Ionospheric Data Assimilation: Techniques and Performance

Brian Wilson

Jet Propulsion Laboratory, 4800 Oak Grove Dr., Pasadena, CA 91109, USA
Brian.Wilson@jpl.nasa.gov

Abstract

Driven by the illuminating power and global coverage of new remote sensing datasets from satellites – the COSMIC constellation of space-based GPS receivers, UV limb and nadir scans from TIMED and DMSP, and the global ground GPS network – we have entered the era of data assimilation for the ionosphere, and more generally for space weather. The six-satellite COSMIC constellation provides global coverage of GPS limb scans or occultations (~5000 per day), with a latency of 15-120 minutes, each of which yields electron density information with unprecedented ~1 km vertical resolution. The SSUSI & SSULI instruments on current (and future) DMSP satellites provide global coverage and short repeat-times for UV nadir and limb scans. Calibrated measurements of ionospheric delay (total electron content or TEC) are available from two worldwide near real-time (NRT) networks of ground GPS receivers (~75 5-minute sites and ~125 more 15-60 minute sites). The combined NRT ground and space-based datasets provide a new opportunity to more accurately specify and forecast the global, 3-dimensional ionospheric density (ions and electrons) with a short time lag.

Even with the wealth of new data, the coverage is still spatially sparse as a percentage of the volume of the ionosphere-plasmasphere system, and sparse in time given the 15 to 60-minute variability of the ionosphere and how strongly driven it is by the solar UV radiation and the solar wind. This suggests a “formal” data assimilation approach in which a first-principles, physical model of the ionosphere is used to evolve the ion densities in time (and space), and the data are assimilated via an optimization technique (variational or Kalman filtering) to periodically (and continuously) bring the imperfect model back to reality by adjusting the density state and/or key ionospheric drivers. Alternatively, one might say that the physics is being used to interpolate the sparse data in space and time. Since the ionosphere is so strongly driven by solar UV radiation, particle precipitation, equatorial electrodynamics, neutral winds, etc. – and many of these drivers are imperfectly measured or not measured at all – reasonable forecast accuracy can only be achieved by using the data to “invert for” adjustments to the a priori driver values obtained from empirical models.

Multiple groups have embarked on a program of ionospheric data assimilation program during the past decade, but assimilation for space weather purposes is still in its infancy compared to weather and ocean models. It is not at all clear yet which assimilation techniques will be most accurate, make best use of all datatypes (simultaneously), and robustly identify inconsistent or erroneous input data. Operationally speaking, a key question is: Given the expected data coverage, how accurately will we be able to specify and forecast the ionosphere by the next solar maximum in 2011? To address this question in advance, one can use an assimilation model to perform Observation System Simulation Experiments (OSSEs). In such OSSE’s, input data are synthesized using real sensor geometry and a known “ground truth” ionosphere and then fed to the assimilation model to assess the accuracy of the retrieved density field for various grid resolutions, the capability to adjust key ionospheric drivers for varying geophysical conditions, and the effects of many system changes: different data noise levels, introduction of new datatypes, inconsistent or erroneous data, increased or decreased sensor coverage, missing physics during storms, etc.

The University of Southern California (USC) and the Jet Propulsion Laboratory (JPL) have jointly developed a real-time Global Assimilative Ionospheric Model (GAIM) to monitor space weather, study storm effects, and provide ionospheric calibration for DoD customers and NASA flight projects. JPL/USC GAIM is a physics-based 3-dimensional data assimilation model that contains a first-principles forward model with an adjoint model. GAIM uses a sparse Kalman filter to solve for the ion & electron density state and 4DVAR to adjust key drivers such as equatorial electrodynamics, neutral winds, and production terms. The adjoint model allows one to compute all of the “sensitivities” (derivatives) required to adjust

the input drivers so that the evolving physics-based density state better matches today's ionospheric weather. Daily (delayed) GAIM runs can accept as input ground GPS TEC data from 1000+ sites, occultation links from CHAMP, SAC-C, and the COSMIC constellation, UV limb and nadir scans from the TIMED and DMSP satellites, and in situ data from a variety of satellites (DMSP and C/NOFS). RTGAIM ingests multiple data sources in real time, updates the 3D electron density grid every 5 minutes, and solves for improved drivers every 1-2 hours. Since our forward physics model and the adjoint model were expressly designed for data assimilation and computational efficiency, all of this can be accomplished on a single dual-processor Unix workstation.

The tutorial will review various physics-based assimilation approaches – Kalman filter (KF), ensemble KF, variational techniques (4DVAR) – and then present detailed results from JPL/USC GAIM. A series of OSSE's will be presented to illustrate the crucial issues and performance tradeoffs, followed by a series of assimilation runs using real data. Retrieved vertical TEC maps and density profiles are quantitatively validated by comparisons to independent datasets: slant TEC from ground GPS receivers, TOPEX/JASON vertical TEC, ionosonde profiles & critical parameters, and density profiles from incoherent scatter radars (ISRs). In particular, we will highlight the impact of COSMIC occultation data and present results illustrating the power of limb scans to reshape the GAIM density profiles to accurately match nearby measured ISR profiles.