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From ionospheric weather nowcast to forecast: 1. Choice of IRTAM basis

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Abstract

Assimilative empirical models use available geospace observations to transform, on local or global scales, the underlying climatological model, such as International Reference Ionosphere (IRI), into a better match with the observations. Provided with near real-time sensor data, AEMs become useful in applications that rely on an accurate ionospheric weather nowcast. We make another step towards extending the AEM scope to the forecast applications that require knowledge of the ionospheric conditions over next several days. Development of such forecast capability has to emphasize processes that are not local and rethink the reference frame and coordinate system for its representations of the ionospheric dynamics from corotating to solar synchronous frame. We discuss details of the proposed expansion basis functions for implementation in forecasting AEMs.

1. Introduction

Assimilative empirical models (AEM) are recognized for their accurate representation of the ionospheric weather conditions at a low computational expense. The AEM concept began with a forthright initiative to adjust a quiet-time reference empirical model of the ionosphere, such as International Reference Ionosphere (IRI) [1], into a better match with currently available measurements. First taken at a local scale (i.e., constrained to a single site or a region), AEMs extended their coverage to the global ionosphere and then explored recent history of observations to reason about unknown ionospheric conditions outside the sensor locations by means of covariance-controlled extrapolation. The IRI-based Real-Time Assimilative Model (IRTAM) [2] is one example of the global 3D AEMs that draws its strength from treating the ionosphere in terms of its internal "eigen" functions, namely diurnal harmonics from 4 to 24 hours. When analyzed separately by the *temporal* scales of dynamics observed at sensors sites, measurements fall into different *spatial* scales of the undergoing processes that IRTAM senses and treats with different covariance matrices to restore the global picture from its observed fragments.

2. From nowcast to forecast

IRTAM has been designed to compute the ionospheric weather *nowcast*, i.e., specification of the current system state. When projected to future times, the IRTAM representation assumes the underlying climatological, average, quiet-time IRI variation. Even though, in such a treatment, the background IRI model is adjusted to match current conditions and IRTAM includes in some sense the ionospheric dynamics from the measurements during previous 24 hours, in practice we found that such forecasts have a "short memory barrier" of about 4 hours. Forecasting beyond the barrier requires information from the entire heliophysics domain of interconnected components to assess how the cosmic scale processes will impact the ionosphere on longer time scales. More input parameters reflecting the sun, solar wind, and magnetospheric conditions are needed to be included in a forecast model in order to predict ionospheric processes and conditions in advance. Such ability has been a prerogative of *physics-based* models rather than the empirical representations that are built to capture only essential, average behavior; with some notable exceptions.

Analog ionospheric forecasting models [3] are empirical constructs that seek analogies of the current geospace conditions with previous records taken during similar disturbed conditions. Should such analogy be identified, the forecast is formed similarly to the historic information on record. The essentials to a successful analog forecast are (a) finding the optimal selection of characteristic geospace status indicators for their association with the subsequent ionospheric response, (b) selecting a suitable model architecture capable of learning the associations of several relevant geospace indicators with the ionospheric response, and (c) optimizing all components to ensure repeatability of the associations across the timeline of multiple events.

3. Geomap representation

Empirical models of the ionospheric properties (such as electron density, temperature, etc.) are spatio-temporal 4D models whose input is time and location (latitude, longitude, altitude). The common approach to the 4D modeling of the ionosphere is to first define a 1D multi-parameter function of altitude ("vertical profile") to describe the profile shape analytically. For each sensor station, the geographic latitude and longitude are known and fixed. On a surface map, each station is represented as a single point with the vertical profile parameter. These parameters change with time while the station corotates with the earth in space. The horizontal spatial coverage is provided by a large number of stations. Each parameter is then represented as a 3D global "geomap", a function of longitude, latitude, and time. Observed temporal variations include both site-specific (corotating) and heliospheric components.

One possibility to ensure that geomaps produce smooth and continuous representations of the voluminous data in a compact form is to fit available observations to a suitable functional basis of temporal and spatial terms. Training a geomap model becomes a process of computing the expansion coefficients to such a basis. Several approaches have been pursued to simplify the basis design by factoring out natural dependencies of the ionospheric dynamics on solar activity, geometry of the magnetic field, or season. An early design by Jones and Gallet [4,5] (JG), originally developed for modeling the O-wave critical frequency of the F2 layer (foF2) and proven to be effective in a multitude of studies (e.g., [6]), has been accepted for all geomaps in IRTAM. The JG basis solved several important challenges of building an optimal geomap: it used a highly custom function, powers of sine of modified dip angle, modip μ [7], $\sin^k(\mu)$ [5], to simultaneously capture *equatorial* (controlled by the Earth magnetic field) and *polar* (controlled by the solar ionization) features of foF2. Spatial representation of the global 2D map using JG basis requires 76 coefficients; in combination with the temporal harmonic expansion of 6th order, total number of coefficients needed to represent a day in the life of foF2 is 988.

Building a modern forecasting model such as the recurrent or time-delay neural networks seems unrealistic for a system whose quiet-time dynamics requires a thousand-variable description. A compromise simplification of the basis is needed that would reduce its complexity, even though at a potential loss of detail and accuracy.

Because the IRI models of foF2 and M(3000) were developed based on measurements from specific ground stations, the geographic/geomagnetic corotating coordinate system was used to construct the base-functions and their expansion coefficients. This choice of corotating coordinate system has been very successful in best describing the ionospheric conditions at each of these locations. However, development of the IRTAM forecast capability has to emphasize processes that are not local and rethink the reference frame and coordinate system for its representations of the ionospheric dynamics from the *corotating* frame (UT-driven) to the *solar synchronous* frame and geomagnetic coordinate system (local time and magnetic dipole coordinate system). In this coordinate system, measurements from a single station cover a zonal belt along the station latitude of a few hundred kilometers in radius, although this apparent enhanced spatial coverage is at the cost of the temporal resolution.

One possibility that would not only cut the expansion terms, but also place the ionosphere as a system in the solar synchronous coordinates for a more natural view of its behavior under disturbed geospace conditions, is a static (non-corotating) noon LT frame. This frame will capture the basic features of the modeled property of the ionosphere, with diurnal variation only attributed to the meridional movement of the Earth magnetic field. While such representation would not capture the co-rotating area-specific features like the Weddell Sea Anomaly, nor any tidal/planetary longitudinal structures, it requires a significantly smaller number of coefficients to define. Such a significant paradigm change may require a series of substantial investigations before we truly understand it although our objective is to improve the repeatability of the internal geospace dependencies and ultimately, predictive accuracy of the ionospheric weather forecast.

4. References

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