Citizen Scientists Conduct Distributed Doppler Measurement for Ionospheric Remote Sensing

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***Abstract*—Doppler shift measurement using time standard stations as passive radar beacons is well-established as a means of estimating virtual ionospheric height. A community science experiment in distributed Doppler shift measurement was conducted in October 2019 using the time station WWV, on the event of that station's centennial. Participants were asked to collect Doppler shift data from the WWV 5-MHz carrier via the open-source software program fldigi. This experiment garnered participation from stations across the country, demonstrating considerable volunteer interest: 45 recordings of WWV's 5-MHz beacon were collected. The novel element of this study is the use of distributed low-fidelity sensors in this geophysical domain, and the robust participation of the amateur radio community was enabled by inexpensive and readily available instrumentation. In this letter, we present an initial correlation analysis of the resultant data and discuss its implications for future long-term distributed Doppler networks. The data collected are in good agreement and, when examined together, offer some insights into regional trends. Despite the variety of equipment used by the amateur community, this community science approach shows promise for addressing the problem of undersampling in the geospace system.**

***Index Terms*—Citizen science, distributed sensing, Doppler shift, GPS-disciplined oscillator (GPSDO), time standard.**

I. INTRODUCTION

AMATEUR radio is a proven resource for the collection of scientific data in ionospheric physics [1]. The population of amateur radio operators and shortwave listeners is widely distributed, largely technically literate, and socially inclined, making the community well-suited for citizen science. As amateur radio has become more computerized, the number of licensed operators has increased; the same trend enables greater sophistication in scientific data collection at a lower cost. The experiment discussed herein, undertaken in October 2019, leveraged the instrumentation and goodwill of the amateur community for a large-scale data collection exercise [2]. The event sought citizen scientists from the amateur radio community as well as those with HF listening equipment. Instructions were provided at https://hamsci.org/wwv-centennial-festival-frequency-measurements and publicized widely in the amateur radio community. Data were made available in a public archive [3]. This exercise was a pilot experiment for the Personal Space Weather Station project, an effort by the Ham Radio Science Citizen Investigation (HamSCI) collective to create a distributed network of instruments that will gather scientific-grade observations of signals of opportunity across the HF bands from volunteer citizen observers. This will complement current work performing related measurements with dedicated research instruments [4].

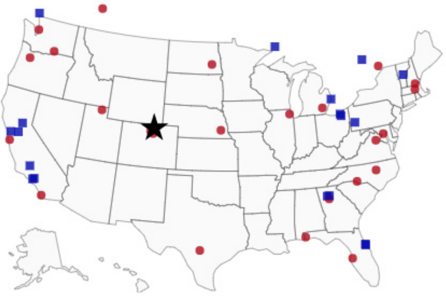

Fig. 1. Map of participants in North America, some international stations not shown. Squares: stations with GPSDOs. Star: location of WWV.

Although its daily and seasonal variations are well-characterized, the ionosphere remains undersampled on regional and global scales. The placement and density of instrumentation networks are limited by logistical and financial concerns, and active instruments such as ionosondes are additionally limited by spectrum allocations. There is, however, no practical limit on the density of receiver networks. Furthermore, the range and density of the amateur community exceeds that of any instrumentation network deployed for research purposes. This volunteer-driven model is therefore a powerful tool for deploying a data collection network in short- or long-term science campaigns.

II. METHODOLOGY

A. Doppler Measurement via WWV

WWV is a radio station of the U.S. National Institute of Standards and Technology (NIST) that transmits standard time and frequency information. Located in Fort Collins, Colorado, since 1966, WWV provides a stable, reliable, and traceable reference for frequency and time that can be received with

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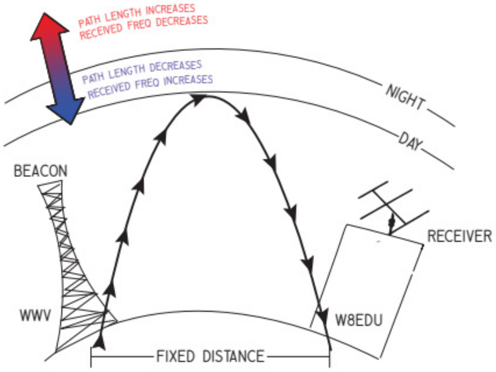

Fig. 2. Conceptual illustration of Doppler measurement of changes in virtual ionospheric height.

simple equipment. Signals from HF time standards stations like WWV propagate via the ionosphere, and the path length of the signal changes with ionospheric conditions. These variations occur on a daily basis, with the virtual ionospheric height at a given location dropping during the day and rising during the night; they also undergo variation on longer (e.g., seasonal) and shorter (e.g., minute) timescales. The frequency of the received signal is affected by Doppler shift, as shown in Fig. 2. For a ray undergoing a single hop, a movement upward in the virtual ionospheric height at the point of reflection results in a drop in received frequency as the wavefronts are stretched farther apart. Conversely, if the virtual height decreases, the wavefronts move closer together and the received frequency is increased. Since WWV's carrier is extraordinarily precise, the change in received frequency may be used as a proxy for change in path length, and therefore change in virtual ionospheric height at the point where the signal reflects off the ionosphere before reaching the receiver. The propagation-induced Doppler shifts are very small. The typical average frequency excursions are less than 1 Hz out of carrier frequencies in the 2.5 to 15 MHz range, and measurement precision is limited by the frequency calibration and stability of the receiver's local oscillator. At standard temperature, a typical crystal oscillator is guaranteed by the manufacturer to be one part in 10^6. However, temperature swings may cause it to exhibit drift on the order of tens of hertz [5]. A GPS disciplined oscillator (GPSDO) removes these limitations by imparting the accuracy and stability of the atomic clocks used in GPS satellites [6]. With atomic clock accuracy on both ends of the transmission path, frequency deviation measurements can be attributed solely to propagation effects.

The technique of measuring Doppler shifts is well-established and has been in use since the inception of ionospheric physics [7]. However, until now, the availability of stations was limited by the cost of instrumentation and data collection apparatus. In particular, single-board computers such as the Raspberry Pi and inexpensive GPS-disciplined (and therefore NIST-traceable) oscillators like the Leo Bodnar (approx. $100 USD) have reduced the barrier to entry for making and disseminating precision frequency measurements.

B. The Festival of Frequency Measurement

In 2019, a gathering was held in Fort Collins to celebrate the centennial of the awarding of WWV's callsign [8]. Because of its long tenure, wide reach, and 24-h programming, WWV is fondly regarded among the international community of amateur radio operators and shortwave listeners. The festival of frequency measurement was conceived as a way to showcase WWV's scientific utility as a beacon for propagation research.

Participants were asked to make recordings using the open-source radio program fldigi [9]. Its frequency analysis mode uses a phase accumulation method which begins with the user's initial best guess of frequency and then tracks the possibly varying signal. Added to fldigi since the Festival is an additional mode titled FMT, which performs a similar function but is based on a frequency estimation algorithm by Tsui and Reisenfeld [10]. This method estimates a received frequency by an efficient discrete Fourier transform method with a faster approach to the Rao–Cramer lower bound than the phase accumulation method. This mode was specifically designed for use in the American radio relay league frequency measuring test (FMT). The FMT is a metrology exercise in which a frequency-precise, stable carrier is transmitted and participants attempt to estimate that frequency as closely as possible. Doppler shift due to changes in the path length is a source of error in the FMT, but since WWV's precise carrier frequency is known *a priori*, the same method may be used to determine that Doppler shift. Since fldigi is already widely adopted among amateur radio operators, this approach enabled wide participation among the community.

Of WWV's five beacon frequencies (2.5, 5, 10, 15, and 20 MHz), the 5-MHz beacon was selected as the one most likely to have favorable propagation range across the United States without being significantly affected by local noise at receiving stations. It is below the Maximum Usable Frequency for 3000 km paths (MUF3000) typically observed by midlatitude ionosondes both day and night, which is in agreement with the IRI climatological model. Participants were asked to collect data for the 24-h period corresponding to the UTC day of October 1, and to begin data collection before and end after that period if possible. A test-run with several stations was held before the experiment in order to ensure the effectiveness of the data collection process [11]. After that, no significant guidance was provided to participating stations. Data sets are identified by participants' amateur radio callsigns (e.g., W8EDU), a unique identifier that is associated with the bearer's name and mailing address. Most participants uploaded data to the repository at www.zenodo.org, while some sent it to the organizers directly.

III. ANALYSIS

A. Initial Review of Data

To gain an overview of the data, we applied a 300 point (5 min) low pass filter and plotted each station's Doppler measurements as shown in Fig. 3.

We removed several data sets as follows:

1) *Too short:* W6MSU, VK3ZAZ, K2LYV.

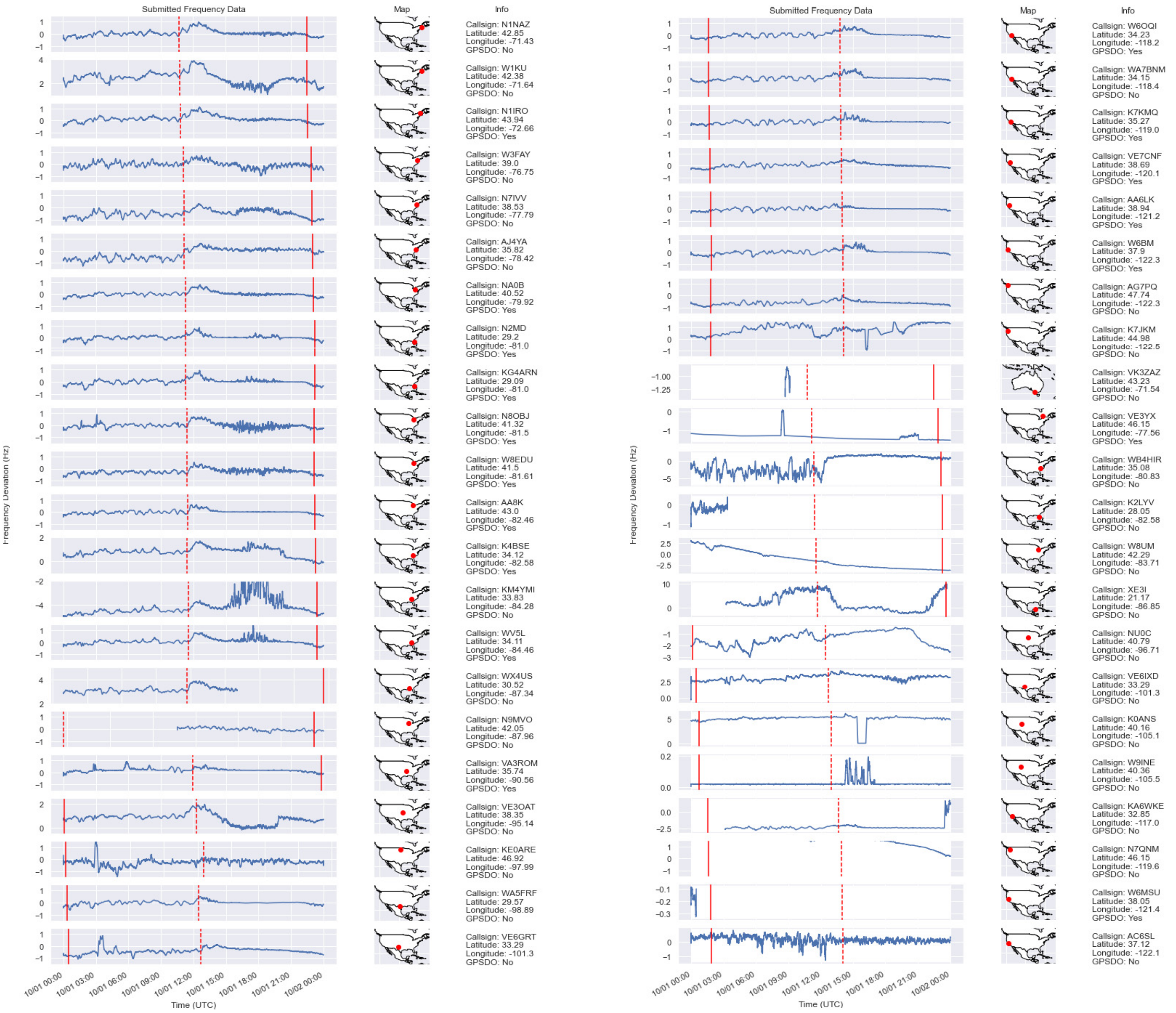

Fig. 3. All Doppler measurements submitted by participants for 5 MHz, filtered and ordered by longitude east to west, following the path of the terminator. Shown to the right of each plot is information about the station which made the measurement. The dotted line indicates local sunrise at each station location, the solid line local sunset. Culled data sets are appended at the end, beginning with VK3ZAZ. A few stations lacked an accurate timebase in the receiver or soundcard, and therefore have a constant offset error. To adjust for this, the plots for these data sets (W1KU, K4BSE, KM4YMI, WX4US, and VE3OAT) have been offset so that the data are shown while keeping the scale the same. Note the presence of some features which appear to align across many submissions, as well as some features that indicate noise, equipment, or data collection errors.

2) *Noise indicating a ground loop:* VE6IXD, WB4HIR, AC6SL.
3) *Frequency drift:* N7QNM, NU0C.
4) *Miscellaneous errors:* XE3I, VE3YX, W8UM, KA6WKE.
5) *Too close to show skywave propagation:* K0ANS, W9INE.

The absolute value of data submitted by N2MD was flipped to account for the fact that it had been measured using a lower sideband rather than an upper sideband. These adjustments are reflected in Fig. 3.

B. Geographical Trends

We sorted stations by region to help illuminate possible correlations since strongly correlated features between nearby stations support the hypothesis that these features are geophysical in nature. In some cases, correlation between data sets was immediately evident: for example, the traces for K7KMQ, WA7BNM, and W6OQI, all stations in California with GPSDOs, show a pronounced similarity.

C. Correlation Analysis

We used the `corr()` function in the Python library pandas [12], [13] to perform Pearson correlations (1) between the data sets for each pair of stations

$$_{X\ Y} = \frac{\mathrm{cov}\ \ X\ \ Y}{_{X\ \ Y}}. \tag{1}$$

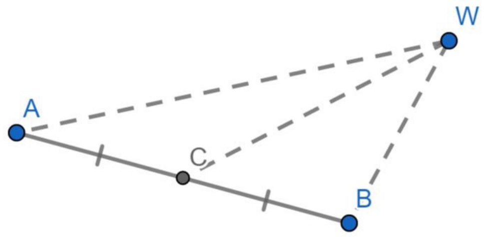

Fig. 4. Illustration of centroid calculations, where A and B represent a pair of stations and W represents the beacon station, WWV.

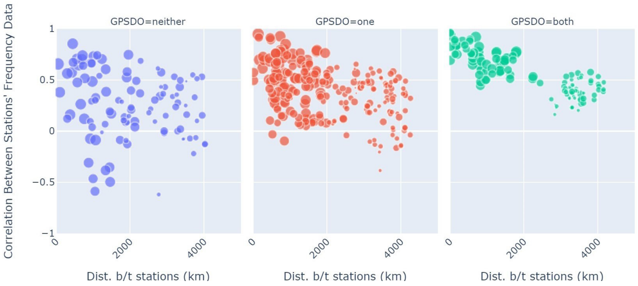

Fig. 5. Correlation versus distance ($\overline{\mathrm{AB}}$, in Fig. 4) for each pair of stations, separated by presence of GPSDOs. Marker size indicates centroid distance $\overline{\mathrm{CW}}$.

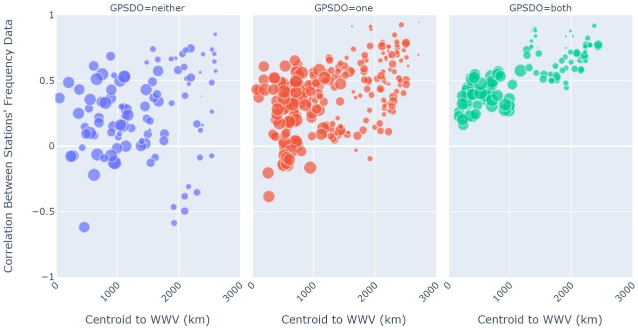

Fig. 6. Correlation versus centroid distance ($\overline{\mathrm{CW}}$, in Fig. 4) for each pair of stations, with marker size indicating the distance between receiving stations.

Two distances were used, as illustrated in Fig. 4: the distance $\overline{\mathrm{AB}}$ between any two stations, and the centroid distance $\overline{\mathrm{CW}}$[1] between the center point of those stations and the beacon, WWV. The former was calculated according to the geodesic distance using the `geopy()` library; the latter was calculated via the haversine method. Results for the filtered, retained data sets are shown in Figs. 5 and 6. Each point on the plot indicates a set of two stations whose frequency data were correlated in this way. (Amplitude data was omitted from this analysis, but is included with the original data set.) In the first case, shown in Fig. 5, two stations that are very close together should have very strongly correlated data sets, and two stations that are far apart should not be as well correlated. We see this trend appear clearly when we restrict the set of stations examined to only those with GPSDOs.

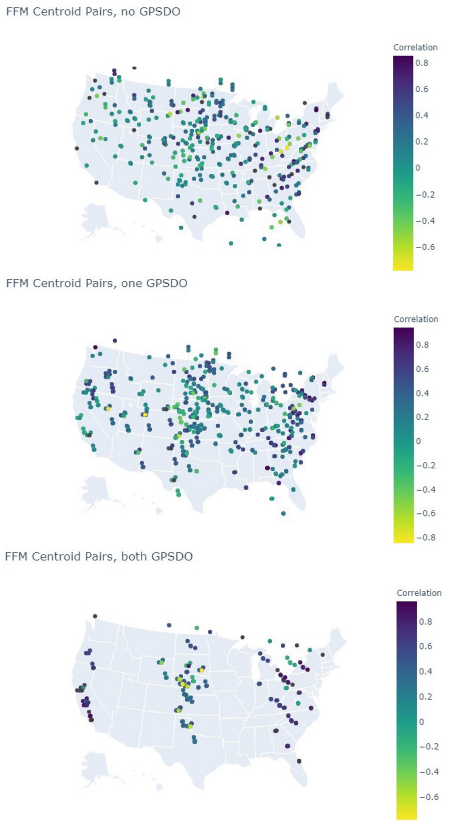

Fig. 7. Center points (C in Fig. 4), with darker colormap suggesting stronger correlation. (Left) for pairs of stations where neither station has a GPSDO; center, where one station does and one does not (Right) where both do.

IV. CONCLUSION

A. Human Factors

The data collection process highlighted several human factors issues, which are being addressed for future experiments.

1) Having participants upload data directly to the Zenodo repository made the data more difficult to retrieve. In later events, this was replaced by an upload page.
2) At the time of the experiment, fldigi's Frequency Analysis mode recorded only timestamps, without noting the date. This deficiency has since been addressed in a software patch to fldigi as a direct result of this experiment.

B. Instrumentation

The instrumentation used to collect data for the Festival varied widely. Volunteers used different makes and models of radios, different antennas, and different oscillators. As discussed above, the use of GPSDOs was a major distinguishing factor between consistent and inconsistent data sets. This pilot experiment demonstrated two important points for future work: First, that valid data can be collected via existing amateur radio apparatus, despite its variety; second, that data sets obtained with precise local oscillators such as GPSDOs may support data sets collected without. The correlation analysis would be improved by a longer data collection period, to reduce the impact of daily variability, and by a more intentional distribution of stations. As shown in Figs. 1 and 7, the volunteer

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[1] Although C is not the literal centroid, $\overline{\mathrm{CW}}$ is termed the "centroid distance," as its distance from WWV maps linearly to the distance between WWV and the centroid of the three points.

distribution for this experiment was uneven, particularly with regard to GPSDOs.

C. Geophysical Observations

Two likely geophysical features are apparent in Fig. 3: First, a rise in frequency can be seen following local sunrise, coinciding with the drop in ionospheric height at the control point (point of reflection) due to ionization during the night/day transition. Second, the shared geophysical features between nearby stations at night are likely indicative of nighttime traveling ionospheric disturbances (TIDs). For example, a set of shared signatures is apparent in the data from NA0B, N2MD, and KG4ARN, and another in the data from W6OQI, WA7BNM, and K7KMQ. These oscillations between 3:00 and 15:00 UTC have a period of approximately 1 h. This is consistent with the period of a large-scale TID [14].

An underlying assumption of the frequency analysis mode—the presence of a single carrier—is flawed for this application, since stations may receive X and O mode signals along different propagation paths, as well as signals from other standards stations. In particular, WWV's sister station WWVH, situated on the island of Kauai in Hawaii, broadcasts on the same carrier frequencies as WWV with slightly different modulation. Since the analysis herein is concerned primarily with the trends among stations, the effects of receiving both signals are outside the scope of this letter. However, their implications are significant for future research and will impact the procedures of future experiments.

V. FUTURE WORK

The internal consistency of this data set having been verified, we will next turn our attention to data assimilation with existing ionosonde networks. In particular, the consistency of Doppler shift observations with virtual ionospheric height measurements is a topic of current research.

The lessons learned from this analysis are being employed in both short- and long-term experiments. We have used the event as a template for similar experiments to collect data from stations worldwide during the solar eclipses of June and December 2020, collecting data for longer periods of time and streamlining the data submission process. Longer-term pilot experiments are also being conducted with a combination of commercial radios and prototype PSWS stations, all equipped with GPSDOs, along great circle paths from WWV across the United States. Before the North American solar eclipse of 2024, we intend to have a robust distributed network of Doppler stations in place, stemming from the knowledge gained through this initial experiment. As the network of receivers becomes denser, we will examine the layers of formation of the ionosphere in greater detail using this method.

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REFERENCES

[1] N. A. Frissell *et al.*, "Modeling amateur radio soundings of the ionospheric response to the 2017 great American eclipse," *Geophys. Res. Lett.*, vol. 45, no. 10, pp. 4665–4674, May 2018.

[2] D. Kazdan *et al.*, "A low-cost HamSCI citizen science HF Doppler receiver for measuring ionospheric variability," in *Proc. AGU Fall Meeting*, 2019, pp. SA43C–3213.

[3] K. Collins, "WWV centennial festival of frequency measurement 5 MHz collected data," Tech. Rep., Mar. 2020, doi: 10.5281/zenodo.3707210.

[4] D. Altadill *et al.*, "A method for real-time identification and tracking of traveling ionospheric disturbances using ionosonde data: First results," *J. Space Weather Space Climate*, vol. 10, p. 2, 2020, doi: 10.1051/swsc/2019042.

[5] *K-Series Clock Oscillators*, Kyocera, Kyoto, Japan, Dec. 2019.

[6] M. A. Lombardi, "The use of GPS disciplined oscillators as primary frequency standards for calibration and metrology laboratories," *NCSLI Measure*, vol. 3, no. 3, pp. 56–65, Sep. 2008, doi: 10.1080/19315775.2008.11721437.

[7] K. Davies, *Ionospheric Radio Waves* (Blaisdell Book in the Pure and Applied Sciences). Blaisdell Publishing Company, 1969. [Online]. Available: https://books.google.com/books?id=6c14AAAAIAAJ

[8] WWV Centennial. (2020). *Celebrating 100 Years of WWV*. [Online]. Available: https://web.archive.org/web/20191127065604/http://wwv100.com/

[9] D. Freese. *Fldigi*. [Online]. Available: http://www.w1hkj.com/

[10] J. Tsui and S. Reisenfeld, "A highly accurate DTF-based parameter estimator for complex exponential," *J. Telecommun. Inf. Technol.*, 2006.

[11] D. Kazdan *et al.*, "WWV centennial trial run recordings of WWV during August 1st, 2019 UTC," Tech. Rep., Sep. 2019, doi: 10.5281/zenodo.3466058.

[12] The Pandas Development Team. (May 2020). *Pandas-Dev/Pandas: Pandas 1.0.4*. [Online]. Available: https://doi.org/10.5281/zenodo.3862857

[13] W. McKinney, "Data structures for statistical computing in Python," in *Proc. 9th Python Sci. Conf.*, S. van der Walt and J. Millman, Eds. 2010, pp. 56–61.

[14] K. Hocke and K. Schlegel, "A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982-1995," *Annales Geophysicae*, vol. 14, no. 9, pp. 917–940, Sep. 1996. [Online]. Available: https://angeo.copernicus.org/articles/14/917/1996/