HF Doppler Observations of Traveling Ionospheric Disturbances in a WWV Signal Received with a Network of Low-Cost HamSCI Personal Space Weather Stations

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Abstract

Traveling Ionospheric Disturbances (TIDs) are quasi-periodic variations in ionospheric electron density that are often associated with atmospheric gravity waves. TIDs cause amplitude and frequency variations in high frequency (HF, 3-30 MHz) refracted radio waves. One way to detect TIDs is through the use of a Grape Personal Space Weather Station (PSWS). The Grape PSWS successfully detected TIDs in the Doppler shifted carrier of the received signal from the 10 MHz WWV frequency and time standard station in Fort Collins, CO. This paper will present an explanation of how the Grape PSWS was used to collect data, and how scientist can use this data to further investigate the ionosphere.

Plain Language Summary

A radio wave is a type of electromagnetic wave that is generated by a transmitter. These waves are refracted off of the ionosphere and can be received by receivers, such as the Grape Personal Space Weather Station (PSWS). The Grape PSWS is very useful in detecting Traveling Ionospheric Disturbances (TIDs), are often defined as moving irregularities of charged particles in Earth's atmosphere. TIDs can cause the transmitted radio wave to have variations in its amplitude and frequency. This paper focuses on the specific observation of variations of signals within the High Frequency (HF) band, which is located from 3–30 MHz. More specifically, it explains the data-collection process through the use of the Grape PSWS and how it detected TIDs through a carrier signal transmitted by a frequency and time standard station known as WWV that is located in Fort Collins, CO. This paper will present the process of using the Grape PSWS to receive these signals and provide an early explanation of the data collected.

1 Introduction

The Grape Personal Space Weather Station (PSWS) is an instrument that has been developed by members of the Ham Radio Science Citizen Investigation (HamSCI) community from Case Western Reserve University [3, 4]. It is a small measurement platform that can be used to make ground-based observations of the space environment. It comprises a Raspberry Pi 4B, a Leo Bodnar mini GPS Discipline Oscillator (GPSDO), and a custom receiver board. It is constantly collecting data and works by using a single channel and antenna. There are currently 15 Grapes set up and collecting data around the United States including places like Ohio, New Jersey, Pennsylvania, and others. This paper will focus on the specific use of a Grape Personal Space Weather Station and its use in obtaining data on various disturbances detected in the ionosphere. The Grape contributing data to this paper is located in Northwest New Jersey.

WWV is a radio station located in Fort Collins, Colorado. It is well-known as a United States Frequency Standard which is extremely accurate as to what frequency it is transmitting on. The frequency is accurate to 1 part in 10^{14}. The station runs in the HF (High Frequency) range of the radio spectrum. WWV transmits at 2.5 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz, and experimentally on 25 MHz. For the purposes of this paper, the authors have considered the transmission that occurs at 10 MHz. Similarly, the station transmits a very accurate time signal, with an error margin of 10^{-7} seconds. The station transmit power is 10,000 W. Another important consideration is that the station is continuously transmitting at all hours of the day, every day of the week. This means that it can be monitored constantly and used to observe disturbances in the ionosphere at any given point in time, which is why it is being monitored by the Grape. WWV utilizes an omnidirectional half-wave vertical antenna [1].

2 Methodology

The data used in this paper was produced by a Grape PSWS receiver located in Northwest New Jersey (at the location of call sign KD2UHN) listening to the 10 MHz signal transmitted by the NIST standards station WWV in Fort Collins, CO. Figure 1 is a map showing the location of both the transmitter and receiver. The Grape PSWS consists of a Leo Bodnar mini GPS Disciplined Oscillator (GPSDO), a sound card, a custom receiver board, and a Raspberry Pi 4B which the processing software runs on. The Grape itself is powered via a regular household outlet. The GPSDO maintains a frequency stability of better than +0.001 Hz at 10 MHz. Figure 2 shows a photo of the KD2UHN Grape station with all components labeled. Figure 3 shows a diagram of the KD2UHN Grape station installation and antenna configuration.

A Buckmaster Off-Center Fed (OCF) HF Dipole Antenna of the Grape is used to continuously receive the WWV signal at 10 MHz. At the same time, the GPS antenna is listening to signals from the GPS satellites. The GPSDO uses the signal received by the GPS antenna to produce a very stable 9.999 MHz output signal. The receiver board mixes the signals received by the OCF Dipole Antennas (10 MHz from WWV) with the 9.999 MHz signal produced by the GPSDO to produce a difference signal of 1 kHz to provide an analog signal to the sound card. The sound card takes this analog signal that from the Grape and digitizes it and sends it to the Raspberry Pi. The incoming signal is analyzed using the frequency analysis mode of the popular fldigi software package. A figure displaying the measurements is automatically produced each day at 00:00 UTC.

The Grape is a small measurement platform that can be used to make ground-based observations of the space environment. It comprises a Raspberry Pi 4B, a Leo Bodnar mini GPS Discipline Oscillator (GPSDO), and a custom direct down conversion receiver board. It is constantly collecting data and works by using a single channel and antenna. Each day at 00:00 UT (Universal Time), a graph which shows the data from the previous day is generated.

It is important to note that the Grape is located in New Jersey, which uses the Eastern Time Zone (ET) and is approximately 5 hours behind the Universal Time Zone (UTC). Therefore, 00:00 UT occurs at 7:00 PM ET at the location of the Grape. The point in time which the radio wave actually interacts with the ionosphere is at the Midpoint Local Time, which occurs in the Mountain Time Zone. For this reason, considerations regarding the detected TIDs are made with respect to the Mountain Time Zone.

3 Results and Discussion

The results discussed in this paper are relatively early, however there is still a substantial amount of data that was collected. Figure 4 shows KD2UHN Grape observations from 24 Jan 2021 and is representative of typical Grape data. The black line shows deviation in Hz of the received signal from the 10 MHz WWV carrier. The red trace shows the signal strength in relative dB, and the green box identifies a period with a typical TID signature.

The way in which the ionospheric disturbances are observed from the Grape data is by looking at the variation in Doppler shift (Hz). The authors manually inspected each figure that was generated and created a spreadsheet using Microsoft Excel that looked at the patterns and categorized which hours had observed ionospheric disturbances each day. That data was then converted to a scatter plot to include a better visualization of correlated behavior between time and the Doppler Shift (Hz). These results are shown in Figure 5.

Another example of an ionospherically active day can be seen in Figure 7. The green boxes outline periods of notable ionospheric behavior. As discussed in this paper, the sinusoidal movement of the area inside the green boxes implies the detection of a TID. The reason that the TIDs form a sinusoidal shape is because they cause the carrier frequency to be Doppler shifted. When the transmitted 10 MHz WWV frequency refracts off the ionosphere, there should be a relatively constant received signal. Because a TID is a propagating perturbation in the density of charged particles, the signal refracts differently than it normally would, and thus is received in a way that portrays the sinusoidal pattern outlined by the boxes. Figure 7 shows the presence of various TIDs in a single day. Figure 6 and Figure 8 both show ionospherically quiet days. With the exception of a small TID at the end of each day, a majority of the hours in the day are very quiet; that is, they do not show clear evidence of any TID occurrence.

The hours with "1" were considered to be TID-active hours, while those with "0" were considered to be TID-quiet. Active hours are those that have a distinct change in Doppler Shift (the black line) that is very close to +0.25 Hz or greater. If the shift was close to 0.25 Hz, but not followed by a sinusoidal pattern, and did not appear to be distinctly different from the preceding and following hours, then that hour was not noted as an active hour. The authors selected only times that had oscillation periods of about 15 minutes or greater. Active hours are frequently followed by other active hours, forming a sinusoidal-like shape. Note that each day, during sunrise there is a sudden peak in the measured Doppler Shift. During sunset, there is a sudden drop in the Doppler Shift. This observation is consistent with those discussed by other authors [2]. It is also important to consider that these are very early results and so there is limited data to consider when making these observations.

Figure 9 shows the distribution of active hours observed by the Grape in the time frame discussed in this paper was graphed. This figure depicts the correlation of the midpoint local time to the observed Traveling Ionospheric Disturbances (TIDs). It can be seen from the figure that the data collected thus far suggests 15:00 Midpoint Local Time to 20:00 Midpoint Local Time to be the hours with the most observed TID activity.

4 Summary and Future Work

In conclusion, The Grape Personal Space Weather Station (PSWS) is making observations consistent with those expected of Traveling Ionospheric Disturbances. A statistical study of Traveling Ionospheric Disturbance (TID) occurrence was conducted with observations recorded from 24 January 2021 to 21 February 2021. While the results are relatively early, they suggest TID signatures are most prevalent during the hours of 21:00 UTC to 02:00 UTC (or 15:00 Midpoint Local Time to 20:00 Midpoint Local Time).

In the future, the authors will investigate the observations of other Grapes located around the United States. This includes applying a method to data from multiple Grape stations to measure the phase velocity and direction of TID propagation. Furthermore, the authors plan to expand the time range of observations used in this statistical study as well as refine the statistical study methodology. The authors will explore the physical mechanisms for TID production by combining the data presented in this paper with data from other sources to help diagnose methods of TID production. In a matter of years the authors will be working with physical models to further the understanding of TIDs. In addition, other authors are consistently proposing physical mechanisms for TIDs and the authors of this paper will see if those suggestions match the data that is collected by the Grapes.

5 Acknowledgments

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Figure 1: The map shown above depicts the path traveled by radio waves transmitted by WWV (left) and received by KD2UHN (right). Notice, due to the distortions of a 2-Dimensional map, the radio wave does not propagate in a straight line on the map, so the Great Circle Path appears curved.

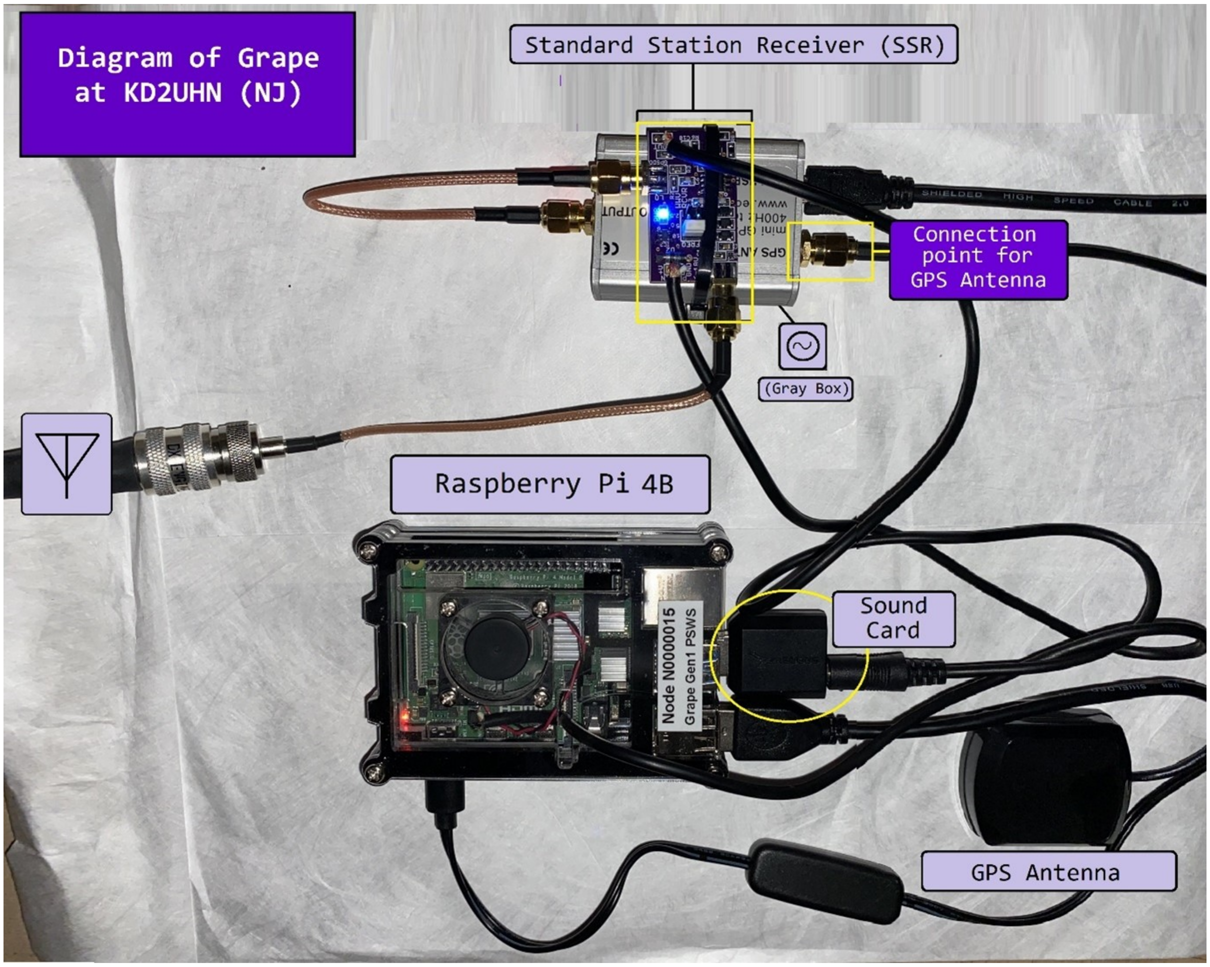

Figure 2: The picture shown above depicts the setup and orientation of the Grape located in Northwest New Jersey. As outlined in the picture, the coaxial cable from the antenna connects to the Standard Station Receiver (SSR). The GPSDO also connects to the SSR. The SSR connects through a sound card to the Raspberry Pi 4B single board computer which allows the data to be transmitted and stored on the internet. The data collected each day can be accessed using a secure shell (SSH) connection to the Raspberry Pi 4B. That makes it accessible from remote locations.

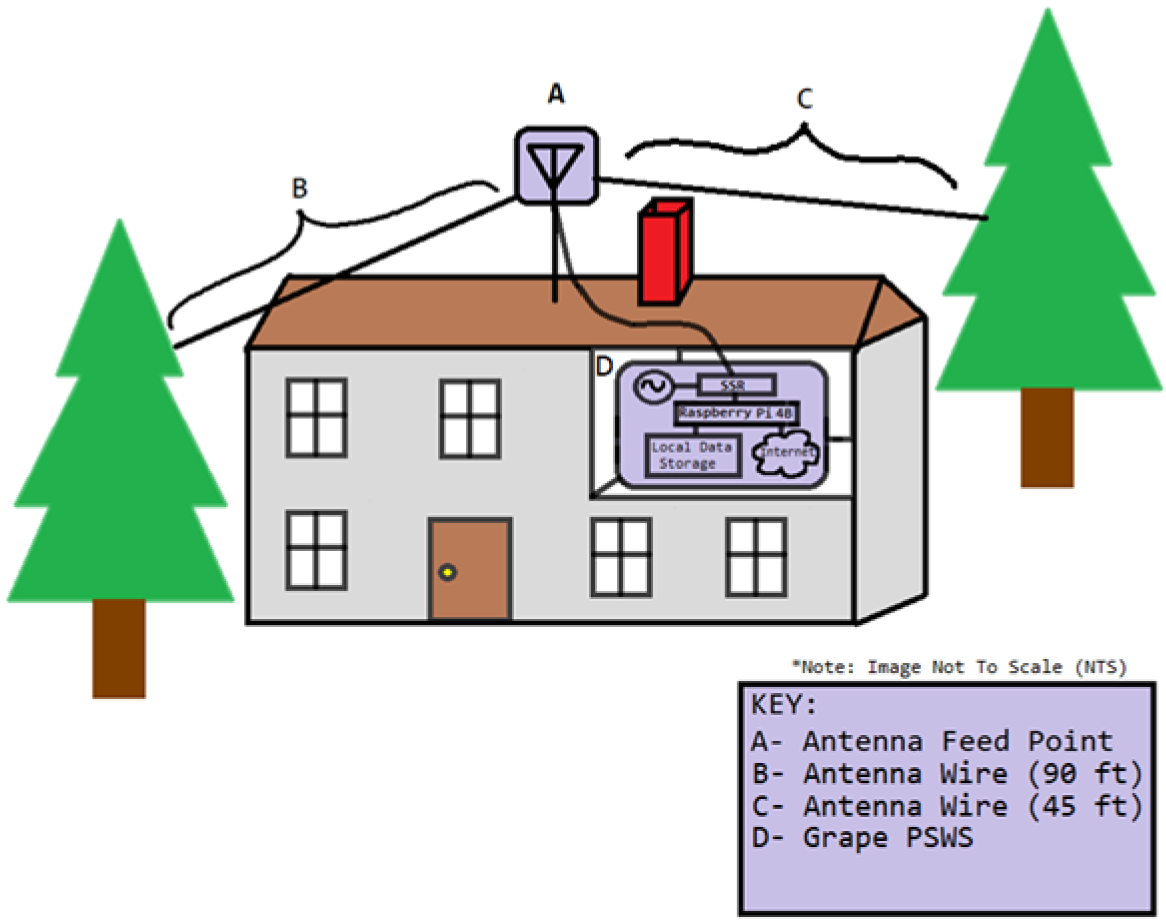

Figure 3: The picture shown above depicts the setup of the Grape. The Buckmaster OCF Dipole Antenna is mounted roughly 30 feet high, on top of the roof. The wires (notated as B and C in the image) connect to the antenna feed point and are an approximate cumulative length of 135 feet (one side is 90 feet, the other is 45 feet long). There is about 25 feet of coaxial cable running from the antenna to the Grape.

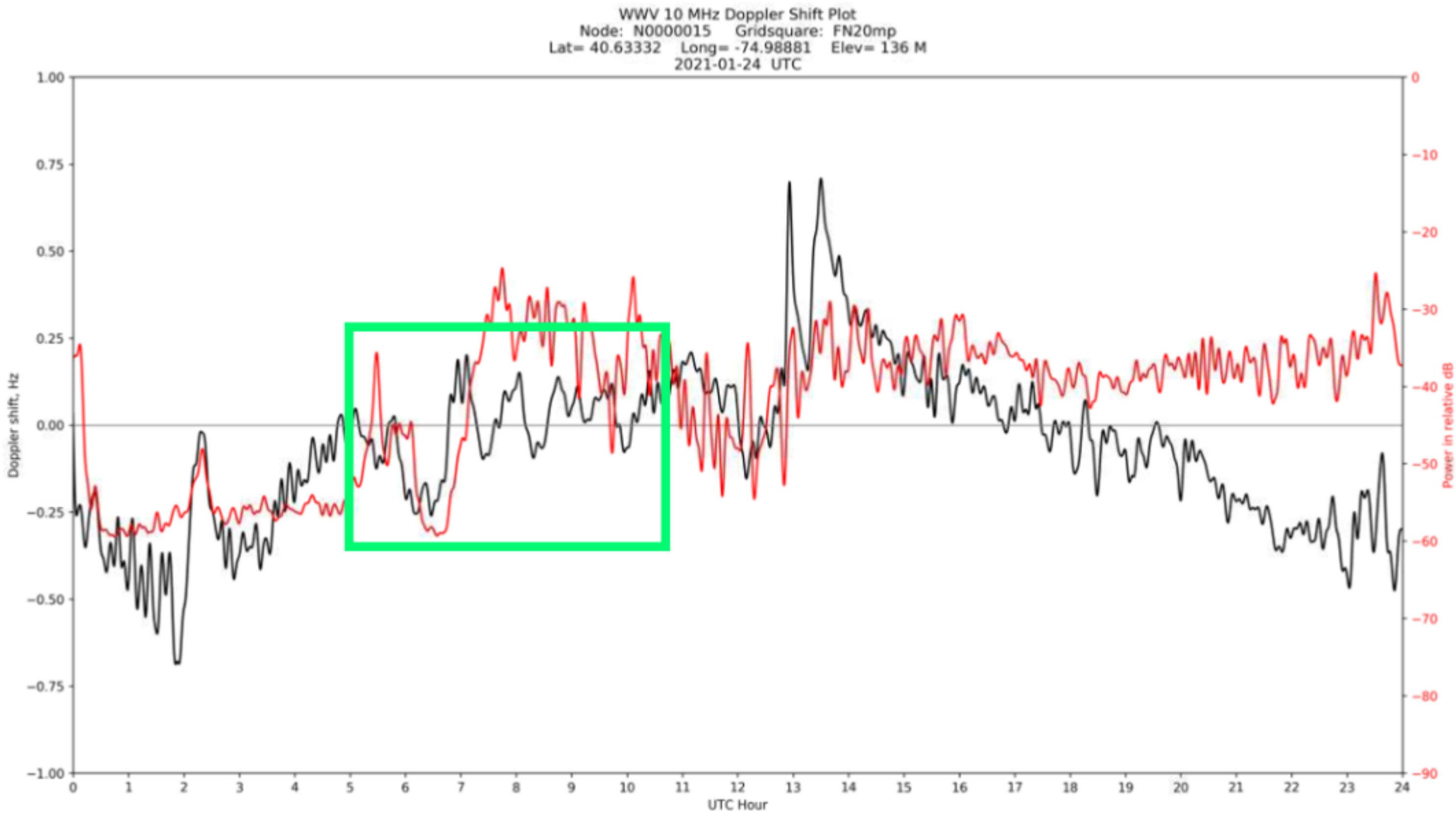

Figure 4: As discussed in the methods section, a graph generated using the data collected by the Grape is shown above (NJ). The black line represents the change in the received WWV carrier frequency from 10 MHz in Hz. The red line represents measured signal strength. This graph provides a visual understanding of what the Grapes are looking to find: ionospheric disturbances. One such disturbance is outlined above in the green box. The box outlines a sinusoidal movement detected in the received frequency by the Grape. This movement can be attributed to an ionospheric disturbance.

Observations of Active Hours as Seen by a Grape Receiver in Northwest New Jersey (January 24, 20201-February 21, 2021)

	UTC:	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5	TOTALS PER DAY
Central Time	Midpoint Local Time	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
Date	1/24/2021	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	4
	1/25/2021	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	9
	1/26/2021	1	1	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	0	1	1	1	1	1	1	12
	1/27/2021	1	1	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1	1	1	0	1	0	0	0	9
	1/28/2021	1	0	0	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	0	0	0	0	1	0	10
	1/29/2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
	1/30/2021	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	0	7
	1/31/2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	2/1/2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	2
	2/2/2021	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	20
	2/3/2021	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0	1	0	1	0	0	12
	2/4/2021	0	1	1	0	0	0	0	0	0	0	1	1	0	0	1	1	1	1	1	0	0	0	1	1	11
	2/5/2021	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0	1	1	0	19
	2/6/2021	0	0	0	0	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	12
	2/7/2021	1	1	1	1	0	0	1	1	1	0	0	1	1	0	0	0	0	1	1	1	0	0	1	1	14
	2/8/2021	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	3
	2/9/2021	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	0	0	7
	2/10/2021	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	8
	2/11/2021	0	0	0	0	1	1	1	0	0	0	1	1	1	1	0	0	1	1	0	0	0	0	0	0	9
	2/12/2021	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	0	0	0	0	17
	2/13/2021	0	1	1	0	0	0	1	1	1	0	1	1	1	1	0	0	1	1	1	0	0	0	0	0	12
	2/14/2021	1	1	1	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	19
	2/15/2021	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	1	10
	2/16/2021	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	0	1	1	16
	2/17/2021	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	1	14
	2/18/2021	1	1	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	14
	2/19/2021	0	0	0	0	0	0	1	1	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	10
	2/20/2021	0	0	0	1	1	1	1	1	0	0	1	0	1	1	0	0	1	1	1	1	1	0	0	0	13
	2/21/2021	0	0	1	1	1	1	1	0	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1	0	13
TOTALS PER HOUR		11	13	15	12	14	12	15	12	9	6	13	14	15	9	9	16	22	25	18	16	9	6	9	8	

Figure 5: Excel table showing TID-active and TID-quiet times from 24 Jan 2021 through 21 Feb 2021 observed by the Grape at KD2UHN in New Jersey. The hours with "1" were considered to be TID-active hours, while those with "0" were considered to be TID-quiet. Light green shading indicates a TID-active period. Dark green shading indicates that hour has higher than average TID activity; dark gray shading highlights days with higher than average TID activity. Universal Time (UTC) is the time that the Grape PSWS runs on. Midpoint Local Time, is the time zone where the radio wave actually interacts with the ionosphere, and this occurs in the Mountain Time Zone.

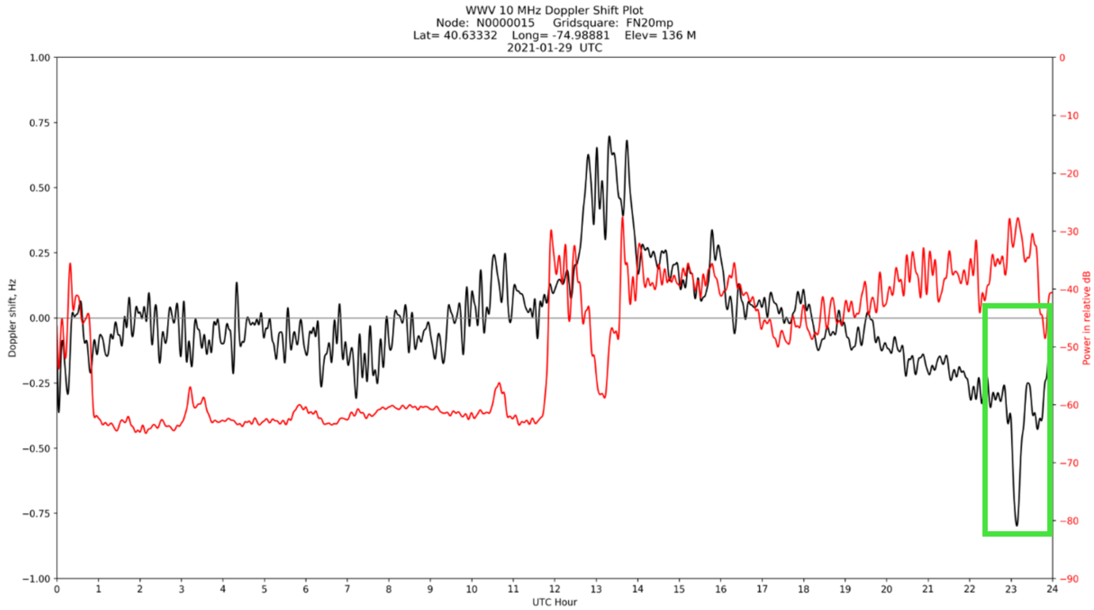

Figure 6: The graph shown above depicts a relatively quiet day in the ionosphere. With the exception of the last hour, as notated by the green box, there are no clear variations in Doppler Shift to indicate the detection of an ionospheric disturbance.

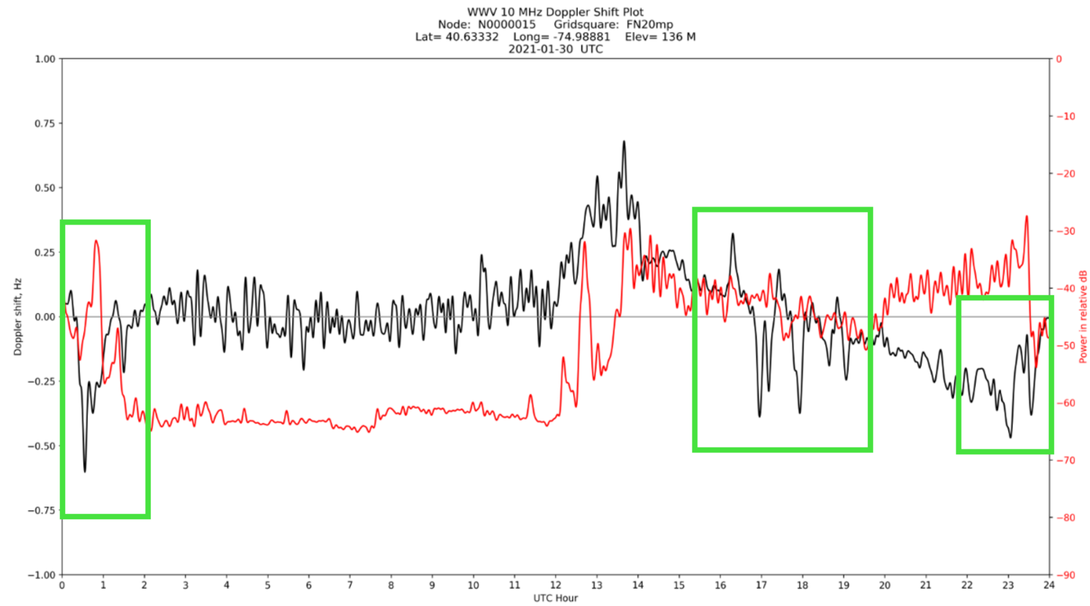

Figure 7: The image above shows another active day. Notice the sinusoidal movement that was detected on this day. This movement is outlined by the green boxes.

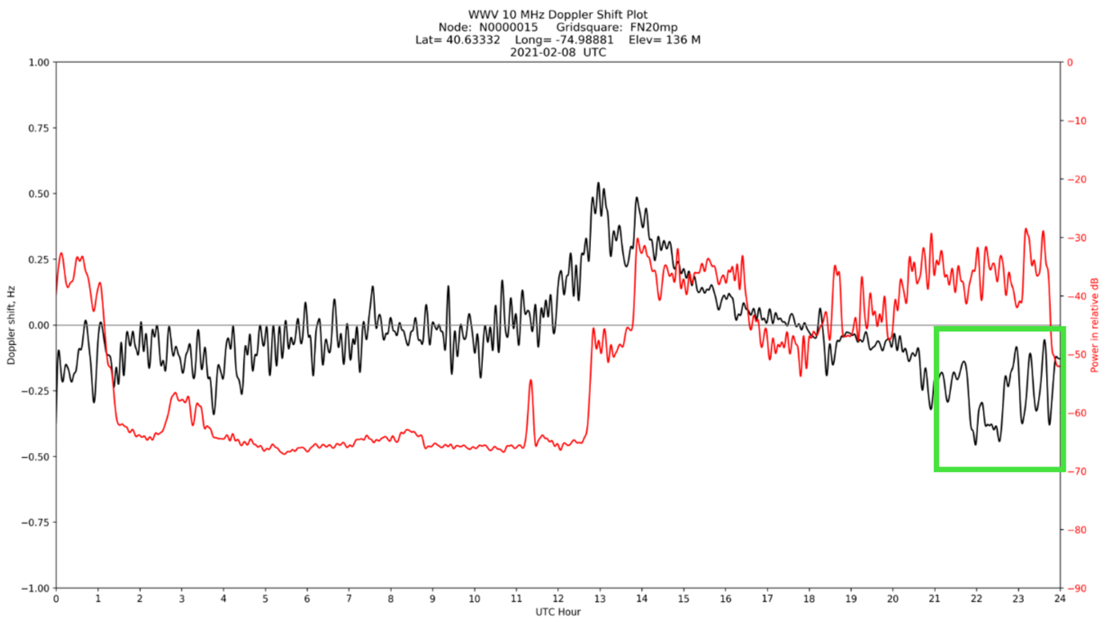

Figure 8: The day shown above is an example of a relatively quiet day in the ionosphere as detected by the Grape. The green box outlines the only disturbance that was observed this day, in the last few hours. Notice how the rest of the day includes no clear sinusoidal variation in Doppler Shift

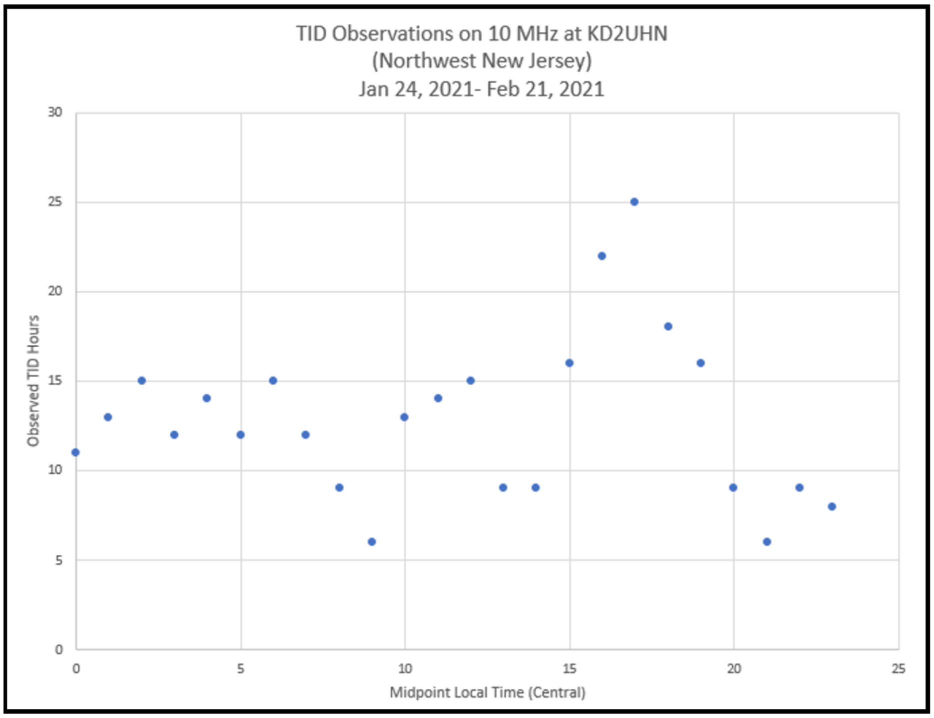

Figure 9: The graph above shows the distribution of total active hours between January 24, 2021 and February 21, 2021.