During this period, work proceeded on using the band-limited Kalman filter approach to assimilate both GPS occultation data and UV limb scans. In this report we will briefly describe some of the UV results. The UV data from the LORAAS instrument provided by NRL consisted of calibrated radiances at 1356 Angstroms from nighttime scans during October 2000, along with information about the geometry of the scans. The observed intensity can be modeled as an integral along the ray path:

$$I(\text{observed}) = 10^{-6}\alpha \int n_e(s)\ n_{o^+}(s)\ ds \ + \ \nu$$

where I is the intensity in Rayleighs, n_e is the electron density, n_{o+} is the O^+ density, α is the radiative recombination rate, and υ is the data noise. For a single-species (O^+) model, this equation reduces to an integral of the square of the electron density (n_e). This observation operator is then linearized within the Kalman filter and a few iterations are required for convergence.

We have performed multiple assimilation runs using ground GPS TEC data alone, UV data alone, and GPS and UV data combined. The figure below shows four electron density retrievals for a 2D slice below the 11^{th} nighttime track of the ARGOS LORAAS instrument on 10/03/2000. The NRL retrieval is a 2D tomographic technique in which 18 Chapman layers (one for each scan) are solved for simultaneously using all of the radiances from the 18 scans. The other three retrievals are interpolations of the GAIM 3D model grid onto the orbital plane, where the resolution of GAIM has been artificially reduced to match the 18 “panels” of the NRL retrieval.

The GAIM Climate run represents the output of the physical (forward) model with no data assimilated; the GAIM UV run used the same UV radiances that went into the NRL retrieval; and the GAIM GPS & UV run used the UV data and 166,000 ground GPS TEC measurements (5-minute data) from 97 globally-distributed receiver sites. Note that the GAIM “climate” exhibits larger densities than the actual ionospheric “weather” on this day, but after assimilation the NRL and GAIM UV retrievals are similar. These results are preliminary and a much larger UV comparison and validation study is planned.



5. *Transition of GAIM Toward Operational System*

With the new development of GAIM, we have decided that a more streamlined, regular validation effort is required. We have added into our computational facility two Linux-based dual processor Xeon workstations. A mirror system is also established at JPL. The current version of GAIM is being transitioned onto these more powerful computers. GAIM will be routinely validated using daily GIM TEC maps based on ground GPS and independent ionospheric measurements from TOPEX/JASON and ionosondes.

6. *Simultaneous Estimation of Densities and Driving Forces*

We have started to develop codes that will allow for the simultaneous estimation of ion densities and the driving forces. Our approach is based upon the extended Kalman filter. Extended Kalman filtering is based upon first order linearization of the underlying nonlinear system. It is well known that the use of extended Kalman filtering as a basis for an adaptive observer can result in biased estimates and divergence. This is primarily due to incomplete knowledge of the noise covariances and the fact that the dependence of the Kalman gains on the unknown system parameters being estimated has not been taken into account when the sensitivities required by the linearization are computed. We are testing a modification of the extended Kalman filter which is based upon an innovations form of the model and the direct parameterization of the Kalman gains. It has been shown that such an approach produces unbiased estimates and global convergence. Because of the large number of parameters and states involved, it is anticipated that the extended Kalman filtering will be done on a coarser grid and will make use of the efficiency enhancing approaches we have developed earlier for the standard Kalman filter (e.g. the band-limited approach, etc.). The resulting estimates for the driving forces will then be introduced into our standard linear Kalman filters for the densities alone. We have started our investigation by developing the technique for the simultaneous estimation of the ion densities and a spline-based paramterization for the E x B drift.

RESULTS

The GAIM model can now accept as input TEC values from ground GPS, TEC values from space-based GPS occultations, radiances from UV limb scans, and densities from ionosonde profiles. The preliminary validation of GAIM using GIM TEC maps, NRL 2D density retrievals, and independent measurements from TOPEX and ionosondes demonstrates that the approaches we have taken in data assimilation can significantly increase the accuracy of ionospheric specification. In particular, use of the large volume of ground GPS TEC alone can significantly increase the accuracy of the specification of electron density profiles.

IMPACT/APPLICATIONS

This work will have a strong impact on the implementation of an operational space weather model for ionospheric specification and forecast. The results of this study have been well received by the ionospheric research communities. Several research groups including AFRL and NRL have shown strong interest in future collaborative research.

TRANSITIONS

Our project is still in its initial stage. No software has been transitioned to other institutions or agencies yet.

RELATED PROJECTS

Several key investigators on our team are also key members in the ionospheric and atmospheric remote sensing group at JPL working on improving and maintaining JPL's ionospheric mapping capabilities, which have been used by and are supported in part by grants from the Air Force and Navy.

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