A Low-Cost Citizen Science HF Doppler Receiver for Measuring Ionospheric Variability

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Abstract

Advancement in understanding short term and small spatial scale ionospheric variability requires high resolution measurements on a global scale. Ionospheric sounding networks are extensive and capable, yet more measurements are still needed due to the strongly magnetized nature and large extent of the ionosphere. High frequency (HF, 3-30 MHz) radio signals are refracted by the ionosphere, and therefore are modulated by processes such as traveling ionospheric disturbances (TIDs) and geomagnetic storms. By measuring the amplitude and Doppler shift of trans-ionospheric HF signals, it is possible to detect signatures of ionospheric absorption and changes in propagation path length. We present a design for a low-cost, citizen-science HF multi-band receiver that measures the amplitude and Doppler shift of reference signals of opportunity from the US National Institute of Standards and Technology station WWV and the Canadian Institute for National Measurement Standards station CHU. The receiver will make 1 s cadence measurements on nine HF beacon frequencies and subsequently upload the results to a central server for scientific analysis. The local user will be able to review data daily, both locally and in aggregate on a web server, and participate in discussion of the ionospheric measurements. This receiver forms one component of the low-cost version of the Ham Radio Science Citizen Investigation (HamSCI) Personal Space Weather Station (PSWS), and is designed with the intention of distribution to hundreds to thousands of citizen science observers. Preliminary results from the prototype receiver will be presented.

Introduction

Space weather and ionosphere studies are of increased interest for their own sake and for predicting disruptions of communications, navigation (GPS), and power systems [1, 2]. Ionosphere electron density has long been measured by sounding rockets and ground-based ionosondes. Satellite-borne, downward-looking ionosondes were added in the 1960s. Most recently, GPS and other satellite signals' phase shift has been measured at ground stations to evaluate ionospheric delays and infer ionosphere structure [3, 4]. Those satellites are not launched to provide such information; the method was developed for earthquake monitoring. It demonstrated its usefulness for ionospheric monitoring during the 2017 total solar eclipse.

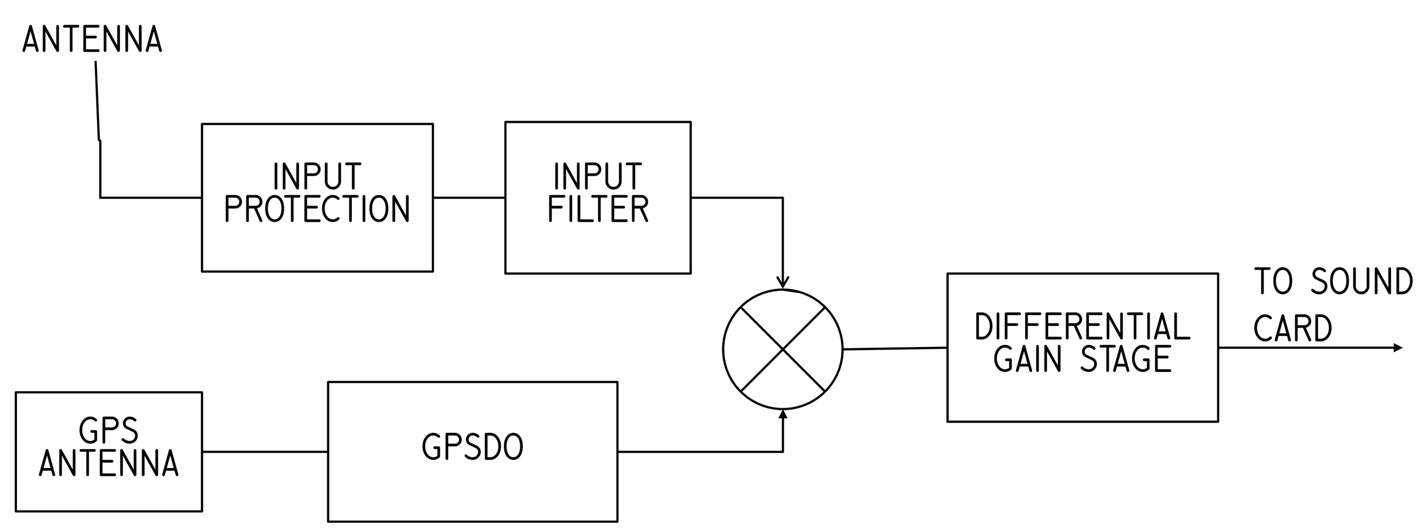
Distant reception of frequency-accurate terrestrial beacons provides another approach. NIST radio transmitters WWVB, WWV, and WWVH are stable, accurate, high-power beacons on 0.06, 2.5, 5, 10, 15, 20, and 25 MHz in Colorado and Hawaii. CHU-Canada is in Ottawa on three frequencies near amateur bands, and other national standard transmitters exist. Operational for many years, these stations provide frequency and time of day information. The frequencies were chosen internationally for their property of being refracted and reflected by the ionosphere: They can be received far past the horizon under favorable ionospheric conditions. Higher frequencies largely pass through the ionosphere on out into space. The long-distance properties of NIST's frequencies permits them to be "repurposed" for ionospheric sounding. Current methods are inexpensive and suitable for citizen-science.

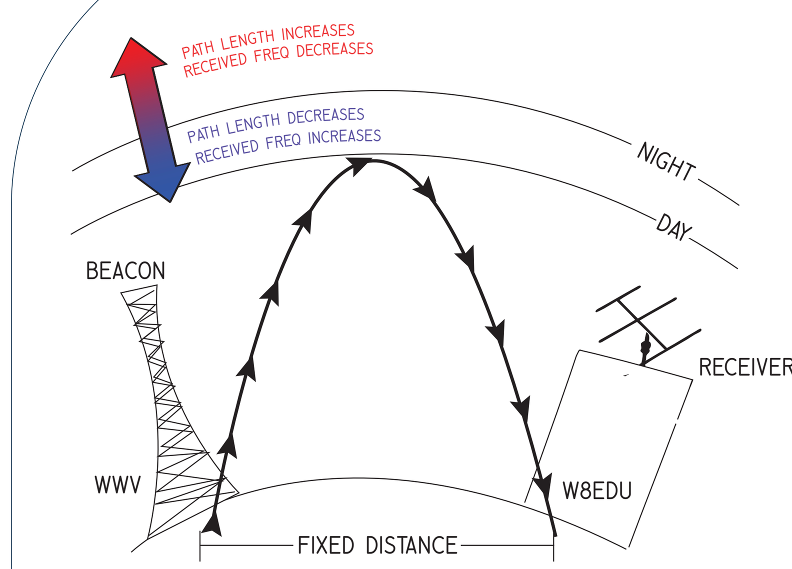
Some sounding experiments have been performed with signal received amplitude measurement. These include perhaps the earliest of radio citizen-science efforts to measure "skip" effects, *Scientific American*'s 1925 request [5] for observer data of AM broadcast signals during the total solar eclipse. A modern replication is documented by Hall-Patch [6]. HamSCI sponsored a citizen-science effort during the 2017 eclipse as well [7].

The Personal Space Weather Station includes radio receiver for these signals among its sensors. A continent-spanning grid of inexpensive receivers is planned, collecting data on a second-by-second basis and uploading those data to central servers. Data are to be collected for as many beacon frequencies as possible, primarily of signal Doppler shift.

Festival of Frequency Measurement

A data collection exercise was conducted on October 1, 2019 to mark the centennial of WWV. HamSCI issued an open call to amateur radio operators and shortwave listeners to gather Doppler shift data in an event dubbed the Festival of Frequency Measurement. Stations participating are mapped at right. Various equipment was used; a simple block diagram is below. Data will be available on the HamSCI website.





Doppler Measurements

A signal's received frequency matches its transmitted frequency unless transmitter and receiver are getting closer or farther apart. Christian Doppler explored this for acoustic waves; a similar effect holds true for radio waves, as has been known by stopped motorists since 1947. In the case of a stationary transmitter such as WWV and a stationary receiver, the path length of the signal may change as the effective height of the ionosphere changes. The received frequency's deviation from the transmitted frequency is proportional to the rate of change of that path length. That rate of change is affected by ionospheric dynamics, which enables the Doppler measurement to serve as a surrogate space weather measurement. See schematic left.

WWV transmits a high-accuracy, stable frequency derived from a cesium clock. Similar accuracy at the receiver permits the Doppler-shift measurement. A local frequency standard available now is the GPS constellation, and it provides timing within the precision required for these Doppler measurements. In the past ten years, suitable programmable, GPS-disciplined digital oscillators have become available that are robust and inexpensive enough to provide the required local time standard for comparing WWV's nominal frequency from that measured.

Frequency Estimation Problem

Precise measurement of a beacon's frequency is a multifaceted engineering and mathematics problem.

The receiver timebase must be accurate, or at least precise and stable. Quartz-crystal oscillators are good to about a part per million (10^6); the WWV Doppler shift is at the 10^8 level. To the degree required for this work, GPS-disciplined oscillators with 10^{12} accuracy are now inexpensive, compact, and foolproof enough. Many are packed with programmable synthesis systems that permit the WWV receiving frequency to be generated directly. Rubidium standards may also be used at about the same accuracy level but require frequency synthesis circuitry. They are more expensive and less rugged than GPSDOs.

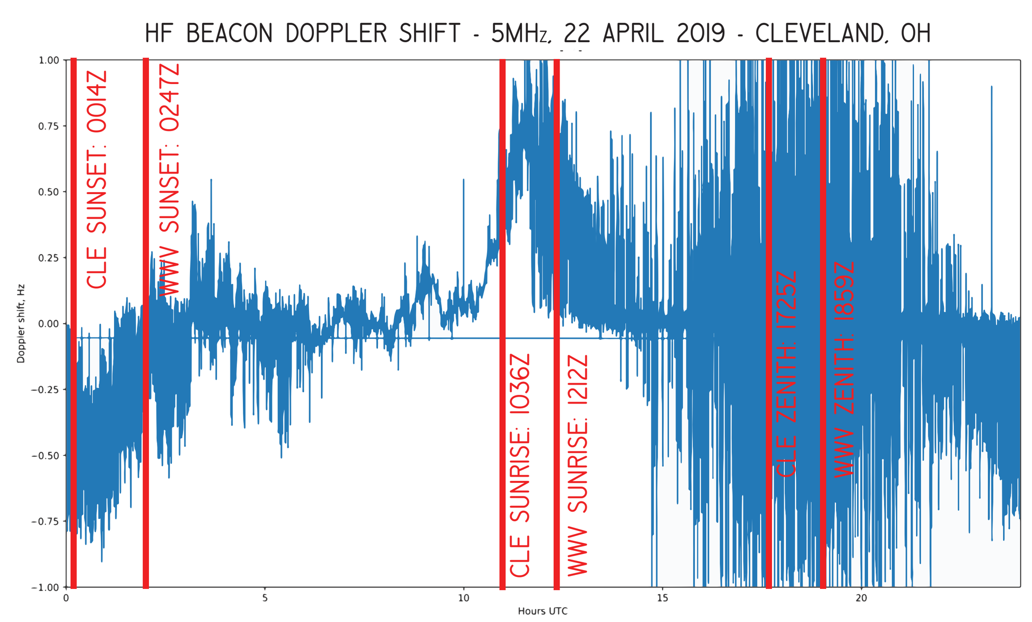
Mathematically, the deterministic problem begins after received signal sampling: The signal will be sampled and windowed. With one second of sampling, discrete Fourier transform frequency bins will have width 1 hertz. Greater precision than this is required, at least 0.1 Hz and preferably 0.01. Curve-fitting across frequency bin amplitudes provides adequate interpolation.

Second, the statistical problem: High-frequency (shortwave) radio is noisy. Noise sources ranging from the Gaussian internal, thermal noise of the receiver circuitry to the nonstationary noise of distant lightning strikes expand the frequency uncertainty across Fourier bins. Statistical frequency estimation is required. Our approach to this is derived from J. Tsui and S. Reisenfeld [8] via the fldigi software suite (a thorough review is due to P.J. Kootsookos [9]).

Doppler Measuring Receiver

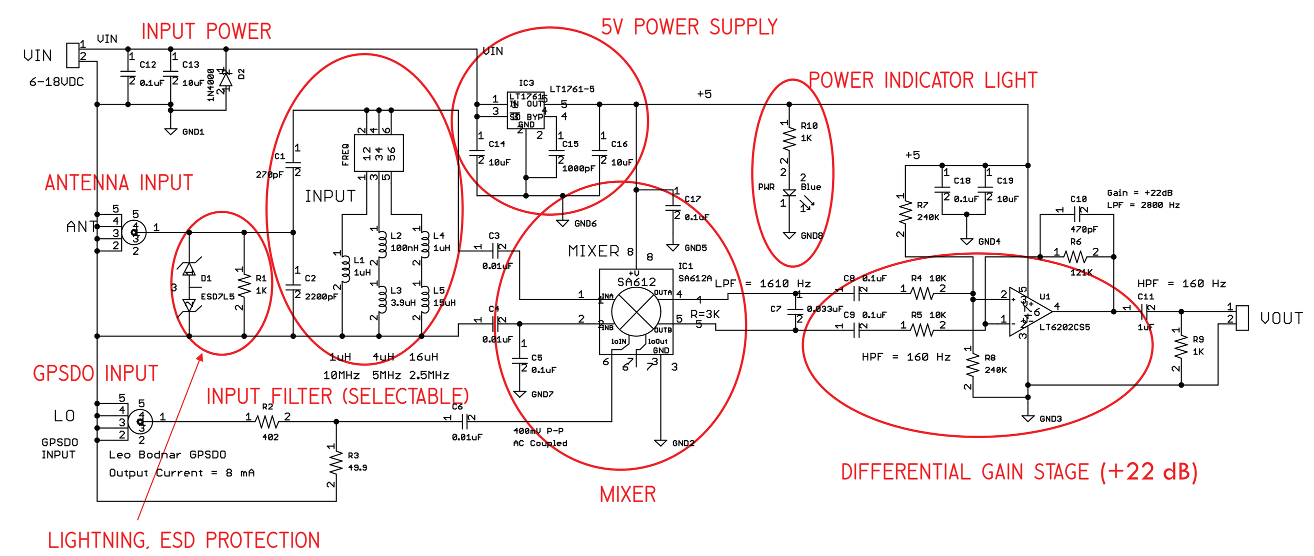
The prototype receiver is of low-IF (intermediate frequency) architecture to facilitate the use of inexpensive sound cards as analog-to-digital converters. A straightforward Gilbert cell (NE612 integrated circuit) receiver architecture with a single conversion stage and no other amplification is used. The antenna signal goes through a simple bandpass filter to the frequency converter; the other converter input is the local frequency standard as synthesized by the GPSDO. See annotated schematic right. The receivers' data are collected and processed on-site by a minimal Linux computer (Raspberry Pi). The processing consists of estimation as described earlier. Those processed data are uploaded to a central repository daily.

The programmable GPS is set to provide a receiver intermediate frequency within the audio passband, 300-3000 Hz. The fldigi analysis module is then used to provide a frequency estimation every second with interpolated precision to 0.01 Hz. This file is saved once per UTC day. It may be graphed for manual examination, usually after lowpass filtering. Empirically, filtering at 0.1 Hz retains Doppler features as identified by solar-induced changes while removing the worst of atmospheric noise. A sample graph with annotation is shown below.

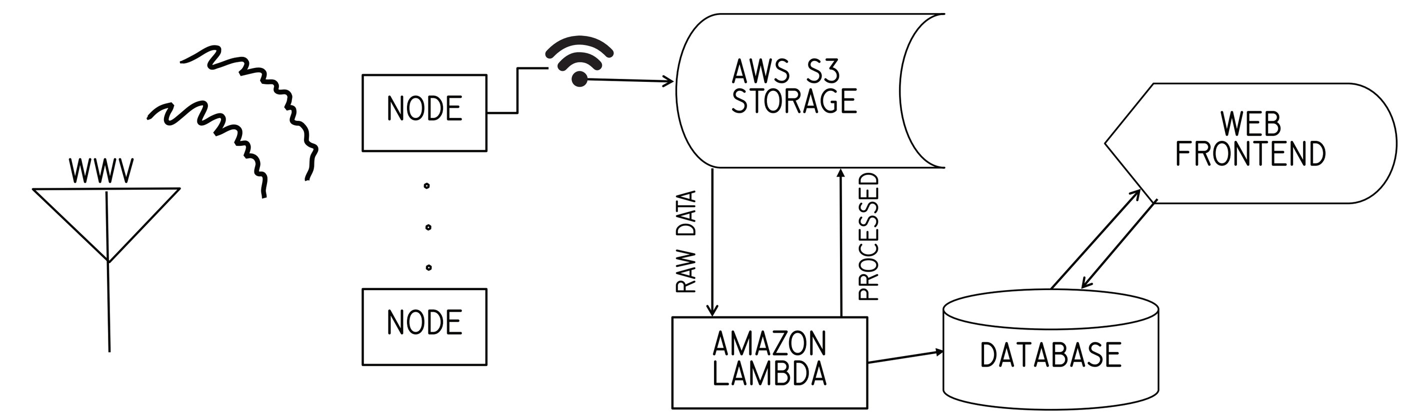


Next Steps

The Personal Space Weather Station overall will include local magnetic field measurements as well as the described beacon Doppler shift and field strength measurements. The current prototype (schematic below) has been demonstrated to record Doppler shift for a single channel of selectable frequency; in future revisions, more channels are to be added to accommodate carriers from multiple standards stations simultaneously.



In preparation for the 2024 North American total solar eclipse, we plan a network of approximately 300 stations distributed across the United States and possibly Mexico and Canada. Data is to be stored in a repository system for future analysis; a notional version is illustrated below.



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