# Amateur Radio: An Integral Tool for Atmospheric, Ionospheric, and Space Physics Research and Operations


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**Abstract**

The large-scale observational capabilities of distributed instrumentation fielded by amateur radio operators and radio science enthusiasts offer tremendous opportunity for advancement in the fields of heliophysics, radio science, and space weather forecasting and operations. Well-established amateur radio networks such as the RBN, WSPRNet, and PSKReporter already provide a rich, ever-growing long-term dataset of bottomside ionospheric observations. Conversely, up-and-coming purpose-built citizen science networks offer opportunities to field novel instrumentation optimized to make measurements targeting specific science questions and operational needs. When these measurements are used in conjunction with existing networks of professional instrumentation, the potential for discovery becomes even greater.

## 1 Introduction

Amateur radio, also known as ham radio, is a non-commercial radio service for people interested in wireless communications, experimentation, engineering, and science. There are over 770,000 licensed operators in the United States and over 3 million worldwide, providing the basis for a large and distributed citizen science community with the potential to advance atmospheric, ionospheric, and space science and operations. Projects such as the Ham Radio Science Citizen Investigation (HamSCI, https://hamsci.org) are already working to foster collaborations between the amateur radio and professional space science communities.

The power of amateur radio as a heliophysics remote sensing tool lies in the way its signals interact with the ionosphere and atmosphere. Extremely Low Frequency (ELF, $< 3$ kHz) and Very Low Frequency (VLF, 3 – 30 kHz) waves propagate in the Earth-Ionosphere waveguide, while Low (LF, 30 – 300 kHz), Medium (MF, 0.3 – 3 MHz), and High (HF, 3 – 30 MHz) Frequency signals can be refracted back to Earth by the ionosphere. Figure 1 illustrates HF ionospheric refraction. Higher frequencies may also propagate back to Earth under certain ionospheric conditions such as Sporadic E or neutral atmospheric conditions such as temperature inversions. In all of these cases, the ionosphere or atmosphere will modulate the signals as they propagate, allowing the received signal to be used for remote sensing the path between the transmitter and receiver.

In this paper, we describe current technical and scientific capabilities of the global amateur radio community and the role they play in the advancement in heliophysics and space weather operations. Section 2 describes the large-scale automated communications monitoring networks that have been built and operated by the amateur radio community over the past decade and are now being used for ionospheric research. Section 3 describes new instrumentation networks that are purpose-built for citizen radio science. Section 4 describes the complementary relationship between models, professional observations, and amateur observations. Section 5 discusses specific scientific areas in heliophysics that amateur radio observations are well positioned to advance as well as how amateur radio can contribute to the Space Weather Research to Operations and Operations to Research (R2O2R) framework. Section 6 provides recommendations on how to include amateur radio observations into heliophysics over the next decade. Section 7 is a summary.

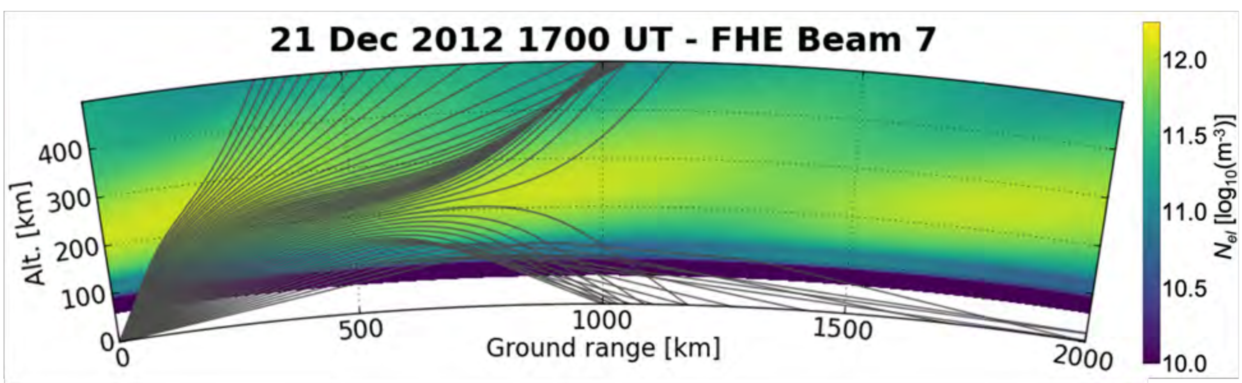


**Figure 1:** Illustration showing how HF radio amateurs can remote sense the ionosphere. This raytrace simulation shows 14.5 MHz radio waves transmitted from Fort Hays, Kansas propagating toward the northeast through the IRI model perturbed with a Medium Scale Traveling Ionospheric Disturbance. Radios located at points where the rays touch the ground are predicted to receive the signal transmitted from Kansas modulated by the ionosphere that it propagates through. From Frissell et al. [18].

## 2 Global Scale Amateur Radio Observational Networks

The amateur radio community has voluntarily built and currently operates a number of automated networks that routinely monitor amateur radio communications in near-real time and report these observations back to central databases. The three major networks that are currently operational include the Reverse Beacon Network (RBN, http://www.reversebeacon.net/), PSKReporter (https://pskreporter.info/), and the Weak Signal Propagation Reporter Network (WSPRNet, https://www.wsprnet.org/). Each of these systems has a different architecture and primarily monitors different types of amateur radio modes. For instance, the RBN reports primarily amateur radio Morse code transmissions (known colloquially to amateurs as Continuous Wave or CW), PSKReporter monitors a variety of digital amateur communication modes, and WSPRNet reports only on the WSPR mode [44] that was designed specifically to probe weak signal HF propagation paths.

These networks have been operational on a near-global scale since approximately 2008. While these systems have been built primarily for the internal use of the amateur radio community, the operators of these networks have graciously allowed the science community access to this data for research purposes. The use of such data for space weather and space physics research was first demonstrated by Frissell et al. [17], who showed a solar flare HF radio blackout observed by the RBN. Subsequent studies have used these systems to study Large Scale Traveling Ionospheric Disturbances (LSTIDs) [22], characterization and prediction of Sporadic E [15, 14, 3], asymmetries in ionospheric greyline propagation [32], 160 m band propagation [45], geomagnetic storm and solar flare ionospheric impacts [20], plasma cutoff and single-mode fading [36], solar eclipse ionospheric impacts [19], and understanding of localized radio propagation anomalies [41].

To illustrate the scientific and operational capabilities of these networks, we present figures from two of these recent studies. Figure 2 is from Frissell et al. [20] and shows an example of solar flare-induced HF radio blackouts observed over Europe by both the RBN and WSPRNet on 6 September 2017. In another example from Frissell et al. [22], Figure 3 shows an example

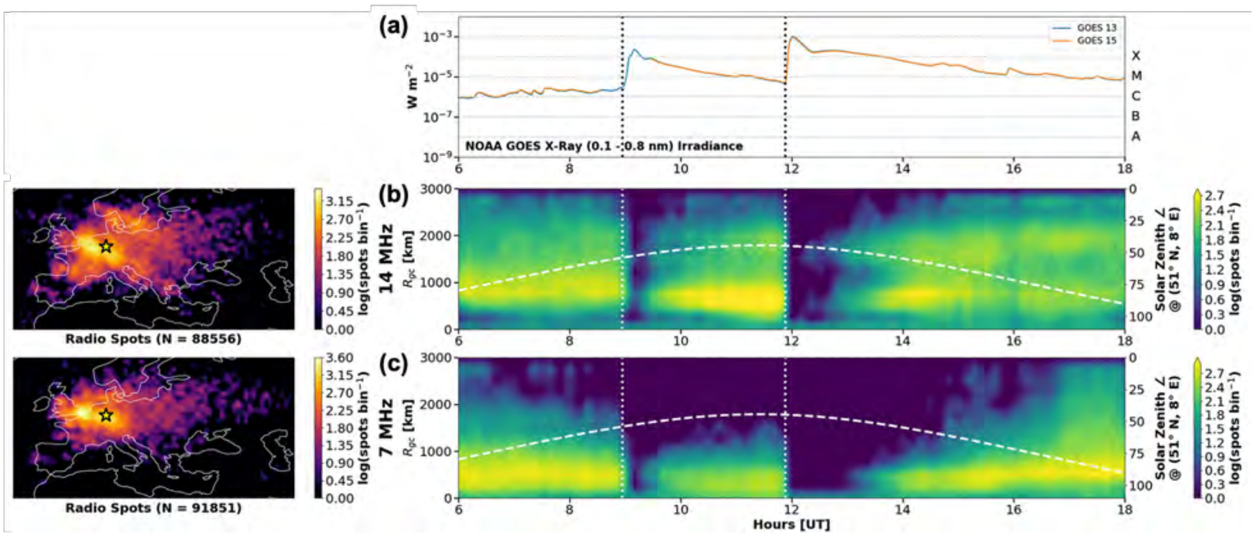


**Figure 2:** Example of solar flare ionospheric impacts observed by amateur radio observing networks over Europe on 6 September 2017. (a) GOES-13 (blue) and GOES-15 (orange) XRS 0.1–0.8 nm X-ray measurements. Flares are observed at 0857 UT (X2.2), 1153 UT (X9.3) and indicated with dotted vertical lines. (b–c) 2D contour histograms of RBN and WSPRNet spot data for the 14 and 7 MHz amateur radio bands, respectively. Bin size is 250 km x 10 min. To the left of each histogram is a map showing the log density of TX-RX midpoints of all spots used in the histogram. The white dashed lines on the histograms show the solar zenith angle computed for (51° N, 8° E), the point indicated by the yellow star on each map. Radio blackouts across the HF bands can be seen in response to the solar flares. From Frissell et al. [20].

of Large Scale Traveling Ionospheric Disturbances (LSTIDs) observed in the RBN, PSKReporter, and WSPRNet data, along with coincident observations by the Blackstone (BKS) SuperDARN HF radar and in Global Navigation Satellite System (GNSS) differential Total Electron Content (dTEC) measurements. A Fast Fourier Transform (FFT) of the unfiltered data in Figure 3f reveals a spectral peak at 2.5, demonstrating remarkable consistency between the amateur radio, SuperDARN, and LSTID observations.

With quasi-global data coverage back to 2008, there is great potential to do large scale statistical investigations with the existing data set, such as the LSTID studies currently being conducted by Sanchez et al. [40] and Engelke et al. [16]. These networks can be easily expanded by encouraging more amateurs to use these systems and field receivers and by having researchers directly field stations themselves. Finally, all of these amateur radio networks have real-time displays and can provide real-time data streams. Currently, these real-time capabilities are not used in any official operational capacity; however, the global scale nature of these systems and direct applicability to real-time HF communications provides a compelling motivation to utilize these systems for operational purposes.

## 3 Purpose-Built Citizen Science Instrumentation

While existing large-scale, amateur radio networks such as the RBN, PSKReporter, and WSPRNet offer tremendous capabilities in terms of geospatial coverage, wide-scale amateur adoption, real-time reporting, and duration of historical archives, these systems have been designed for monitoring of radio propagation path openings, not for making finely-calibrated measurements for ionospheric physics. Limitations of these systems include temporal uncertainties on the order of ±1 s, frequency uncertainties on the order of $\pm 1$ Hz, spatial uncertainties on the order of kilometers, and uneven sampling cadences on the order of 1 to 2 minutes.

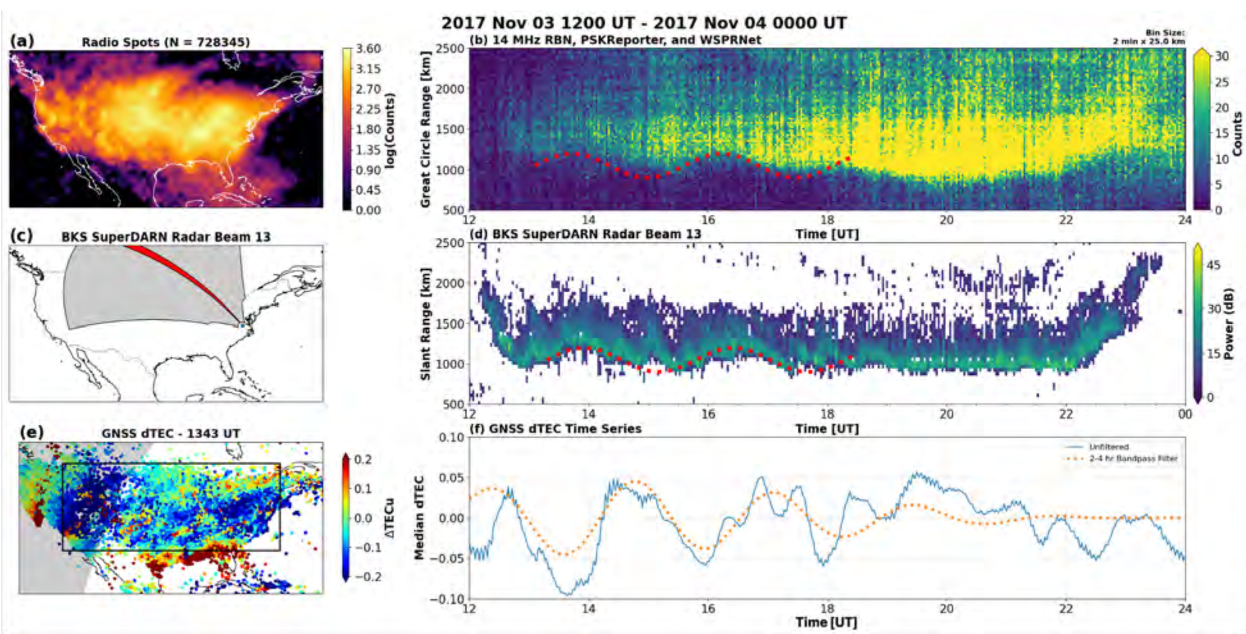


**Figure 3:** Example of Large Scale Traveling Ionospheric Disturbances (LSTIDs) observed using amateur radio networks, the Blackstone (BKS) SuperDARN radar, and GNSS dTEC. (a) Geographic distribution of TX-RX midpoints of amateur radio communications observed over the continental United States on 3 Nov 2017 from 1200-2359 UT. (b) Time series showing the TX-RX distance for 14 MHz amateur radio spots in 2 min by 25 km bins. (c) Location and FOV of the BKS SuperDARN radar; Beam 13 is highlighted in red. (d) Ground scatter power observations of BKS Beam 13 with ~11 MHz transmit frequency. (e) GNSS dTEC measurements at 1343 UT. (f) Time series (blue line) of GNSS dTEC median values calculated from measurements in the black box region in (e). Dotted orange line shows data filtered with a 2 – 4 hr bandpass filter. Red dots overlaid on (b) and (d) show a sinusoidal 2.5 hr oscillation in skip distance common to both the amateur radio and SuperDARN measurements. From Frissell et al. [22].

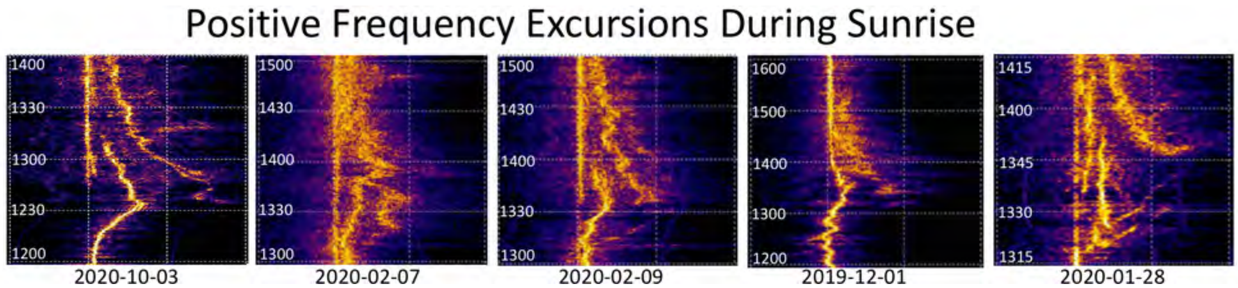


**Figure 4:** WWV spectra received at WA5FRF (Mico, TX) on 5 MHz during five sunrises showing Doppler shifts, mode splitting, and abrupt mode manifestation and extinguishment. Horizontal scale is 1 Hz/div. From Collins et al. [10].

Recent technological advances allow for many of these limitations to be overcome with orders of magnitude improvement. For instance, low-cost (US$50 to $150) GNSS disciplined oscillators (GNSSDO) can now be integrated into instrumentation to automatically provide not only precision location information, but also precision time ($\pm 50$ ns) and frequency (down to parts in $10^{-10}$ using 1 s averaging) measurements [21]. This level of precision at this low cost was not available just a few years ago, nor was the need for such precision recognized widely by the amateur radio community.

More affordable hardware, the relatively recent advent of the Internet and high-speed computing, and recognition among the amateur radio community of the importance of precision measurements for understanding radio propagation have led to the development of novel instrumentation and techniques specifically targeted at citizen science study of the ionosphere and space. This new instrumentation can be broadly separated into two categories. First, there is passive instrumentation that relies on receiving signals-of-opportunity, such as GNSS signals, government-run beacons and radars, and broadcast radio stations. Passive instrumentation typically does not require a license and is unlikely to cause interference to other equipment, thus allowing for broad citizen science participation. Active instrumentation, on the other hand, generates the radio signals that will be used for remote sensing and generally requires a license. It can take advantage of the amateur radio community's unique transmitting privileges, and is discussed in Section 3.2.

### 3.1 Passive Observations of Signals of Opportunity

As an example of these precision measurements, Figure 4 from Collins et al. [10] presents Doppler shift observations during five different sunrises of the 5 MHz WWV signal received by HamSCI volunteer Steve Cerwin WA5FRF at his station in Mico, TX located about 1370 km south-southeast of the transmitter. WWV is a time and frequency reference station located near Fort Collins, CO operated by the US National Institute of Standards and Technology (NIST) with atomic clock accuracy, and the WA5FRF receiver has been stabilized with a GNSSDO. Variability in ionospheric layer height, electron density, and/or layer thickness causes changes in the propagation path that are sensed as positive Doppler shifts for decreasing path lengths and negative Doppler shifts for increasing path lengths [33].

Novel systems capable of making and reporting these types of measurements automatically, easily, and at low costs are now being developed. One such system is the NSF-funded HamSCI Personal Space Weather Station (PSWS) project, which aims to create a network of ground-based space weather sensing instruments to advance scientific understanding and improve propagation nowcast/forecast capabilities for radio operators [21, 9]. The PSWS uses a modular approach to integrate a variety of instruments including a HF radio receiver, GNSS TEC receiver, ground magnetometer, and VLF receiver. A low-cost variant ($\lesssim$US$300) of the HF receiver known as the "Grape" can make Doppler measurements as shown in Figure 4

[12, 10, 23], while a wideband software defined radio (SDR) known as the "TangerineSDR" is being developed to take advantage of signals of opportunity such as oblique chirp ionosondes [46, 26] and oceanographic HF radars known as CODARs [27]. Another important Citizen Science project is the ScintPi, a low-cost solution to measure ionospheric scintillation using a GNSS receiver coupled with a RaspberryPi single-board computer [38].

### *3.2 Active Sounding*

One of the unique traits of collaborating with the amateur radio community is the fact that licensed amateurs have permission to transmit radio signals. While these licenses do carry country-dependent restrictions that prevent certain types of transmissions that would be desirable for ionospheric sounding (e.g., wideband HF transmissions, pulse transmissions, fully automated and unattended transmissions at all frequencies), there is significant room for the development of active ionospheric sounding modes and equipment that can be used by the amateur radio community. Some techniques may be designed solely for the purpose of ionospheric sounding, such as the development of a low-cost, low-power vertical incidence ionosonde designed to work within the amateur radio bands [31, 35]. However, as amateur radio is primarily a radio service for two-way communications rather than scientific research, the development of techniques that simultaneously allow for communications and improved ionospheric sounding are particularly valuable. An example of this would be the use of coherent CW, where computer-generated Morse code transmissions are synchronized using GNSS Pulse-Per-Second (PPS) timing, thus allowing for time-of-flight measurements of radio transmissions [28]. Similar timing measurements or coding for ionospheric measurement could conceivably be incorporated into amateur radio digital modes such as WSPR or FT8. Such measurements would be a boon for amateurs as well as scientists, as it could give the amateur more information to determine the exact propagation mode used for that particular communication.

## 4 Relationship to Modeling and Professional Observations

The development of large and robust amateur radio citizen science networks is compelling in that it provides a unique way to increase ionospheric sampling while benefiting from the creativity and expertise of the amateur radio community working in collaboration with the professional science community. These networks should be viewed as an integral part of the existing space science and space weather infrastructure, which includes ionosondes, SuperDARN radars, Incoherent Scatter Radars (ISRs), GNSS TEC and scintillation receivers, professional ground magnetometers, rockets, space craft, and more. Each of these techniques have both limitations and advantages, and thus should be used in a complementary fashion to develop a complete understanding of the geospace environment. A natural use of amateur radio observations in this regard would be to link bottomside ionospheric observations to height-integrated GNSS TEC measurements (e.g., Figure 3), as well as provide observations of the impact of space weather activity on actual communications systems (e.g., Figure 2).

Modeling provides another important tool in using amateur radio observations for scientific purposes. HF raytracing through numerical ionospheric models as demonstrated in Figure 1 provides a method for linking even simple binary propagation path observations to potentially valid physical realities. This is a particularly powerful investigative technique when modeling hundreds of thousands of propagation paths, such as when HF radio communications observed on multiple frequencies during the 2017 Great American Total Solar Eclipse were raytraced through an eclipsed version of the first-principles physics-based SAMI3 ionosphere [19]. As advances in this type of modeling, as well as other techniques such as data assimilation and ionospheric tomography, improve, so will the ability to use amateur radio observations to advance the field of heliophysics.

## 5 Amateur Radio and the Advancement of Heliophysics

### *5.1 Scientific Advancements*

Already, amateur radio and citizen science networks show great promise in addressing open questions within heliophysics, radio science, and space weather. Figure 2 showed how these networks can be used to measure the ionospheric impacts of solar flares and their direct effects on HF radio communications [20]. Systems such as the RBN, WSPRNet, and PSKReporter can provide timing measurements of HF absorption and recovery relative to solar flare timing as a function of frequency and geographic location. Precision HF Doppler receivers such as the Grape (Section 3.1) can also provide measurements of flare-induced Sudden Frequency Deviation (SFD), and provide insights as to the mechanism causing these deviations [10, 11]. These measurements, especially when made over large geographic regions, can be used in conjunction with physics-based models such as WACCM-X [30] or TIME-GCM [42] to address open questions regarding how solar flares can affect certain D-region parameters (such as changes in electron temperature and collision frequencies) or how ionospheric HF absorption mechanisms may change as a function of latitude [8].

Similarly, Figures 1 and 3 showed how the amateur radio networks can measure TIDs and how those measurements can be linked with observations from other instruments. TIDs continue to be a frontier topic in ionospheric heliophysics, as they may be associated with atmospheric gravity waves (AGWs) [e.g., 25, 5] or electrodynamic processes [e.g., 29, 2] and can propagate large horizontal distances (even to the opposite hemisphere) [47]. Advanced physics-based models such as SD-WACCM-X/SAMI3 [34] and HIAMCM [4] coupled with raytracing tools such as PHaRLAP [7, 6] provide the ability to link TID observations with theoretical understanding. Therefore, TIDs provide information critical to understanding atmosphere-ionosphere-space coupling and atmospheric energy transport between latitudinal and longitudinal regions. Large-scale statistical studies of TIDs using amateur radio data such as Sanchez et al. [40] and Engelke et al. [16], as well as the development of techniques for using HF Doppler sounding to determine TID parameters such as period, wavelength, and direction [13, 39] open the door to future advancements in this area.

Mid-latitude Sporadic E, or intermittently occurring patchy, thin layers (few kilometers thick) of enhanced ionization between ∼90-130 km altitude [24], continues to be an active area of interest for both professionals and amateurs alike. This is due to both the interesting propagation conditions that occur for amateur radio operators in the Very High Frequency (VHF, 30 – 30 MHz) and high HF bands, as well as the open questions regarding the formation of Sporadic E. Questions include “Can we observe Sporadic E forming in place?”, “Sporadic E patches seem to be advected regions, given how they move with amateur radio spots, but where do they come from? Where do they form?” and “What physics was going on there that caused their formation?” The actual formation of Sporadic E is still unresolved. Wind shears play a role, but there is still some dispute even how localized they need to be. Recent works by Deacon et al. [15, 14] are working to identify and characterize Sporadic E patches with amateur radio, and Bacon [3] is developing a model for predicting Sporadic E and its effects on amateur radio propagation.

### *5.2 Research to Operations and Operations to Research (R2O2R)*

Research to Operations (R2O) is the process by which research observational capabilities and models are transferred to operations, and conversely Operations to Research (O2R) is where the operations community identifies gaps in these capabilities. These processes form a feedback loop that has been formalized as the Space Weather Research-to-Operations and Operations-to-Research Framework [43] in response to the Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow (PROSWIFT) Act (Public Law No: 116-181, Oct. 2020) [37]. The amateur radio networks, which provide both real-time and historical observations of actual communications systems, speak directly to this mandate. These systems can provide data for nowcasting and forecasting purposes, the development of new models and data products, and the validation of current models, such as the NOAA SWPC D-Region Absorption Prediction (D-RAP) model [1]. These amateur radio datasets may be the only such datasets available, as observations from other services (e.g. defense, maritime, and aviation) may not be systematically collected or publicly available. If the resulting operational products are made available and are useful to the amateur radio community, they will be able to help improve them.

## 6 Recommendations

To maximize the benefit of amateur radio networks for heliophysics, we recommend:

- Increased support for large-scale observational capabilities of distributed instrumentation fielded by amateur radio operators and radio science enthusiasts.
- Ensure the continued operation of transmitters of opportunity that are used for citizen science experiments, including WWV/WWVH, R-OTH radars (chirpsounders), CODARs, and defense VLF transmitters.
- Develop citizen science receivers that make use of established professional transmitters for coordinated experiments.
- Develop new amateur radio modes that simultaneously allow for communications and ionospheric sounding.
- Strategically expand citizen science networks to other countries and regions of the world to ensure truly global observations.
- Formally incorporate the amateur radio community and observational assets into Space Weather R2O2R Framework.

## 7 Summary

The large-scale observational capabilities of distributed instrumentation fielded by amateur radio operators and radio science enthusiasts offers tremendous opportunity for advancement in the fields of heliophysics, radio science, and space weather forecasting and operations. Well-established amateur radio networks such as the RBN, WSPRNet, and PSKReporter already provide a rich, ever-growing long-term dataset of bottomside ionospheric observations. Conversely, up-and-coming purpose-built citizen science networks offer opportunities to field novel instrumentation optimized to make measurements targeting specific science questions and operational needs. When these measurements are used in conjunction with existing networks of professional instrumentation, the potential for discovery becomes even greater.

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