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Towards a Predictive Model of Sporadic E using Planetary Wave Signatures Quantified with the N Dimensional Lomb Scargle Peridogram

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Abstract

Sporadic E is a strong plasma density enhancement in the E region of the ionosphere that can severely degrade the performance of Over The Horizon (OTH) radar and other High Frequency (HF) technologies. Sporadic E is known to vary on tidal (1,2,3, … times per day) as well as planetary wave (2 - 30 day periods) timescales. We use a novel dataset and method to study the connections between planetary waves and sporadic E, and show progress towards a rudimentary predictor. The dataset consists of retrieved sporadic E parameters (foEs, hmEs) from Radio Occultation (RO) measurements. The method is the N-Dimensional Lomb-Scargle Periodogram (ND LSP) which allows planetary waves and tides to be quantified without the need for averaging or interpolation of the raw data. This is especially valuable for the irregular temporal and spatial sampling characteristic of RO measurements. This technique shows expected seasonal trends and evidence of non-linear interactions between tides and planetary waves.

1. Introduction

Sporadic E is an ionospheric phenomenon characterized by vertically thin enhancements in electron density in the E region (90-150 km altitude). The plasma frequency of this enhancement is denoted foEs. At times, foEs can exceed the critical frequency in the F layer (foF2). Sporadic E can severely affect HF communications and Over The Horizon (OTH) radar. It is now known that sporadic E is primarily driven by wind shear squeezing metallic ions of meteoric origin into a vertically thin layer [1]. Sporadic E is strongest on summer afternoons at mid latitudes, but has been observed at lower rates and strengths in nearly all locations and local times. Sporadic E varies along both tidal and planetary wave frequencies (e.g. [2]). Tides are described using the following form:

$$A \cos(2\pi(n\,\lambda/360 - s\,t)) \qquad (1).$$

Where λ is longitude in degrees, t is time in days, and n and s are integers. Values of (1,2,3) for s are referred to as Diurnal, Semidiurnal, and Teridiurnal respectively. Planetary waves follow a similar form, with the key difference being that m need not be an integer, and describes periods of 2-30 days.

$$A \cos(2\pi(n\,\lambda/360 - (1/m)\,t)) \qquad (2).$$

Planetary waves and tides can interact and produce spectral signatures at s +/- $1/m$. This paper investigates the connection between planetary waves and sporadic E using Radio Occultation (RO) measurements to quantify sporadic E intensity, and the newly-developed N Dimensional Lomb Scargle Periodogram (ND LSP) to extract spectra [3].

2. Data and Methods

Radio Occultations are a measurement technique where Global Navigation Satellite System (GNSS) signals are measured from Low Earth Orbit (LEO). Distortions in these signals can be used to extract multiple ionospheric quantities of interest, including Total Electron Content (TEC) and sporadic E intensity (foEs) and height (hmEs). We use a machine learning approach to retrieve these sporadic E intensity parameters described in [4]. This retrieval method agrees with parameters extracted from digisonde data with errors of 0.63 MHz. This method was applied to data from COSMIC-2 and 1 hour of the extracted parameters are shown in Fig. 1.

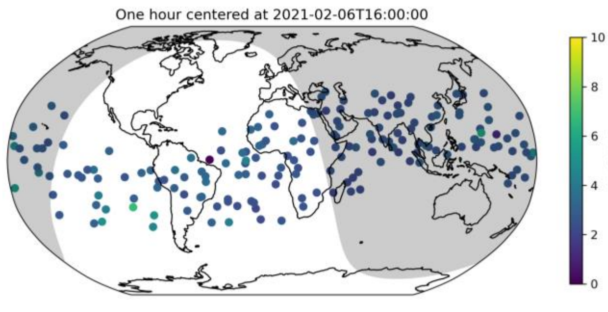

Figure 1. foEs retrievals from COSMIC-2 Radio Occultation data.

Radio Occultation measurements are typically distributed quasi-randomly, which makes spectral analysis non trivial. Several methods involve averaging the measurements into latitude/longitude/time bins [5]. Once the data are in these regularly-spaced positions, traditional spectral analysis methods (Fast Fourier Transforms, FFTs) can be used. Another approach is to use the ND LSP [3] which does not require averaging or interpolation, essentially projecting the raw data onto different planetary waves and tides.

2. Results

We divide the data into three magnetic latitude regions: southern mid latitude (-50 to -20), equatorial (-20 to 20) and northern mid latitude (20 to 50) degrees and apply the ND LSP to each region using inputs of magnetic longitude and time. We do this for data in a 20 day window that slides 5 days at a time. Spurious signals can appear due to irregular sampling. To guard against this, we employ the same empirical method that was used in [3], which is to shuffle the input data (foEs in this case) while keeping the sampling locations (magnetic longitude and time) the same. We do this 10 times, and compute the 95% quantile, which is the average of the 1st and 2nd highest amplitudes, for each unique wavenumber/period pair. Signals in the real data that are stronger than this value have less than a 5% chance of being due to sampling geometry instead of a physical process. Amplitudes less than this are not statistically significant, and are set to zero in all subsequent analysis.

The results for the time segment beginning June 5th, 2021 are shown in Fig 2. Each subpanel shows a different latitude region, with color indicating the amplitude of foEs as a function of period and zonal wave number. The southern hemisphere is dominated by diurnal periods, with the strongest signature at a wavenumber of -1 (DW1), but significant contributions at DW2 and D0 are also present. Nonlinear interactions between DW1 and planetary waves with periods of 7, 5, and 2.9 days are evidenced by power at the sums and differences of these periods with DW1, although very low amplitudes are observed at the planetary wave frequencies themselves. In the equatorial region, similar trends hold except that the planetary waves are more evident. Additionally, very weak TW3 and SE2 waves are observed. In the northern hemisphere, there are far more significant waves. The planetary waves previously noted (7, 5, 2.9 days) are present, as well as many others that are difficult to distinguish. There are many more tides present, including SE1, SW2, and TW2 and TW3.

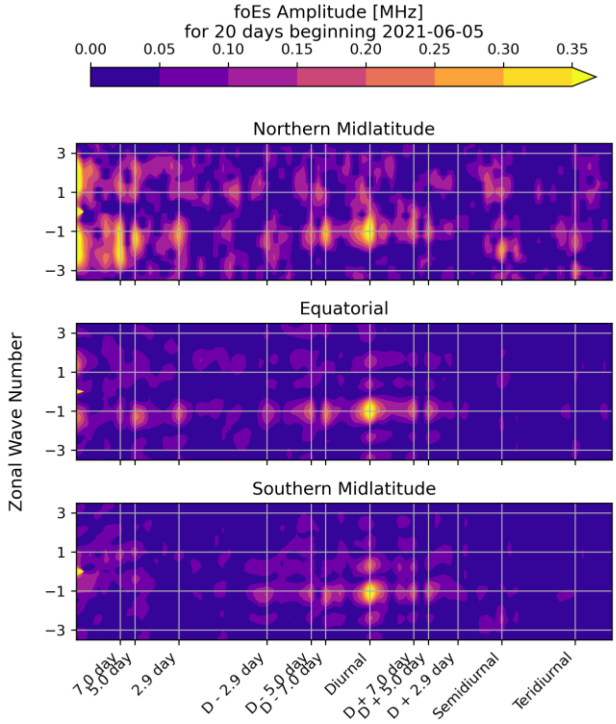

Figure 2. Amplitude of foEs oscillations as a function of wavenumber and period. Results are shown for latitudes of -20 to -50 (top), -20 to 20 (middle) and 20 to 50 (bottom) degrees magnetic latitude.

We now investigate the presence, strength, and dynamics of these planetary wave signatures over time. We focus on the westward wavenumber 1 in the northern hemisphere since it gives the most interpretable results. The upper panel of Fig. 3 shows the foEs amplitude in a manner similar to Fig. 2, but only at one wavenumber and for the whole year. In this plot, the time on the *x* axis indicates the beginning of the time window, which is 10 days ahead of the middle of the window used to make that spectra.

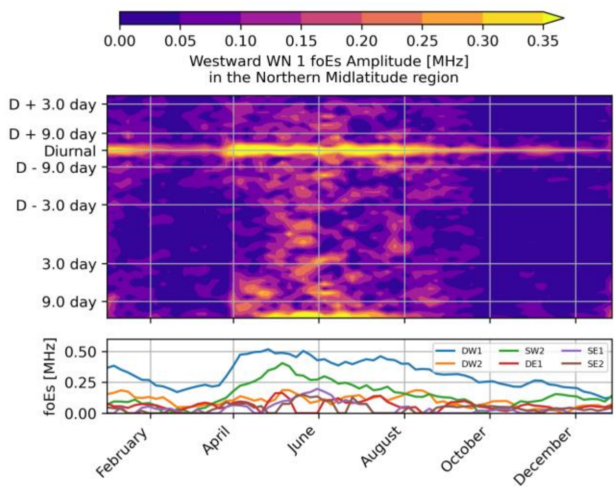

Figure 3. foEs amplitude at westward wavenumber 1 spatial frequencies as a function of time and period over the whole year.

The lower panel shows the amplitude of certain tides. We note that both DW1 and SW2 peak in summer, although DW1 is still quite strong in January. The top panel shows numerous planetary waves, many of which interact with DW1 to produce sidelobes. These effects amplify from April to August. After October, sporadic E is dominated by DW1 and SW2.

3. Future Work

In addition to studying the connections between sporadic E, planetary waves, and tides, this type of analysis can be used to create a predictive model of sporadic E that is set to outperform climatology. Intuitively, if there is a strong six day wave present in the foEs data that is currently peaking, one could make an educated guess that foEs will decrease for the next three days and then rise again for another three. More mathematically, this can be done by taking the inverse FFT of the spectra and then applying that forward in time. This will only outperform climatology as long as the planetary wave environment stays constant, but that does not preclude operational timescales of 2-6 days.

In order to realize this goal, the basis set must be orthogonal, which is not true for the ND LSP. To fix this, we will move to a Spherical Least Squares Periodogram approach instead of a ND LSP. In addition to allowing reconstructions, this should enforce continuity at the longitude break at either 180 or 360 degrees as well as continuity at high latitudes. We plan to have predictive results and preliminary validation by the time of the URSI meeting in August.

6. Acknowledgements

Geographic coordinates were transformed into magnetic using Altitude Adjusted Corrected Geomagnetic Coordinates (AACGMC) [6]. This was done using the AACGMV2 python package: https://zenodo.org/record/3598705 . The foEs data result in applying the ML model described in [4] to COSMIC-2 data, which is hosted here: https://www.cosmic.ucar.edu/what-we-do/cosmic-2/data

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