

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

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## ABSTRACT

The US Air Force Coverage and 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. Even after such great expense, significant limitations exist in the breadth of available truth data. The ability to conduct an OSE without having to deploy sensors and personnel would vastly expand research opportunities. 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 not present in smooth climatological or physics-based models. We present a synthetic truth model and a path of further development which we believe will achieve this objective.

Our synthetic truth model is constructed from the smooth physics-based TIE-GCM model by incorporating spatial and temporal electron density variations informed by two years of ionosonde measurements at mid-latitudes. Recently, using data from AFCAP experiment 2, we have performed validation of the truth model’s representation of the HF propagation environment (E, F1, and F2 layers). Improvements to the truth model are also being explored. For example, using a N-dimensional Lomb-Scargle Periodogram is a more consistent treatment among spatial and temporal correlations, allowing the truth model to capture phenomena that are coherent in space and time, such as traveling ionospheric disturbances and sporadic E.

## 1. INTRODUCTION

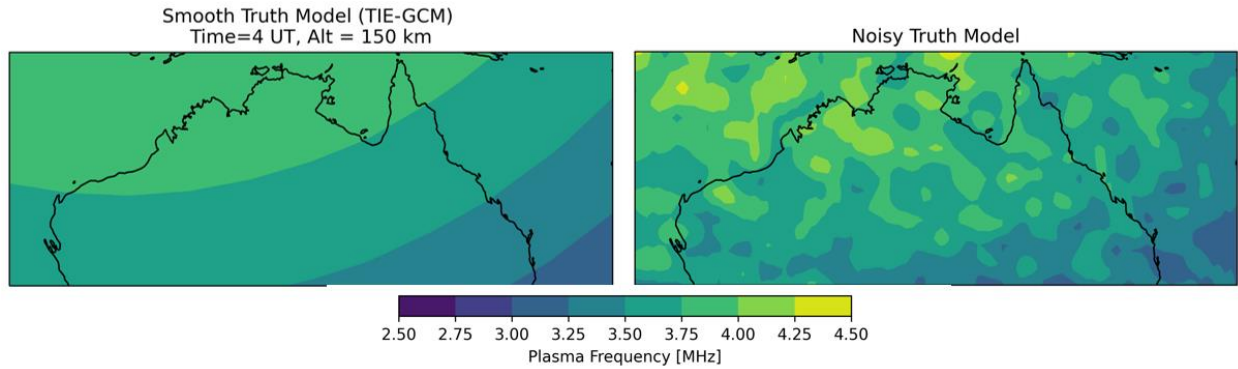
Although there are multiple uses and motivations for creating a synthetic or “noisy” truth model (NTM), the primary one is for more accurate Observation System Simulation Experiments (OSSEs). An OSSE has three steps:

- 1) Choose a sensor set and simulate measurements using a truth model. In meteorology, the truth model is commonly referred to as a “nature run.”
- 2) Ingest these simulated measurements with an assimilator to produce an analysis by updating the background to better match measurements.
- 3) Compare both the background and analysis to the truth model to assess the impact of the observation system.

The degree to which the analysis improves relative to the background indicates the value of the observation system. This process can be repeated with many different observation system configurations to optimize accuracy for the minimum cost and effort – providing the best ionospheric specification “bang” for a real life “buck.” However, the accuracy with which an OSSE predicts real life ionospheric specification depends on the accuracy of the truth model. Many OSSEs have used smooth climatological or physics-based models

which do not contain small-scale features. This limitation can lead to overly optimistic assessments of the utility of a given sensor architecture. For example, an OSSE using a smooth truth model will show improvements between two sensor locations even though no measurements are taken there because the truth model is well-approximated by the interpolant between these measurements. Since the real-life ionosphere is more variable and is not well-modeled by an interpolant, this is an optimistic assertion of the improvement in the specification. It is therefore crucial to have a truth model with realistic variances to ensure accurate OSSE results. In other words, it is impossible to know if a sensor system can resolve small-scale features if there are no small-scale features in the truth model.

To address this limitation in smooth truth models, we created the noisy truth model which contains variations in electron density that have horizontal, vertical, and temporal structure which is informed by two years of ionosonde data [Hughes *et al.*, 2022]. An example comparison of TIE-GCM and the NTM is shown in Figure 1 for an altitude of 150 km. Notice that the plasma frequency varies only with the solar zenith angle (SZA) in the TIE-GCM model. While the NTM plasma frequency has some SZA dependence, it is dominated by small regions of high and low frequency. The physical size, temporal duration, and amplitude of these enhancements and depletions are based on an analysis of ionosonde data. However, the NTM previously received only cursory validation with a single independent data type (total electron content time series). In this work, we validate the NTM using ionospheric soundings from the Air Force Coverage and Analysis Program (AFCAP) experiment 2.



**Figure 1.** Example of TIE-GCM and the Noisy Truth Model

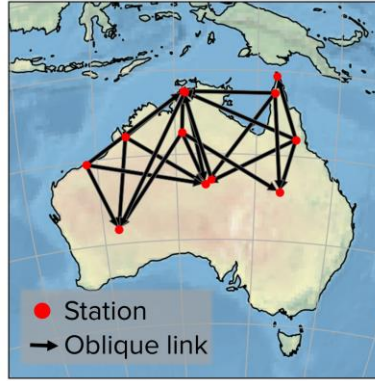
## 2. COMPARISON TO AFCAP EXPERIMENT 2 OBSERVATIONS

To validate the NTM's representation of small-scale electron densities in the bottomside ionosphere, where HF skywave propagation occurs, we use observations from AFCAP experiment 2 (AE2) in Australia on June 29, 2019. Figure 2 depicts the stations and oblique links between them. Validation is performed using hand-scaled vertical and oblique soundings. For the smooth truth model, we use a global TIE-GCM run driven by the geophysical indices observed on same day. The electron densities are reported hourly on a  $5^\circ \times 5^\circ$  horizontal grid. The NTM is created from the TIE-GCM parent model on a  $0.5^\circ \times 0.5^\circ$  regional grid in the vicinity of Australia, enforcing the spatial and temporal correlations of small-scale electron density irregularities for the proper season, local times, and altitudes. We note that this is just one instantiation of the NTM because it is created starting from random noise.

### 2.1 COMPARISON TO VERTICAL SOUNDINGS

The vertical sounding observations from AE2 consist of ionograms and corresponding hand-scaled electron density profiles. Although the observations from each station are collected at a nominal 15-minute cadence, the observation times are not necessarily synchronized between stations. The electron density profiles are filtered to ensure that no model-driven points are used in the comparison to the NTM. The valley region and topside are excluded, and any points with plasma frequencies outside of the frequency range of the

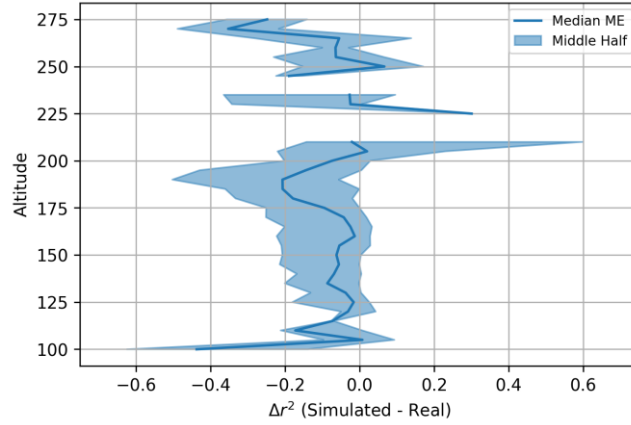
ionogram trace are removed. To compare to AE2, both TIE-GCM and NTM electron densities are interpolated to the same station locations, times, and observed altitudes of the AE2 electron density profiles. The horizontal and vertical correlations of electron density deviations for AE2 and the NTM are compared. The electron density deviation is relative to the smooth TIE-GCM model and is defined as  $x = \log(n) - \log(n_{TIEGCM})$ , where  $n$  is the electron density of either AE2 or the NTM. We compare how well  $x_{NTM}$  resembles  $x_{AE2}$  for horizontal correlation and vertical correlation. These are described separately below.



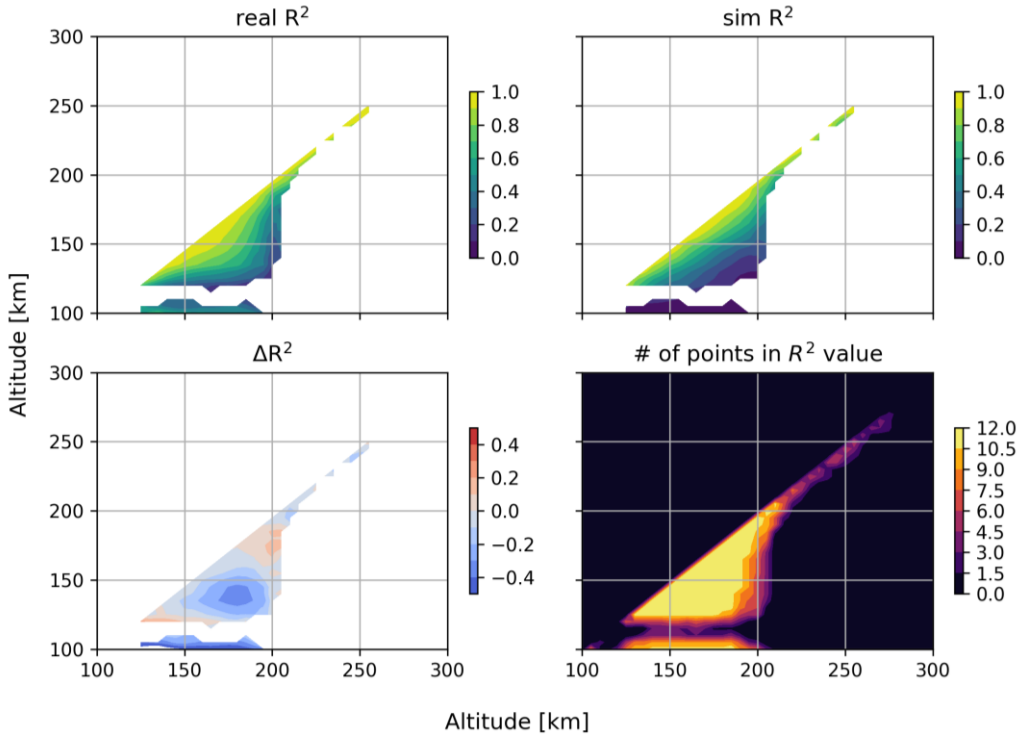
**Figure 2.** Locations of vertical and oblique soundings in AFCAP experiment 2

The horizontal correlations for  $x_{AE2}$  and  $x_{NTM}$  are determined by looking at the full-day time series data across all altitudes for all possible pairs of stations. The geographical distance between pairs of stations ranges from about 200 to 3500 km. At each altitude for each possible pair of stations, the  $r^2$  value is computed between the two electron density time series (some time interpolation is necessary because station observations are not synchronized). This process is performed separately for AE2 and the NTM. Finally,  $\Delta r^2$  is computed as the difference between  $r^2$  for the NTM and AE2. If the NTM perfectly represented the horizontal correlations of small-scale electron densities, then  $\Delta r^2$  would be zero. The results of the comparison are summarized in Figure 3. At each altitude, there is a  $\Delta r^2$  for each pair of stations. In this plot, the values at each altitude are summarized by their median (blue line) and middle half (blue shaded region). For many altitudes,  $\Delta r^2$  is close to zero, indicating good performance of the NTM. The largest discrepancy is between 175 and 200 km altitude, where the NTM underrepresents the horizontal correlation of electron density deviations as compared to the AE2 observations. There is also an apparent discrepancy above 250 km altitude, although this is likely due to the lack of observations at these higher altitudes.

The vertical correlations for  $x_{AE2}$  and  $x_{NTM}$  are determined on a per-station basis. For each station, the  $r^2$  value is computed between the two electron density time series for all possible pairs of altitudes where the time series have at least 20 points in common. As with the horizontal correlation comparison,  $\Delta r^2$  is computed as the difference between  $r^2$  for the NTM and AE2. These results are then aggregated for all stations, as shown in Figure 4. The top left panel is the mean  $r^2$  for AE2, the top right panel is the mean  $r^2$  for the NTM, the bottom left panel is the overall  $\Delta r^2$  (difference between mean  $r^2$  values), and the bottom right panel is the number of stations that contributed to the results at each pair of altitudes. Pairs of altitudes with contributions from fewer than 6 stations are excluded from the results. At many pairs of altitudes,  $\Delta r^2$  is small, indicating good performance of the NTM. The largest difference is the blue region centered on 130 km altitude along the vertical axis. The  $r^2$  for  $x_{NTM}$  at 180 km and 130 km is about 0.5 lower than for  $x_{AE2}$ . Another discrepancy is the blue region located just above 100 km altitude along the vertical axis. The  $r^2$  for  $x_{NTM}$  at 100 km and at altitudes between 125 km and 200 km is up to 0.5 lower than for  $x_{AE2}$ . This indicates that the NTM underestimates the amount of vertical correlation of electron density deviations between the E region and altitudes above as compared to the AE2 observations.



**Figure 3.** Summary plot of horizontal correlation difference  $\Delta r^2$  between NTM and AE2



**Figure 4.** Summary plot of vertical correlation difference  $\Delta r^2$  between NTM and AE2

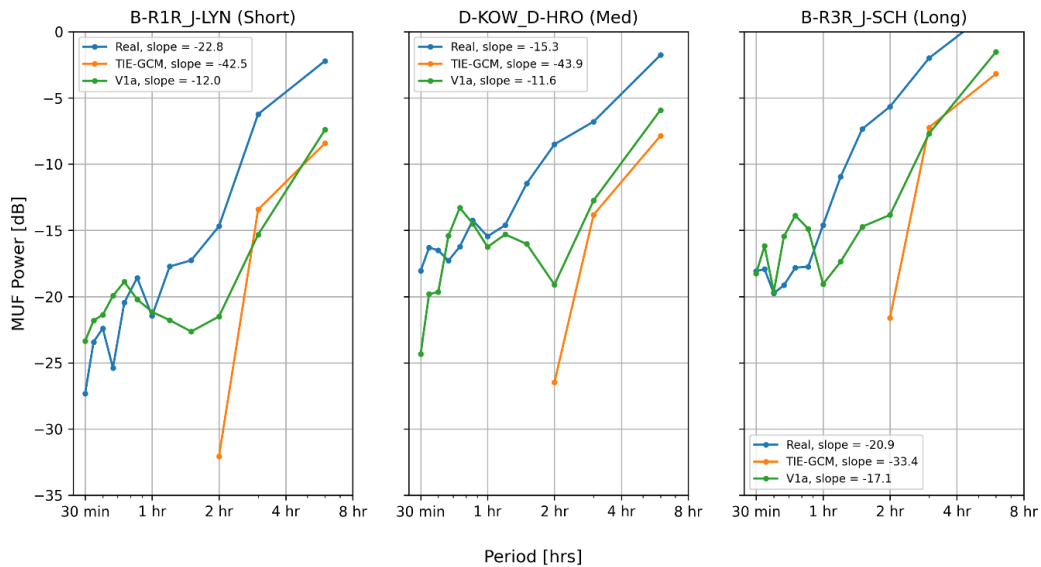
## 2.1 COMPARISON TO OBLIQUE SOUNDINGS

The oblique soundings from AE2 consists of oblique ionograms captured at a nominal 15-minute cadence. The oblique ionograms are hand scaled, including identification of the maximum useable frequency (MUF), which is the highest frequency observed in the ionogram trace, and the corresponding delay. The full-day time series of the MUF for each oblique link is used as the point of comparison to the NTM.

For TIE-GCM and the NTM, the time series of the MUF is synthesized. The MUF is found by doing HF raytracing in homing mode through the TIE-GCM or NTM electron density grid to find the ray with the highest frequency that can be transmitted along the oblique link. Rather than comparing the MUF time series directly, the MUF spectra are compared. A MUF spectrum is computed by first interpolating the

MUF time series to fill gaps in the regular 15-minute sampling and then using Welch's method (6 hour segments with 3 hour overlaps) to compute the spectral power.

Figure 5 compares the MUF spectra for oblique links of three different lengths. The blue curve is the MUF spectrum from AE2, the orange curve is TIE-GCM, and the green curve is the NTM. The TIE-GCM MUF spectrum only goes down to a period of 2 hours because the TIE-GCM electron density grids used were only available hourly. Nevertheless, the steep fall-off of the MUF power is apparent. TIE-GCM does not contain the short-period variations present in the real ionosphere. In contrast, the AE2 and NTM MUF spectra fall off more gradually, with more MUF power at shorter periods down to the shortest observable period of 30 minutes. These spectra demonstrate the impact of small-scale irregularities that cause fluctuations in the MUF at shorter time scales. As designed, the NTM captures small-scale irregularities that cause changes to the HF propagation environment (at least as seen in the MUF) at these time scales.



**Figure 5.** Comparison of MUF spectra for AE2 (blue line), TIE-GCM (orange line), and the NTM (green line) at three different oblique link lengths.

### 3. CONCLUSION AND NEXT STEPS

As is shown above, the NTM is far more capable than a smooth model such as TIE-GCM of replicating the variability of the ionosphere. This allows more accurate OSSEs and other simulation studies. However, the construction of the NTM has inherent limitations to the types of variabilities possible. The NTM is created in four steps:

- 1) Random white noise of the appropriate shape is created.
- 2) Horizontal and vertical smoothness is enforced using a gaussian kernel
- 3) This “smoothed noise” is Fourier transformed across the time dimension
- 4) A frequency dependent gain is applied in the time dimension and then an inverse Fourier transform is performed

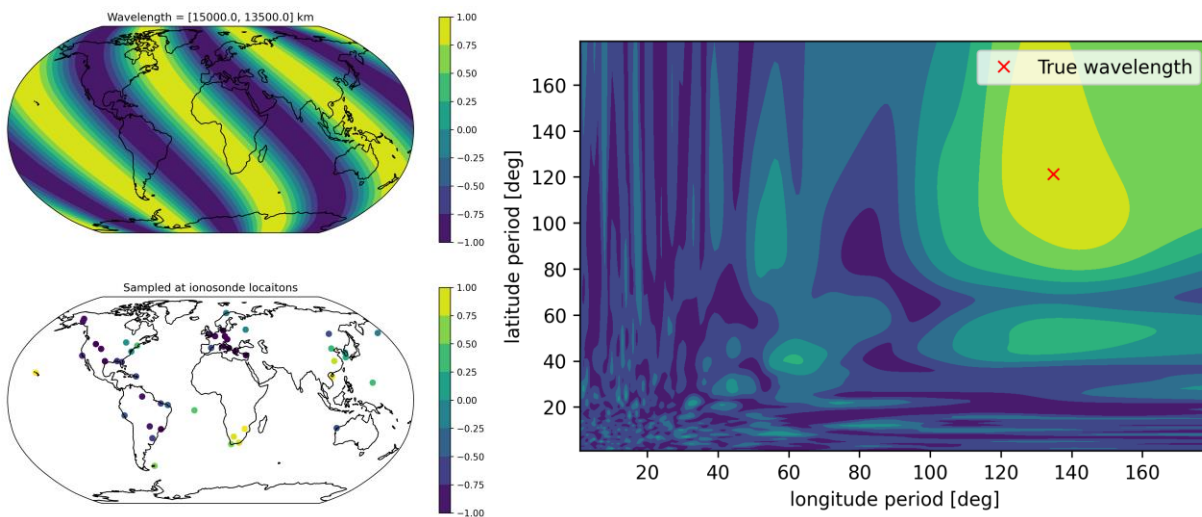
Because the spatial (2) and temporal (3&4) steps are independent, this method for creating at NTM is not capable of replicating phenomena that have correlated spatial and temporal behavior such as Traveling Ionospheric Disturbances (TIDs) or sporadic E. To address this limitation, we are currently exploring an alternate method for computing the NTM which has one fewer step:

- 1) Random white noise of the appropriate shape is created
- 2) This white noise is Fourier transformed across the time, altitude, latitude, and longitude dimensions

- 3) A frequency dependent gain is applied in every dimension and then an inverse Fourier transform is performed

This approach would allow for a coherent structure such as a TID or planetary wave to be represented since the spatial and temporal smoothing are applied consistently and simultaneously. In this approach, a peak in the frequency dependent gain would necessarily have a wave vector and a temporal angular frequency. This peak would turn into a wave in the NTM once the inverse Fourier transform is applied.

Although this method is more capable than the original method for creating NTMs, it has a difficulty: it requires knowing the frequency-dependent gain spatially. This is very difficult when using ionosonde data since ionosondes are not spaced uniformly around the globe. Many of them do measure at a uniform cadence, which is why a frequency-dependent gain is used for the time dimension in the first case. To address this, we have developed the N-Dimensional Lomb-Scargle Periodogram (ND LSP) to compute the spectra of irregularly spaced measurements in time, latitude, longitude, and altitude. A simulated example of this is shown in Figure 6.



**Figure 6.** Example of ND LSP for a generic global-scale wave sampled at ionosonde locations

The top left panel shows a wave which is sampled by the ionosondes shown in the bottom left. A visual inspection of the lower left panel would not be able to completely reconstruct the wave shown above, although it is evident that there are periodic structures. We passed the simulated ionosonde measurements to our ND LSP and computed the spectrum shown in the right panel. The red ‘x’ shows the true wavelength of the simulated wave, and we see that the ND LSP does indeed identify this wavelength, albeit with a broader spectral peak. These sensitivity studies will inform the observability of spectral structures in the ionosphere and eventually compute the frequency-dependent gain.

## ACKNOWLEDGEMENTS

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## REFERENCES

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