Observations and modeling of traveling ionospheric disturbance signatures from an Australian network of oblique angle-of-arrival sounders

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Abstract

An Australian network of oblique angle-of-arrival (AoA) ionosondes was installed as part of the ELOISE experimental campaign in September 2015, aimed at an improved understanding of the spatial and temporal structure of traveling ionospheric disturbances (TIDs) at mid-latitudes. In this paper, the array design and signal processing for the AoA sounder is described, along with a sample of results showing typical disturbance signatures. Realistic parameterized models of electron density perturbations, along with geometric ray tracing, were used to synthesize the effects of medium to large scale TIDs on the sounder observables and aid in classifying the measurements.

1. Introduction

Traveling ionospheric disturbances (TIDs) are one of the key contributors to spatial and temporal variability of HF radio propagation through the ionosphere. These wave-like perturbations in the background electron density are in many cases the ionospheric manifestation of atmospheric gravity waves (AGW) in the thermosphere. Within the F2 layer, medium-scale TIDs (with periods of 15–60 minutes) are thought to originate from tropospheric sources, while large-scale TIDs (with periods of greater than 1 hour) are associated with geomagnetic sub-storms in auroral regions. TIDs are frequently responsible for large off-angle deviations, additional discrete propagation modes and night-time spread-F in ionograms, and their occurrence is also closely linked to scintillation effects caused by small-scale plasma bubbles.

In recent years there has been increased interest in monitoring and forecasting these disturbances to support a diverse range of technologies sensitive to space weather, including GNSS, low-frequency radio astronomy and HF sky-wave radar systems. Operational HF radars, in particular, may suffer from reduced target detectability and coordinate registration accuracy in the presence of TIDs.

DST Group ran an experimental campaign (‘ELOISE’, the Elevation-scanned Oblique Incidence Sounder Experiment) in September 2015 to observe ionospheric variability across a number of different radar and optical systems in Australia. The experiment included two 19-element oblique incidence sounder receiving arrays in Laverton, Western Australia and Coondambo, South Australia, observing nine mid-latitude paths across the HF band. These systems are capable of measuring group delay, angle-of-arrival (AoA) and Doppler for each ionospheric mode, thus providing a rich data set for analyzing the effect of disturbances such as TIDs on HF propagation.

This paper will present a sample of the results collected as part of the ELOISE campaign, showing the off-angle returns and perturbed Doppler spectra characteristic of disturbances and dynamic behavior in the ionosphere. Examples of quasi-periodic and spatially-consistent disturbances across the sounder network are interpreted as TIDs, and one of the aims of the subsequent analysis was to evaluate how well these TID signatures can be synthesized by ray tracing through realistic parameterized models of electron density perturbations. Alternative TID models, from the simple corrugated mirror reflector to the AGW-seeded formulation of Hooke [1], are evaluated in terms of their ability to reproduce the AoA observations.

2. Array design and signal processing

While there exist a number of commercially available vertical incidence sounders with an AoA and/or Doppler capability (e.g. the Digisonde [2]), such systems are not as common for one-way oblique incidence as they require comparatively large arrays. Notable examples of previous work include [3] and [4]. For the ELOISE campaign, a new system was built from DST Group’s own direct-digital HF transmitter and receiver designs, which operate using a low-power (20 W) wide-band chirp waveform.

The two ELOISE receiving arrays each consisted of 19 elements, arranged as an orthogonal pair of uniform linear arms with a multi-channel direct-digital HF receiver per element. One 10-element arm (of length 90 m) observed the oblique paths of interest close to broad-side, while the other 10-element arm (of length 180 m) observed close to end-fire. A map of the two array locations and ELOISE AoA paths are shown in Figure 1. The path lengths ranged from 900 km to 2700 km.
A sophisticated suite of on-board processing included the following components, some of which were adapted from DST Group’s existing oblique incidence ionosonde:

- A robust RFI rejection scheme, to improve the clarity of ionogram trace features.
- An ionogram feature extraction and fitting algorithm, to parameterize the midpoint electron density profile.
- A clear channel evaluator and adaptive scheduler for making channel scattering function (CSF) observations, which are interleaved with the wide-band soundings to characterize the ionospheric Doppler spectra at key operating frequencies.
- A 2D angle-of-arrival (AoA) technique to extract bearing and elevation estimates for each ionogram/CSF pixel, based on a least-squares planar wavefront fit to the elemental phases.

All transmitter and receiver sites communicated via a virtual private network, which enabled schedules to be distributed and processed results to be retrieved in near real-time throughout the campaign. Further offline analysis has also since been developed to perform automatic peak detection and mode classification of ionogram/CSF images, and map the ionospheric reflection points geographically.

Array calibration was carried out using a combination of known line-of-sight, surface-wave and sky-wave signals, covering different angles of arrival. With this approach, bearing and elevation uncertainties of a few tenths of a degree were typical, although uncertainties increased for elevations below 10° and in the presence of unseparated multi-mode returns (e.g. the complex mode structure associated with spread-F). A directly injected reference waveform was also used to calibrate individual receivers.

3. Sample results

A sample ionogram from the Laverton array is shown in Figure 2, with colors scaled according to both received power (left) and bearing offset measured clockwise from the great circle path (right). This example represents relatively disturbed night-time conditions on the oblique path from Humpty Doo (near Darwin) to Laverton, with ground range 1989 km. Elevation measurements are also available, although not shown here for sake of brevity. The off-angle (‘satellite’) trace that appears at group delays between 2100 and 2200 km, with a bearing offset of almost 20°, is a signature of large-scale TIDs frequently seen in the post-sunset ionosphere at mid-latitudes. It is often found to be a precursor to spread-F irregularities [5].

An enlarged portion of the same ionogram is shown in Figure 3 alongside a neighboring CSF dwell at 5.7 MHz. This frequency corresponds to the dashed vertical line on the ionogram. The peak extraction algorithm has identified three 1-hop F2 returns in the CSF image, including the unperturbed shorter path (at 0.0 Hz Doppler and 2076 km group delay), and two off-angle longer paths: one with its reflection point advancing (at +0.8 Hz and 2123 km) and one receding (at -0.7 Hz and 2134 km). Their great circle bearing offsets were +10° and -7°, respectively, indicative of a TID propagating transversely (roughly north-westward) to the direction of the HF reception (north-eastward). The time evolution of ionograms supports this mode interpretation.

The 2-hop F2 mode structure (above 2300 km group delay) is considerably more complicated, although also contains both advancing and receding components in the CSF dwell.
4. Synthetic TID modeling

To aid the interpretation of results, realistic TID models and associated ray tracing/homing algorithms were developed that synthesize the observables from the AoA array (i.e. group delay, Doppler, bearing and elevation). The effects of TIDs on HF propagation have been widely synthesized in the past using such models, which seek to parameterize the TID (or its underlying AGW) in terms of amplitude, period, wave-vector and phase. In this paper, the following models are considered:

1. A corrugated mirror reflector (e.g. [6, 7]).
2. An AGW-seeded physics-based model, driven by collisional interactions with the neutral atmospheric constituents (e.g. [1, 8]).

The corrugated mirror reflector (model 1) is the simplest of the candidate TID models, consisting of a spherical shell ionosphere with sinusoidal perturbation superposed. It has the advantage of being quick to compute (being specular reflection only) and directly invertible under certain conditions [9]. It can also be relatively easily extended to support multiple harmonic components and large-scale tilts. Such a model is therefore useful for classifying disturbances in the observed data and providing first-order estimates of the TID parameters.

As an example of its utility, Figure 4 shows a time series of CSF observables (fitted F2 peak data from Kalkarindji to Laverton, 1507 km) with synthesized values overlaid for a corrugated mirror moving transversely to the HF propagation plane. The modelled TID had a 15 km amplitude, 80 minute period, 400 km horizontal wavelength, and midpoint bearing of -53 °N (north-westward). This is characteristic of a large-scale TID, potentially of southern auroral origin, and similar to the disturbance signature shown previously in Figure 3. While not a perfect match to the observations, the model is successful at reproducing the dominant features.

The AGW-seeded approach (model 2), developed by Hooke [1], applies perturbations to the continuity equations governing ion production, loss and transport, and is combined with 3D magneto-ionic ray tracing [8] to produce a more physically realistic TID representation. Although more computationally demanding, it supports multiple ionospheric layers/modes and the iso-ionic contours correctly capture the characteristic forward-tilting wavefront. Over time, this appears as a height-descending phase progression, illustrated in Figure 5.

The synthetic observables from ray tracing at 8 MHz are shown in Figure 6. The modelled TID is again moving transversely to the HF propagation plane with a period of 80 minutes and horizontal wavelength of 400 km, and with amplitude governed by the neutral wind perturbation and dissipative terms. The background ionosphere is a fixed spherically symmetric profile based on the mean of parameters fitted to the surrounding 3-hour ionogram sequence (the same path as in Figure 4). Not all scales of disturbance are able to penetrate to F2 heights, and in this night-time example, it appears damping effects make it difficult to realistically reproduce the full amplitude of the observed perturbation in Figure 4.

Note that, for this 1507 km path, the ray apogee heights for an 8 MHz operating frequency correspond roughly to the 3 MHz plasma frequency contour in Figure 5 (yellow line centered about 240 km height). This puts it slightly
beyond the sinusoidal contour regime, where the corrugated mirror reflector might be expected to have more validity. Conversely, it means that at lower frequencies/heights, or for lower amplitude perturbations, the mirror reflector may remain a good approximation.

Figure 5. Illustration of iso-ionic contours (i.e. lines of constant plasma frequency in MHz), overhead a fixed point for the AGW-seeded model.

Figure 6. Observables synthesized from the AGW-seeded TID model in Figure 5. The panels depict group delay (top left), Doppler (top right), bearing offset (bottom left) and elevation (bottom right), for a fixed operating frequency of 8 MHz. Both O-mode (red) and X-mode (blue) components are calculated by 3D ray tracing [8].

5. Conclusion

An overview of the ELOISE oblique AoA sounder system, developed by DST Group, has been provided, along with a sample of results from a recent campaign in September 2015. Signatures of traveling ionospheric disturbances have been identified in the observations, and comparisons with synthetic results from two candidate TID models show encouraging results, in terms of their ability to classify and parameterize the disturbance field. Despite its limitations, the simple corrugated mirror can still be effectively used to identify general classes of TIDs under certain conditions. However, with TIDs being so ubiquitous, the challenge ahead is in analyzing the many examples of AoA perturbations that do not have a single dominant spectral component, and modeling each spectral component in a spatially consistent way across the network of ELOISE AoA paths.

6. References


