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Systematic Statistical Identification of Lower Region Ionosphere Acoustic Waves through VLF Remote Sensing

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Abstract—We present a method to automatically statistically characterize ionospheric acoustic wave (1-5 minute period) disturbances propagating through the lower region ionosphere (75-85 km) by analyzing magnetic field recordings in the very-low-frequency (VLF) band. The ionosphere is an electrically charged layer at the top of the atmosphere (60-500 km) formed from solar radiation. The lowest region, known as the D-region (60-90 km), is difficult to sense as it is above an elevation suitable for balloons yet below that of satellites. The ionosphere impacts global communications solutions due to its ability to transmit signals beyond line-of-sight to global distances. Acoustic waves are periodic moving oscillations that can disrupt conditions in the lower ionosphere. We describe a method to locate acoustic waves that relies on identifying outliers in the frequency spectrum of 30-minute periods of magnetic field data. These outliers may correlate to acoustic wave disturbances. Past studies of acoustic waves in the ionosphere have been anecdotal case studies. However, detailed information about their occurrences is needed to further reason about the causes of these disturbances, such as hurricanes, thunderstorms, space weather, and air turbulence over mountain ranges.

Key Words - Lower Region Ionosphere, D-Region, VLF Remote Sensing, Acoustic Wave Disturbances

I. Introduction

The lower region of the ionosphere, known as the D-region (60-90 km), contains characteristics that make it unsuitable for monitoring with either weather balloons or satellites. In addition, the D-region's properties facilitate global communications. For example, submarine communications utilize it to guide very-low-frequency (VLF, 3-30 kHz) signals to global distances [1]. The D-region also impacts the absorption of high-frequency (HF, 3-30 MHz) radio, which is found in applications like aviation communication, energy response preparedness, and amateur radio, among other uses. It is known that propagating periodic oscillations can move through the top of the atmosphere, thereby impacting the D-region [2]. However, in the past, studies of this phenomenon have been anecdotal, based on case studies [3], [4], [5], [6], [7]. We present a method that enables statistically reliable identification of lower region ionospheric acoustic wave disturbances. With the usage of VLF signals to remote sense changes in the conditions of the ionosphere, limitations of current solutions can be overcome.

We focus on the identification of D-region acoustic waves (1-5 minute period). These waves can connect atmospheric disturbances over a wide range of altitudes, transferring a lot of energy [4]. These waves can, in turn, hinder the communication systems that rely on the ionosphere. In [8], simulations of radio signals that used the lower region ionosphere showed diminished intensity in the presence of ionospheric disturbances. Based on the suggested impacts they can have, acoustic waves may play an important role in overall ionospheric conditions and are worthwhile studying.

VLF remote sensing is a powerful method of identifying these fluctuations in the D-region. The D-region ionosphere efficiently reflects VLF waves within the D-region, which allows for a method of identifying changes in the region by changes in the amplitude and phase of any VLF signal at any receiver. There is a long history of VLF remote sensing, but one area where this technique has lagged is in identifying acoustic wave disturbances. In [4], VLF remote sensing was used to study acoustic wave disturbances produced by solar terminator motions at the transition between dusk and dawn and dawn and dusk. In [6], VLF remote sensing was used to observe acoustic waves thought to be generated by convective storms in the troposphere, which helped set the groundwork for VLF's remote sensing potential. While proven possible to identify them, it is not known how often gravity waves can be detected in VLF data and how that varies as a function of wave period, time of day, season, etc. It is also not known how prevalent each of their possible sources are. A general statistical method for gravity waves' identification in VLF data, therefore, will help provide the information for these future analyses.

II. Description of Data

We use VLF radio receiver data from the AWESOME instruments [9], [10]. The receiver detects two horizontal components of the magnetic field between 500 and 470 kHz, and records with 1 MHz sampling frequency, 16 bit dynamic range, and 20 ns timing accuracy. The receiver is capable of detecting broadband emissions such as impulsive radio atmospherics launched by lightning strokes, which occur millions of times per day. However, in this project, we focus on narrow frequency transmissions from VLF transmitters, which are primarily used for submarine communications by the US Navy. These signals can be detected tens of thousands of km away, and are minimum shift key (MSK) modulated at 200 baud. As we are interested in the remote sensing properties, and not the transmission, the recording software demodulates the MSK transmission, and reports the amplitude, carrier phase and clock phase of the transmitter, in this case with 1 Hz resolution. The demodulation algorithm is described in [11].

The Georgia Tech LF Radio Lab operates a number of VLF receivers, each of which monitor a number of VLF transmitters. However, in this paper we focus on the NAA transmitter in

Cutler, Maine, USA, at 24.0 kHz, received at Arecibo, Puerto Rico. This particular radio signal transmission path was chosen since it traverses the portion of the Atlantic Ocean where tropical storms and hurricanes enter the Caribbean Sea, as displayed in Fig. 1. Intense thunderstorms and hurricanes are one source anecdotally seen to launch gravity waves [3], [5], [7]. However, our methodology could be applied to any VLF transmitter-receiver path.

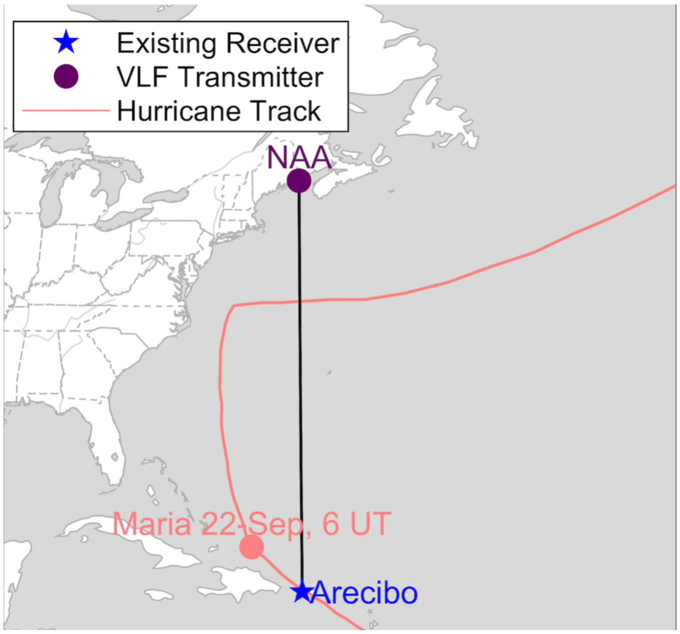

Fig. 1. Map displaying the signal transmission path from the NAA transmitter in Culter, Maine, USA, to Arecibo, Puerto Rico. Line in pink shows the movement of the tropical storm which became Hurricane Maria traversing directly through the signal transmission path.

An example of the raw data collected is presented in Fig. 2 as a graph of amplitude (dB) vs time. This is a single 24-hour day in universal time (UT), and it demonstrates a typical diurnal pattern. During nighttime hours (00:00-10:00 UT) the signal is more erratic, as the D-region is weaker and more unsteady. Daytime (12:00-22:00 UT) shows a classic pattern as the sun, which dominates ionization, rises and then sets. Between day and night is a transition period when the transmitter-receiver path is only partially illuminated.

III. Methodology

Fig. 3 zooms into the period from 04:55-05:25 UT of Fig. 2 and displays an acoustic wave disturbance outlined. The acoustic wave disturbance has a distinct periodic oscillation compared to the rest of the data. Acoustic wave disturbances can be found in the data manually through recognition of these periodic oscillations but would be time-intensive, and likely fraught with errors due to noise and multiple periodic oscillations superimposed. As such, we prefer an automated identification.

We will perform our automatic identification in the frequency domain. Fig. 4 shows the result of the transformations applied.

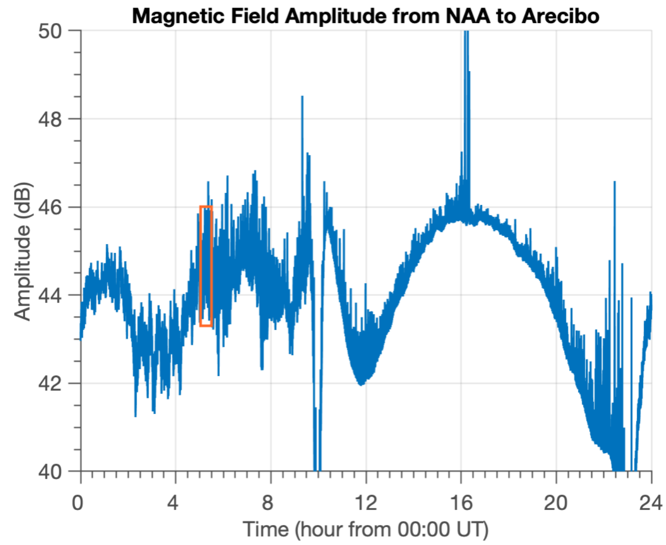

Fig. 2. VLF amplitude data of a full day between NAA and Arecibo from 2017-Sep-22. Rectangular box indicates a period within which a periodic oscillation was identified, from approximately 04:55–05:25 UT. Data is sampled in real time at 1 Hz.

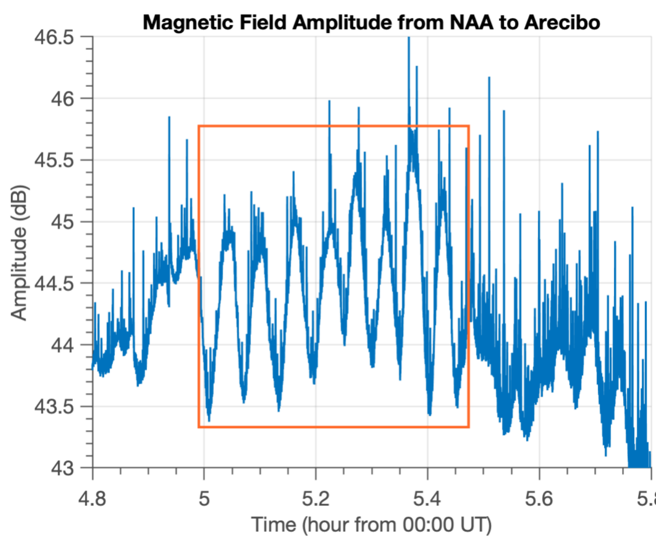

Fig. 3. Zoomed-in view of 04:55-05:25 UT from Fig. 2 with outlined periodic oscillation.

Presented is the FFT of the 30-minute block from Fig. 3, in dB scale, where the horizontal axis is period, or $1/f$. Prior to the FFT computation, a 3-point median filtering is applied to smooth out impulsive lightning energy. Post-FFT computation, the mean of the signal is subtracted to level the dB scale, enabling comparison of several different 30-minute blocks.

Due to acoustic waves' very short periods, we chose to work with 25 samples of 30-minute periods of data to capture them effectively over a range of time. And to boost the time resolution, we overlapped consecutive periods by 50%. We are interested specifically in nighttime hours, when ionospheric disturbances are much easier to detect, therefore we used data between 00:00-10:00 UT.

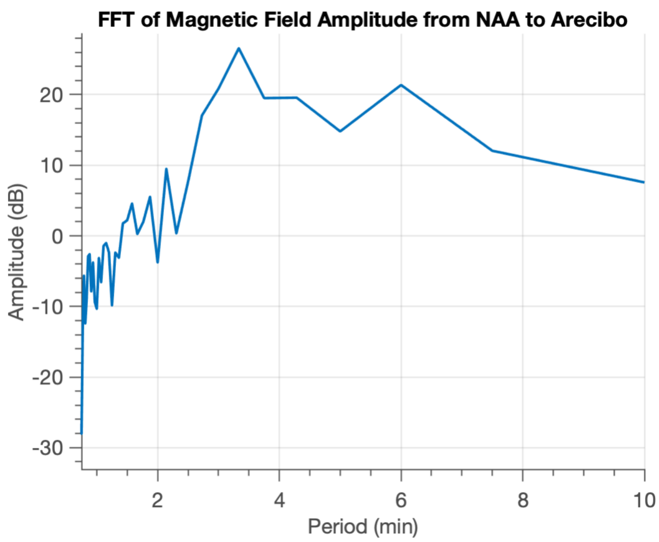

Fig. 4. The frequency-domain representation of 30-minute period, 04:55–05:25 UT, after some processing.

As seen in Fig. 4, the periodic oscillation identified in the time domain corresponded to a peak in the intensity at □200 s period, which matches the time domain dataset. However, to establish that this oscillation is unusually strong, we use the rest of the night's dataset to establish a statistical baseline. The 22 blocks of 30 minutes that do not overlap with this one (unless first or last block, then 23 blocks) are used to establish the standard deviation.

We can then pick out any frequency where the intensity exceeds the bounds of 3 standard deviations above the mean, which we report as statistically significant periodic oscillations that may correspond to acoustic wave disturbances with relatively high confidence. It should be noted that peaks that exceeded the bottom bounds were not considered in this project, only peaks that exceeded the top bounds.

The AWESOME receivers that collect the data used in this project provide antennas oriented in a pair of east and west (E/W) or north and south (N/S). To obtain as complete a picture of the path from NAA to Arecibo, data from both of these antenna orientations were averaged together and then used to produce results. The resulting dataset appeared more smooth than the data from an individual antenna orientation and highlighted potential outliers more prominently.

IV. Results

Seen in Fig. 5 is the final product of transformations to the dataset and application of the standard deviation bands. Graphed is a single period of averaged E/W- and N/S-oriented data, from 04:55-05:25 UT, on 2017-Sep-22, in blue, and the accompanying top and bottom bounds that are three standard deviations ($\pm 3\sigma$) from the mean, in orange. The statistically significant oscillation can be identified in this graph as the frequency at which the blue line exceeds the standard deviation envelope by going above it. This point corresponds to a statistically significant periodic oscillation with a period of approximately 3.33 minutes, which aligns with the periodicity found manually in Fig. 3.

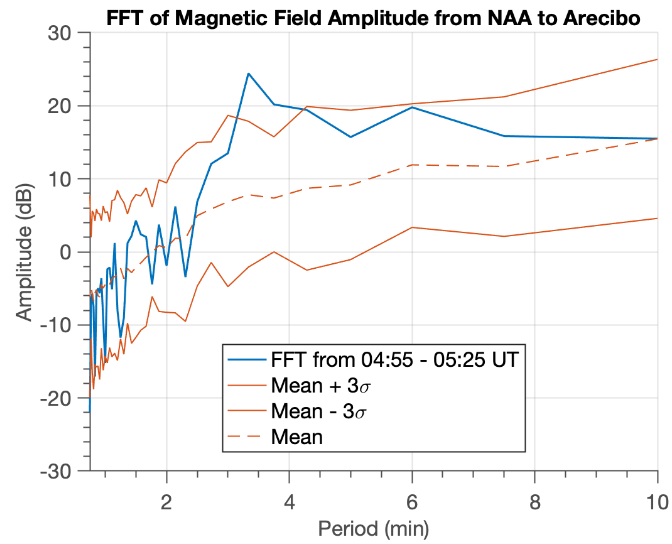

Fig. 5. Frequency-domain representation of magnetic field data, with completed processing, of 2017-Sep-22 from 04:55-05:25 UT with standard deviation envelope.

We now apply this statistical technique to a wider span of data, covering the entire month of September 2017. Fig. 6 and Fig. 7 display an occurrence histogram and bar graph of statistically significant periodic oscillations categorized by period and date, respectively. The majority of acoustic wave identifications appear with 1-3 minute periods, which is to be expected of acoustic wave disturbances that have very short periods. The few observations that exceed the expected 1-5 minute period range are acknowledged as falling within the realm of this method's identification, despite not technically being an acoustic wave. Further verification of these observations come from previous studies. The team in [3] report observing acoustic waves dominated by periods of around three minutes, while in [4], the most prevalent harmonious oscillations are identified to occur within the 1-1.67 minute period range.

Fig. 7 displays the frequency with which this statistical method has identified acoustic waves occur – possibly more so than previously thought. Perhaps intense thunderstorms or hurricanes, as was previously suggested, are not necessities for the generation of acoustic waves, but other origins should be considered as more prolific sources. It should be noted, however, that the range of days in which the tropical storm that became Hurricane Maria appeared to traverse the signal transmission path (shown in Fig. 1) contain clusters of periodic oscillation identifications, indeed supporting previous claims made about the link between intense convective storms and acoustic wave generation.

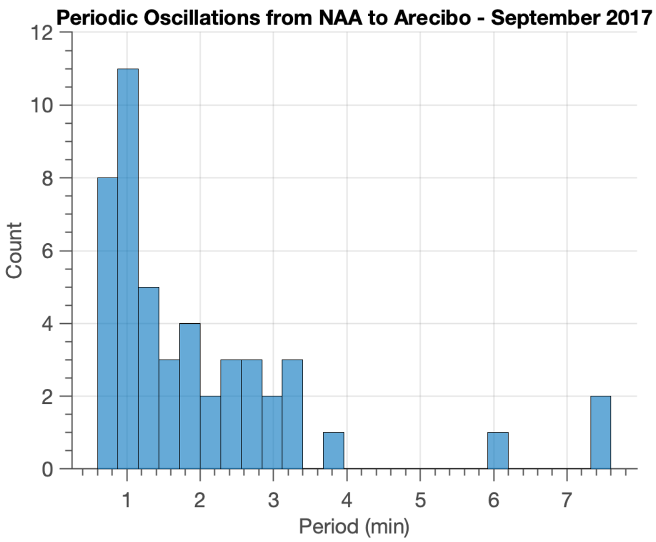

Fig. 6. Histogram of the count of statistically significant periodic oscillations categorized by period for the month of September 2017.

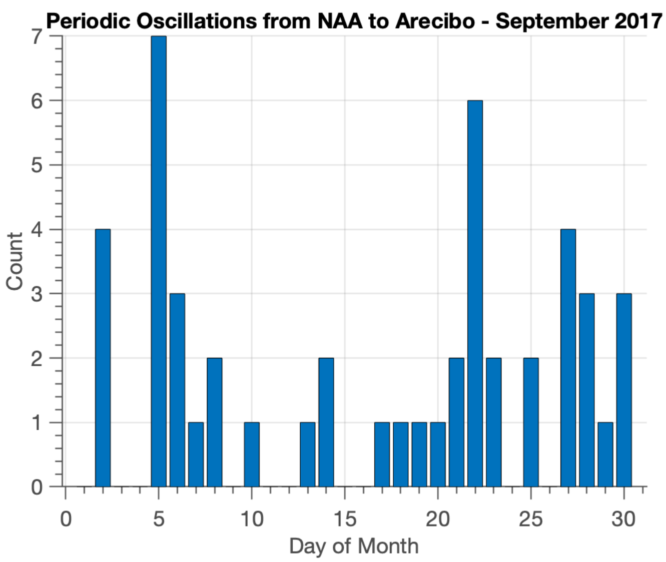

Fig. 7. Bar graph of the count of statistically significant periodic oscillations categorized by day for the month of September 2017.

V. Conclusions

We present a new and novel method to automatically statistically characterize lower region ionospheric acoustic wave disturbances through VLF remote sensing. By identifying statistically significant periodic oscillations, acoustic wave disturbances can be pinpointed at their exact date, time, and frequency. This method can be run on massive datasets to provide insights fast.

The data used in this paper focuses on the magnetic field amplitude data of E/W- and N/S-oriented AWESOME instruments. Phase data, however, is also available, and is of interest to be incorporated in further development to provide a more complete picture of the D-region's conditions. Future work can also investigate the granularity with which this method can pinpoint individual oscillations, as we present the method to only investigate oscillations existing within 30-minute, 50% overlapping periods, which may identify long-persisting acoustic waves multiple times.

The methodology presented enables future works to make use of information about the occurrences of lower region ionospheric acoustic wave disturbances that have not been previously available. Possible avenues of future study include using the data to strengthen the evidence of a link between events in the troposphere and the lower region ionosphere as well as the connection between lower region ionospheric conditions and overall ionospheric conditions. These further analyses will guide a better understanding of the ionosphere and the conditions that affect it.

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