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Validating and Improving a Realistic Ionospheric Truth Model for Observing System Simulation Experiments of HF Propagation

Joseph Hughes*(1), Ian Collett(1), Walter "Junk" Wilson(1), Geoff Crowley(1),
Jonah Colman(2), and Russell Landry(2)
(1) Orion Space Solutions, Louisville, CO, USA; e-mail: joe.hughes@orionspace.com; ian.collett@orionspace.com; geoff.crowley@orionspace.com; junk.wilson@orionspace.com
(2) Kirtland AFB, NM, USA; e-mail: jonah.colman.1@spaceforce.mil; russell.landry@spaceforce.mil

The US Air Force Cover Analysis Program (AFCAP) experiments 1, 2, and 3 have all been multimillion dollar campaigns to perform detailed Observing System Experiments (OSEs) of the ionosphere. Much of that expense has been dedicated to collecting enough observations of the ionosphere to be capable of post processing a "truth" ionosphere that supports additional analysis of alternative OSE experiments. Even after such great expense, significant limitations exist in the regional, seasonal, and decadal breath of available "truth" data. The ability to conduct a quality OSE without having to deploy dozens of sensors and dozens of people to the field would vastly expand the research opportunities across time and location. Such "virtual" OSEs are called Observing System Simulation Experiments (OSSEs) and require a synthetic truth model. For the HF propagation environment relevant to AFCAP, the synthetic truth model must accurately represent small-scale structures that are not present in smooth climatological or physics-based models. These small-scale structures must be physically realistic in both space and time to support OSSEs based on HF propagation. We present a synthetic truth model that attempts to meet these requirements and a path of further development which we believe will achieve this objective.

Our synthetic truth model [1], is constructed from the smooth physics-based Thermosphere Ionosphere Electrodynamics General Circulation Model (TIE-GCM), by incorporating spatial and temporal electron density variations informed by two years of ionosonde measurements at mid-latitudes. The variations present in the ionosonde data that are not resolved by TIE-GCM are stored in terms of vertical, horizontal, and temporal correlations. To produce a realization of the truth model with these realistic electron density variations, to process is to (1) create uncorrelated Gaussian white noise, (2) use a Gaussian kernel in the spatial domain to enforce the vertical and horizontal correlations, (3) transform to the frequency domain to enforce the temporal correlation, and (4) apply this correlated noise to the TIE-GCM parent model.

Recently, using data from AFCAP experiment 2 (AE2), we have performed validation of the truth model's representation of the HF propagation environment. The AE2 data include oblique and vertical incidence soundings with a nominal 15-minute cadence. Ionospheric irregularities manifest as higher frequency variations in the time series of the maximum useable frequency (MUF) of oblique links. For several links of ground distances 500-2000 km, we perform OSSEs (HF raytracing through TIE-GCM and a realization of the truth model) to produce synthetic measurements for comparison. Although the time series observations are not the same because of the random nature of the truth model, we can compare spectral characteristics of the MUF. While the MUF spectrum for TIE-GCM falls off much quicker than the data, the spectrum for the realistic truth model matches the observed MUF spectra much more closely. Further methods of validation, such as a comparison of the E and F1 layer characteristics between the truth model and AE2 vertical incidence observations, are being pursued.

Improvements to the truth model are being explored. As previously described, the current version of the truth model is created by applying the spatial correlations with a Gaussian kernel and applying the temporal correlation in the frequency domain. We are pursuing an alternative approach using a coupled 4D spectrum of the ionosonde electron density variations that can be enforced in a single consistent step. We have developed numerical code for an N-dimensional Lomb-Scargle Periodogram that can reliably resolve spectral information from a set of non-uniform measurements in both space and time, enabling this kind of approach. In principle, the consistent treatment among the spatial and temporal correlations should allow the truth model to capture phenomena that are coherent in space and time, such as traveling ionospheric disturbances and sporadic E.

References

[1] J. Hughes et al., "On Constructing a Realistic Truth Model Using Ionosonde Data for Observation System Simulation Experiments," Radio Science, vol. 57, no. 11, p. e2022RS007508, 2022, doi: 10.1029/2022RS007508.