Ham Radio Creates a Planet-Sized Space Weather Sensor Network

For researchers who monitor the effects of solar activity on Earth's atmosphere, telecommunications, and electrical utilities, amateur radio is a valuable resource for crowdsourced science.

Kristina Collins, KD8OXT; David Kazdan, AD8Y, and Nathaniel A. Frissell, W2NAF

Space weather events, triggered by solar emissions and their interactions with Earth's atmosphere, can have significant effects on communications and navigation technology, as well as electric power systems. As with terrestrial weather events, the economic impacts of space weather-related disruptions can be substantial, affecting satellite systems, as well as systems on the ground. A severe geomagnetic storm (such as the Carrington Event of 1859) could have a catastrophic effect on modern infrastructure. Even solar storms of more ordinary size can induce currents in the power grid that increase energy prices, affecting manufacturing and commerce.

There's considerable interest in developing space weather forecasting technologies that use the Earth's ionosphere as a sensor for events in its neighboring atmospheric layers. The ionosphere occupies a privileged niche in the geospace system, as it's coupled into both the terrestrial weather of the neutral atmosphere below and the space weather of the magnetosphere above.

To fully understand ionospheric variability on small spatial scales and short timescales, the scientific community will require vastly larger and denser sensing networks. Although we have a good understanding of ionospheric climate — daily and seasonal variations are well known, as are the rhythms of the sunspot cycle — there are new and vital areas of research to be explored. For example, it's known that the ionosphere (and near-Earth space) experiences variability (e.g., radio signals can fade in and out over periods of seconds, minutes, or hours due to changes in ionospheric electron densities along signal propagation paths), but this variability hasn't been sampled or studied adequately on regional and global scales. With open-source instrumentation being cheaper and more plentiful than ever before, the time is ripe for amateur scientists to take distributed measurements of the ionosphere, and the amateur radio community is up for the challenge.

Radio Signals and the Changing Ionosphere

Just outside Fort Collins, Colorado, lies the heartbeat of the electromagnetic spectrum — and one key to precision measurements of the interactions between ham radio and solar weather. Shortwave listeners are familiar with the sound of radio station WWV, the time and frequency standard of the National Institute of Standards and Technology (NIST). It's the oldest continuously operating radio station in the US, having been on the air since 1919. Today, WWV and its sister station WWVH in Hawaii, broadcast, "At the tone, the time will be…" on 2.5, 5, 10, 15, and 20 MHz, with the frequencies calibrated to at least nine significant digits.

These stations provide listeners with standardized time information, high seas weather forecasts, and other programming. Station WWVB, located at the same Colorado site, transmits on 0.060 MHz and provides timing information to radio-controlled "atomic" clocks. Recently, WWV's cesium-controlled carrier found another use as a beacon for ionospheric measurements — radio signals.

Radio signals provide a window into the changing ionosphere. The various signals from WWV, reflecting off the ionosphere, undergo changes in path length as the ionospheric electron density profile changes. This results in changes to the observed frequency of radio signals at receiving points, similar to the rise and fall in pitch of a passing train whistle.

Comparing the received radio signal with a precision local frequency standard, such as a GPS-disciplined oscillator, allows a user to measure these ionospherically induced frequency shifts (see Figure 1). This measurement is prepared and recorded with open-source software (visit **www.w1hkj.com** for more information). Numerous data sets recorded simultaneously from multiple locations offer information (when examined individually and collectively) about the ionosphere at the time the data is taken. This information includes the movements of traveling ionospheric disturbances and other important phenomena at various scales.

The Festival of Frequency Measurement

On October 1, 2019, the Ham Radio Science Citizen Investigation (HamSCI) celebrated the centennial of WWV with a Festival of Frequency Measurement.

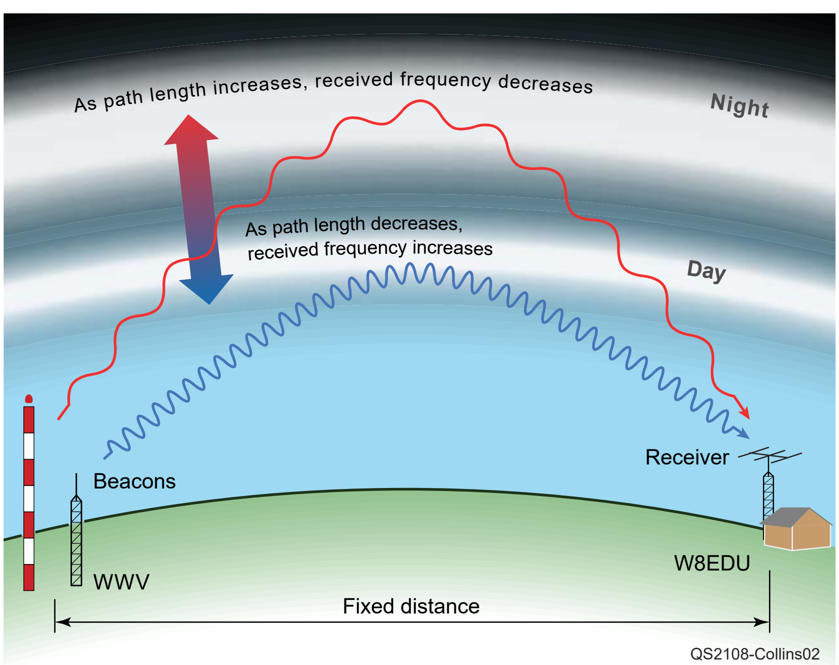


Figure 1 — Signals from radio station WWV reflecting off the ionosphere. Space weather affects how far a signal travels before it's received, and the receiving station detects this as a change in signal frequency. [Kristina Collins, KD8OXT, graphic]

HamSCI issued an open call to amateur radio operators and shortwave listeners to gather Doppler shift data, and about 50 stations responded (see Figure 2). The data is rich with signatures of ionospheric dynamics, including coherent wave-like disturbances with periodicities at night of about an hour. The observations are less active during the day. The data from the experiment is available at **https://zenodo.org/record/3707210#.YL5Tt0wpBdh** and the results are summarized in *IEEE Geoscience and Remote Sensing Letters* (**https://ieeexplore.ieee.org/document/9377452**).

WWV was never intended to provide this data, but the station's exceptional precision, high power, and guaranteed continuous availability make it a perfect beacon. Thanks to the advent of inexpensive GPS-disciplined oscillators and single-board computers, amateur scientists can assemble complete prototype systems to collect such data for less than $200, or they can build systems from existing equipment. Thus, the amateur community, mobilized on a national scale, can generate a large-scale, novel data set for ionospheric study.

Following the success of the WWV Centennial Festival of Frequency Measurement, data collection campaigns during the solar eclipses of 2020 were conducted, and further demonstrated the potential for scientists to engage with the amateur community. Dubbed the Eclipse Festivals, these events followed the template of the WWV centennial event on a global scale, using additional 10 MHz time-standard stations. The June 2020 Eclipse Festival, built around the annular solar eclipse across eastern Africa and Asia on June 21, ran for 3 days and included volunteer participation from 50 stations in 19 countries. The December 2020 Eclipse Festival, a 7-day campaign built around the total solar eclipse across South America on December 14, drew data submissions from over 80 stations. Both were advertised through the same channels used for radiosport contests and other events. The strong participation in these events demonstrates the community's interest in community science and the potential for deployment in science campaigns.

Figure 2 — The Festival of Frequency Measurement events drew participation from stations worldwide. The first event was held in 2019, to commemorate the WWV centennial (participating stations are shown in blue), and two more were held in 2020 — once in June (participating stations are shown in red) and then again in December (participating stations are shown in green) — to gather data during solar eclipses. [Kristina Collins, KD8OXT, graphic]

Making Space Weather Personal

The personal weather station has become a familiar fixture for meteorologists. Stations belonging to hobbyists, networked through sites like Weather Underground (**www.wunderground.com**), provide a dense constellation of sensors reporting air temperature and pressure, as well as precipitation. We have better knowledge of terrestrial weather because of these networks, but no such system exists yet for ionospheric weather.

Through HamSCI, ham radio operators and researchers are bridging this gap by designing hardware for a distributed network of personal space weather stations (PSWSs), accessible to professional and amateur scientists. These stations come in two varieties (see Figure 3): a low-cost model designed only for observations like those performed during the Festival of Frequency Measurement, and a more powerful software-defined radio, called TangerineSDR — a wide-

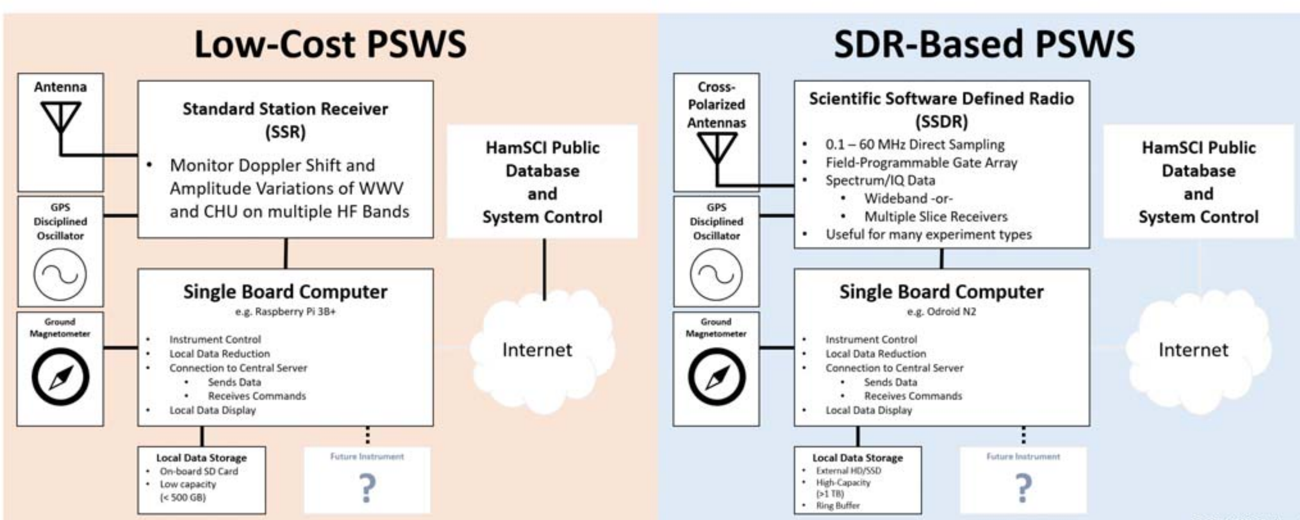
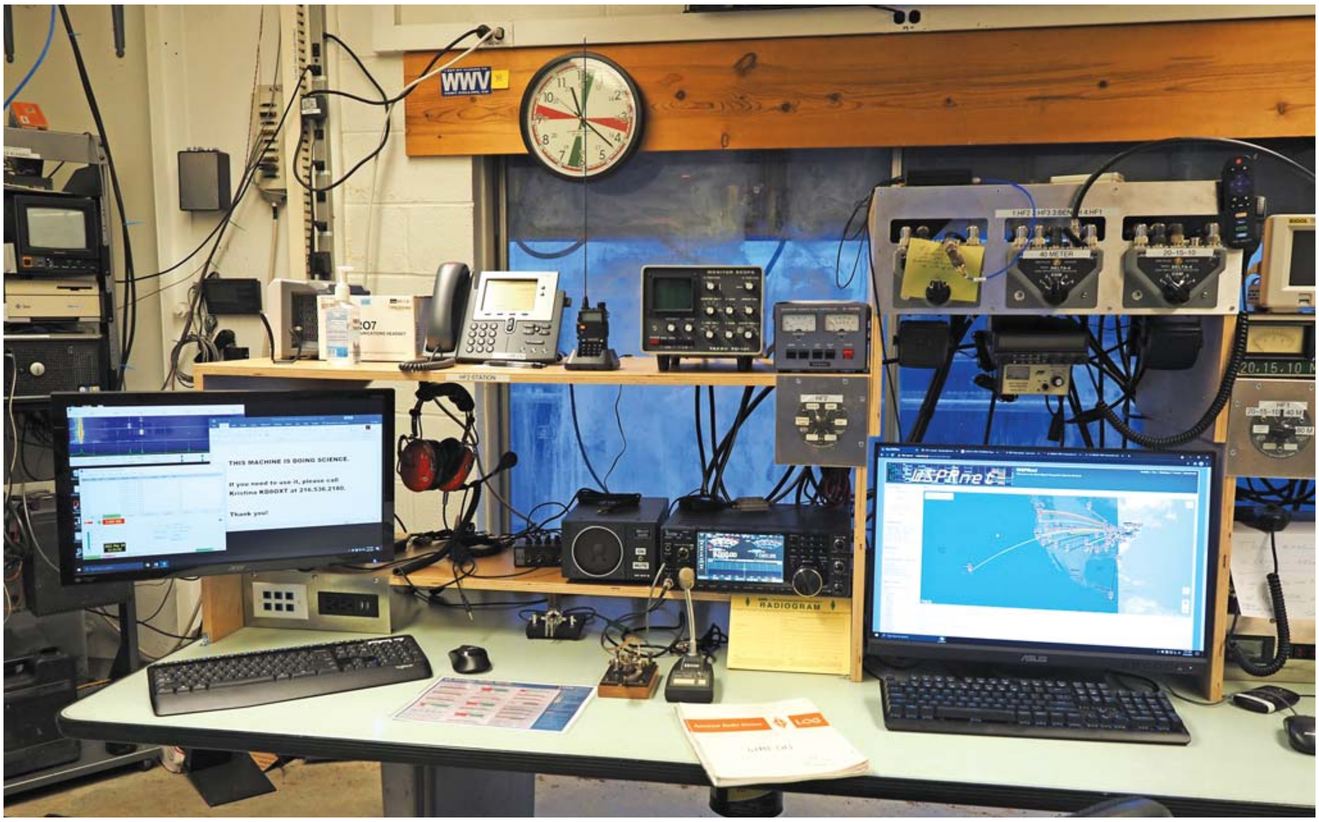


Figure 3 — Low-cost personal space weather stations (PSWS) are designed primarily for measurements of time-standard stations, such as WWV and the Canadian station CHU. More powerful software-defined radio (SDR) PSWS systems can be reconfigured for a range of experiments. [Nathaniel A. Frissell, W2NAF, graphic]



Equipment belonging to the Case Amateur Radio Club, W8EDU. [David Kazdan, AD8Y, photo]

band receiver that can be reconfigured for a range of experiments. At the core of both is a single-board computer, which interfaces with a set of modular instruments (such as a magnetometer) and uploads data to a central database.

These stations are in the prototyping and testing stage, with plans to deploy a network of PSWSs in the next 3 years, just in time to record the 2024 solar eclipse across North America. As the moon's shadow travels across Earth's surface, it will shield the radio stations from solar extreme ultraviolet radiation, providing an excellent opportunity to collect baseline radio data. We hope to have the network running in time for Festival of Frequency Measurement 2024, and we invite hams to join in as volunteer scientists to help improve our understanding of Earth's space environment.

Acknowledgments

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David Kazdan, AD8Y, earned his MD at the University of Cincinnati and his PhD in biomedical engineering at Case Western Reserve University (CWRU). In 2017, the university awarded him with the Carl F. Wittke Award for Excellence in Undergraduate Teaching. As a retired anesthesiologist, David has leveraged his passion for amateur radio in his Seminar Approach to General Education and Scholarship (SAGES) course at CWRU, where all students are required to earn their ham radio license. He can be reached at **ad8y@arrl.net**.

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