A Review of the Development of a Global Assimilative Ionospheric Model

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Abstract

The long-term goal of our research is to develop a reliable and accurate global ionospheric weather monitoring and forecast system that can serve as a prototype for an operational system. To achieve this goal, we are developing and validating advanced data assimilation techniques to analyse 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.

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 data assimilation (4DVAR) method with the use of the adjoint equation. 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 underlying forward model for GAIM is capable of taking inputs from empirical models or direct measurements of auroral precipitation energy and electric potential to compute ion production and plasma convection, respectively (the latter is required to drive the model dynamics at high latitudes). The GAIM has been exercised for global modeling with the high-latitude inputs coming from a few empirical models, such as the Heppner-Maynard convection model and auroral precipitation energy patterns. Several data assimilation methods are currently implemented in GAIM. The 4DVAR approach formulates the data assimilation problem as the minimization of a nonlinear functional, thereby enabling the development of a capability to estimate a large number of ionospheric driving forces. We have developed efficient parameterization techniques that allow us to estimate equatorial ExB drift, neutral wind, and ion production rates. The parameterization of the production and neutral winds was accomplished in a manner that allowed for a significant reduction in the number of parameters that had to be estimated. GAIM also uses the adjoint method from control and optimization theory to significantly reduce the computational effort required to compute the gradient of the least squares cost functional.

Several approximate versions of the Kalman filter have been tested. We have developed a new approach that allows us to significantly reduce the computational cost of the algorithm but retain most of the information in propagating the covariance matrix. This approach allows us to select the length of correlation in a physically meaningful fashion. The number of computational steps required for the implementation is nearly a linear function of the dimension of the model. The GAIM assimilation mode that uses this band-limited Kalman filter has been validated by assimilating real input data from ground and space-based GPS receivers and then comparing the retrieved electron density field to independent ionospheric measurements.

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