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HF Sounder Characterization of Traveling Ionospheric Disturbances using the N-Dimensional Lomb-Scargle Periodogram

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Abstract

Traveling ionospheric disturbances (TIDs) are electron density fluctuations that travel as waves through the ionosphere. Measuring TIDs with HF sounders and other instruments enables the scientific and operational community to better understand the response of the ionosphere and predict its impact on technological systems. Orion Space Solutions is developing a next-generation HF sounding system called the Traveling Ionospheric Disturbance Evaluation Tri-wave (TRIDENT) sensor. This paper describes a novel TID characterization algorithm that we have developed for TRIDENT. The algorithm is based on the N-Dimensional Lomb-Scargle Periodogram (ND-LSP) spectral analysis technique and marks the first application of the ND-LSP to HF Doppler data. The performance of the algorithm is demonstrated in two cases using simulated observations. In the first case, the ionosphere is perturbed with a superposition of three TIDs and the algorithm can characterize each individual TID from the synthetic HF measurements of Doppler frequency. In the second case, the ionosphere is perturbed with a single TID of large enough amplitude to produce multiple off-great circle propagation modes through the F region of the ionosphere. The ND-LSP can handle multiple simultaneous measurements on a single transmit–receive link and, by including angle of arrival information, estimates the TID characteristics accurately.

1 Introduction

Traveling ionospheric disturbances (TIDs) are quasi-periodic perturbations in electron density that propagate through the ionosphere. Medium-scale TIDs (MSTIDs), with periods of 10-60 minutes and horizontal wavelengths of 100-300 km, are usually caused by gravity waves propagating from the lower atmosphere. MSTIDs can emerge due to a variety of natural and anthropogenic causes, including earthquakes, thunderstorms, and rocket launches. With detailed measurements of TIDs, the scientific and operational community can better understand the ionosphere's response to these phenomena and predict the impact of the disturbed ionosphere on technological systems. Although TIDs are observed with a variety of sensors, HF sounding is particularly well-suited for measuring TIDs because the Doppler frequency and other signal observables are highly sensitive to fluctuations in bottomside electron density. An HF radio wave transmitted from the ground propagates through the ionosphere until it reaches the point where the plasma frequency is equal to the transmit frequency and the wave is refracted back to the ground. Electron density fluctuations cause this reflection point to vary with time, and the resulting signature measured by the HF sounder is used to estimate the TID characteristics.

HF sounders have been deployed and used to measure TIDs for decades. Modern systems (e.g., [1, 2, 3]) utilize a distributed network of transmitters and receivers, making measurements of signal observables across multiple oblique links. Many systems transmit continuous wave signals and characterize TIDs using Doppler measurements. One example is Orion Space Solutions' TID Detector Built in Texas (TIDDBIT) [1], which consists of three transmitter sites symmetrically distributed and 50-100 km distant from a central receiver site. With two transmit frequencies, the ionosphere is probed at two altitudes at each of the transmit–receive midpoints. Now, Orion Space Solutions is building on the heritage of TIDDBIT with the new Traveling Ionospheric Disturbance Evaluation Tri-wave (TRIDENT) sensor. TRIDENT consists of two transmit and four receive sites distributed throughout a region $\sim$100 km across. By using frequency-modulated continuous wave (FMCW) signals, group range can be measured. Each of the four receivers processes the signals from two transmitters, on two frequencies, and for ordinary (O) and extraordinary (X) propagation modes. The result is 32 times series measurements of Doppler and group range across the full system. It is also possible to upgrade the antenna system at a receive site to measure the angle of arrival (AoA) of the signal. Results from an early sounding experiment using FMCW on a single link are shown in Figure 1. The Doppler and group range traces capture the dynamics of the ionosphere due to TIDs. Near 12:00 UT, notice the "S-shaped" curve in Doppler and the "loop-de-loop" curve in group range. At this time, multiple propagation paths reflecting from the F-layer occur, each with a distinct Doppler and group range observable. Advanced methods are necessary to characterize TIDs from these types of measurements.

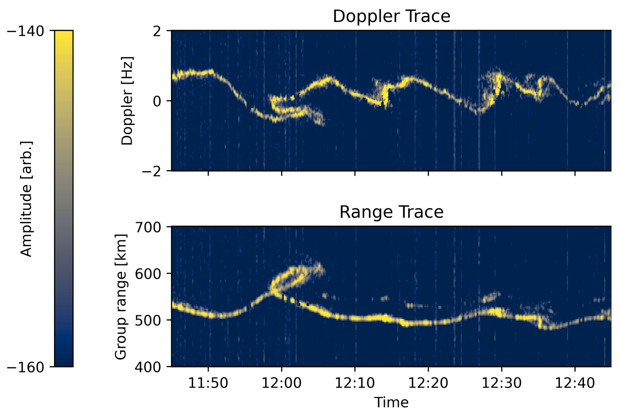

Figure 1. Measurements for a single transmit/receive link (5 MHz, O mode) from an experiment in Florida (2017/09/01, 11:45-12:45 UT).

This paper describes a novel TID retrieval algorithm using the N-Dimensional Lomb-Scargle Periodogram (ND-LSP) technique for spectral analysis [4], which we apply to HF Doppler sounding for the first time. The retrieval algorithm can characterize multiple simultaneously occurring TIDs (Section 3) and handles more complex behavior when multiple propagation paths are possible for a given oblique link (Section 4). In anticipation of the full deployment of the TRIDENT system, we have developed and tested this algorithm using simulated data.

2 Methodology

HF sounding observations are simulated for a hypothetical TRIDENT deployment on the island of Hawaii. Figure 2 shows the locations of two transmit sites, four receive sites, and the 8 transmit–receive midpoints. We choose transmit frequencies of 6 MHz and 7.5 MHz to probe the ionosphere at two altitudes. The "truth" model for the three-dimensional and time-varying electron density N_e in the vicinity of Hawaii consists of a background and a perturbation with a superposition of TIDs. The background electron density $N_{e,IRI}$ is the international reference ionosphere (IRI) at 20 UT on 2020/10/01 (solar minimum and daytime in Hawaii). A simple model of TIDs as plane waves is used to perturb the background:

$$N_e(\vec{r},t) = N_{e,IRI}(\vec{r}) \left(1 + \sum_i A_i \cos\left(2\pi\left(\vec{k}_i \cdot \vec{r} - f_i t\right) + \phi_i\right)\right) \quad (1)$$

where $\vec{r} = [x,y,z]^T$ is the position vector (east, north, up), t is time, and the ith TID has amplitude A_i, non-angular wave vector $\vec{k}_i = [k_x,k_y,k_z]^T$, frequency f_i, and phase ϕ_i. In later sections, TIDs are specified by period $T = \frac{1}{f}$ as well as horizontal wavelength λ, wave vector azimuth angle k_{az}, and wave vector elevation angle k_{el}, related to wave vector as $\vec{k} = \frac{1}{\lambda}\left[\sin(k_{az}),\cos(k_{az}),\tan(k_{el})\right]^T$. Although the simple TID model does not explicitly capture any physical dependence of TIDs on gravity waves, it serves the present purpose of demonstrating the performance of the retrieval algorithm under several challenging scenarios. An effort is made to choose parameters consistent with observed MSTIDs.

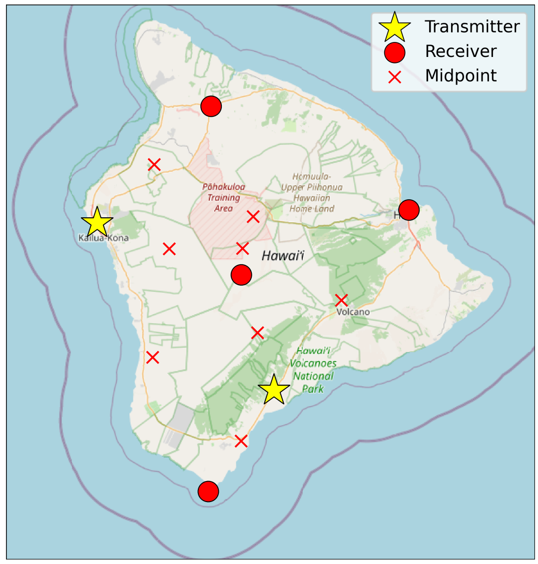

Figure 2. Sites used in the simulation study.

After choosing transmitter and receiver sites, transmit frequencies, and defining the truth electron density, a forward model is used to simulate Doppler frequency, group range, and angle of arrival measurements for each link in the system. The forward model applies HF raytracing to home rays along each of the links. We use the PHaRLAP raytracer via the PyLap Python interface. We have developed a custom homing algorithm based on [5]. The homing algorithm handles the highly-dynamic TID environment that sees significant off-great circle propagation and, at times, multiple simultaneous raypaths for a single link. The result of the forward model is time series measurements for all 32 links in the system at the 7.5 second measurement cadence planned for TRIDENT.

Lastly, we solve the inverse problem of estimating TID characteristics from the synthetic measurements and assess performance by comparing to the truth model. It is straightforward to estimate T and there are several existing methods to estimate $\vec{k}$ from HF Doppler measurements. For example, the variety of methods in [2] are well-suited for estimating a single TID but have not been extended to multiple simultaneously occurring TIDs. The method of [1] for TID-DBIT uses cross-spectral analysis and can estimate multiple simultaneous TIDs; however, it has not been extended to a least-squares solution to accommodate the greater number of links available in TRIDENT. Furthermore, all of the aforementioned methods use a "midpoint assumption" wherein the measurement is assigned to $\vec{r}_m = [x_m,y_m,z_m]^T$, with $x_m = \frac{1}{2}(x_{Tx} + x_{Rx})$, $y_m = \frac{1}{2}(y_{Tx} + y_{Rx})$ and altitude z_m where the plasma frequency (from an assumed electron density profile) matches the transmit frequency. Here, Tx and Rx denote the transmitter and receiver.

Table 1. Truth model and retrieval results for a superposition of TIDs. Units are minutes (T), km (λ), and deg. (k_{az}, k_{el}, ϕ).

		T	λ	k_{az}	k_{el}	ϕ
Truth	TID 1	10	100	75	-30	0
	TID 2	13.3	150	180	-20	45
	TID 3	20	200	210	-10	90
Retrieval	TID 1	-	105.9	74.2	-27.9	-
	TID 2	-	150.0	180.0	-20.6	-
	TID 3	-	210.5	212.7	-11.9	-

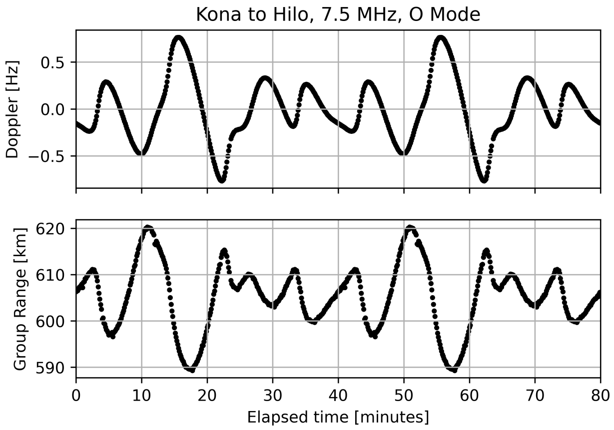

Figure 3. HF measurements for an example link.

To solve this inverse problem while addressing several drawbacks of existing methods, we have developed a novel retrieval algorithm that uses the ND-LSP. The ND-LSP is described in detail in our previous work [4] that introduced the ND-LSP for ionospheric applications and used it to find TIDs in ionosonde data. At a high level, it suffices to understand that the ND-LSP is a spectral analysis technique in the least-squares family that can be applied to a signal that is irregular in space and time. For the TRIDENT retrieval algorithm, the inputs are (1) Doppler frequency f_d and associated time/position $(t, \vec{r})$ for all samples across all links, and (2) a selection of spatial and temporal frequencies to probe: $(f, \vec{k})$. The output is the spectral amplitude at the specified frequencies: $A_s(f, \vec{k})$. TIDs are identified by finding peaks in A_s. A benefit of the ND-LSP is that a position can be assigned to each individual Doppler sample. Although Section 3 utilizes the typical midpoint assumption, Section 4 uses AoA information to better estimate $\vec{r}$. Lastly, we note that group range information, while not used explicitly in the current retrieval algorithm, is important for filtering out unwanted propagation modes such as multi-hop that contaminate the Doppler measurement.

3 Superposition of TIDs

The first case study of the retrieval algorithm uses a superposition of three TIDs detailed in Table 1. The time series measurements of Doppler and group range for an example link (Kona to Hilo, 8 MHz, O Mode) are shown in Figure 3.

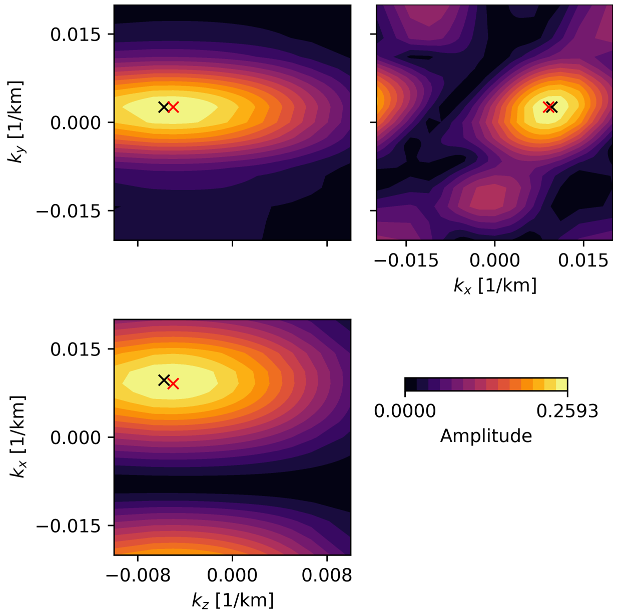

Figure 4. ND-LSP output for TID 1.

For simplicity, we assume each T_i is known (it is straightforward to estimate from any individual link by using Fourier analysis) and retrieve $\vec{k}_i$. The ND-LSP is run separately for each T_i, resulting in a 3D array $A_{s,i}\left(f = \frac{1}{T_i}, \vec{k}\right)$. The estimate of the wave vector is $\vec{k}_i^* = \text{argmax}_{\vec{k}}\left(A_{s,i}(\vec{k})\right)$. The ouput of the ND-LSP for TID 1 is visualized in Figure 4. The three panels of the figure show slices of A_s along the $k_z k_y$, $k_z k_x$, and $k_x k_y$ planes, centered on $\vec{k}_1$. The black X marks $\vec{k}_1$ and the red X marks $\vec{k}_1^*$ projected onto these planes. The estimated $\vec{k}_1^*$ is close to the true value. The results for all three TIDs converted to λ, k_{az}, k_{el} are listed in Table 1. The ND-LSP estimates each λ to within $\sim$10 km and k_{az}, k_{el} to within a few degrees.

4 TID with Multiple Propagation Modes

As the TID amplitude increases and/or the wavelength decreases, it becomes possible for multiple rays to propagate from the transmitter to the receiver. These are not the typical multiple propagation modes often discussed for HF measurements of the ionosphere (e.g., multi-hop and reflections from different ionospheric layers) but are rather multiple reflections from the same ionospheric layer along different bearings. The second case study of the retrieval algorithm uses a single TID that leads to this more complicated behavior where the presence of multiple homed rays for a single link results in multiple simultaneous Doppler measurements. The TID characteristics are detailed in Table 2 and the time series measurements for an example link are shown in Figure 5. Like in Figure 1, we see "S-shaped" curves in Doppler (see also observations in [3]) and "loop-de-loop" curves in group range (see also simulation in [6]).

The ND-LSP can easily accommodate a link with multiple measurements at a given time. As before, the samples sim-

Table 2

	T	λ	k_{az}	k_{el}
Truth	10	100	180	-20
AoA-based retrieval	9.6	100.0	180.0	-24.0

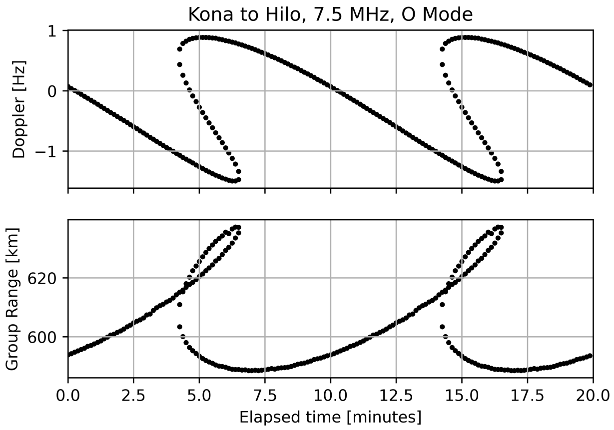

Figure 5. HF measurements for an example link showing the effect of multiple propagation modes support by the F layer.

ply need to be passed into the algorithm with the associated time and assumed position. For this example, the midpoint assumption is a poor approximation. The multiple rays with different Doppler and group range observables clearly do not pass through the same point, let alone the midpoint. We see as much in the raytracing results, where the apex locations of the multiple rays can be spaced 10s of km apart. If AoA information is available, a better estimate of the associated positions can be made. Let $\vec{r}_A = [x_A, y_A, z_A]^T$ be the unit vector tangent to the raypath at the receiver and pointing away from the receiver. Each received ray at a given time will have its own $\vec{r}_A$. The location where this vector intersects the $z = z_m$ plane is $\vec{r}_{m'} = [x_{m'}, y_{m'}, z_m]^T = \vec{r}_{Rx} + \alpha \vec{r}_A$, where $\alpha = \frac{z_m - z_{Rx}}{z_A}$. As shown in Table 2, using the AoA-based $\vec{r}_{m'}$ in the ND-LSP results in a reasonable estimate of the TID. The estimates of λ and k_{az} are exact, while estimates of T and k_{el} have some error. In the future, we will further improve estimates of position using AoA and other information. The current approach does not account for deviations of the raypath from the straight-line path of $\vec{r}_A$ extended to z_m, or deviations in height away from z_m.

5 Summary and Outlook

We have introduced a novel TID retrieval algorithm for HF sounder observations that uses the ND-LSP spectral analysis technique. The algorithm is intended for use with Orion Space Solutions' TRIDENT sensor, though it could also be applied to existing HF sounders with observations of Doppler and, optionally, angle of arrival. An initial deployment of the full TRIDENT system is planned for 2025. In the meantime, we plan to conduct a more complete simulation study, covering a full range of TID characteristics, different selections of transmit/receive sites, and the addition of errors including measurement noise. We will also explore whether including group range information explicitly in the retrieval can improve performance. Once the TRIDENT system is deployed, we will rigorously test the retrieval algorithm with real observations. We plan to use the retrieved TID information to feed regional models of the ionosphere, enabling better predictions of how the disturbed ionosphere impacts technological systems.

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