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

Nathaniel A. Frissell [4,1,2], John R. Ackermann[2,1], Laura Brandt [5,3], Stephen A. Cerwin [1], Kristina V. Collins [6,1], Scott H. Cowling[2,1], Devin M. Diehl [4,1], Timothy J. Duffy[1], David Kazdan [6,1], John Gibbons [6,1], William D. Engelke [7,1], Rachel M. Frissell [4,1], Robert B. Gerzoff [1], Frank M. Howell[8,1], Stephen R. Kaeppler [9,1], Hyomin Kim [10,1], David R. Larsen [11,2,1], Vincent Ledvina [12,3], William Liles [1], Michael Lombardi [13,1], Elizabeth MacDonald [5,3], Julius Madey[2,1], Francesca Di Mare [5,3], Thomas C. McDermott[2,1], David G. McGaw [14,1], Robert W. McGwier, Jr. [15,1], Ethan S. Miller [16,1], Cuong D. Nguyen [4,1], Gareth W. Perry [10,1], Gerard N. Piccini [4,1], Jonathan D. Rizzo [1], Veronica I. Romanek [4,1], Simal Sami [4,1], Diego F. Sanchez [10,1], Muhammad Shaaf Sarwar [4,1], H. Lawrence Serra[1], H. Ward Silver [1], Tamitha Mulligan Skov [17,1], David R. Themens [18,19,1], Francis H. Tholley[4,1], Mary Lou West [20,1], David Witten[2,1], and Nisha Yadav[4,1]

[1] *Ham Radio Science Citizen Investigation Community*
[2] *Tucson Amateur Packet Radio*
[3] *Aurorasaurus, New Mexico Consortium, Los Alamos, NM 87544, USA*
[4] *The University of Scranton, Scranton, PA 18510, USA*
[5] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[6] *Case Western Reserve University, Cleveland, OH 44106, USA*
[7] *The University of Alabama, Tuscaloosa, AL 35487, USA*
[8] *Mississippi State University, Mississippi State, MS 39762 USA*
[9] *Clemson University, Clemson, SC 29634, USA*
[10] *New Jersey Institute of Technology, Newark, NJ 07102, USA*
[11] *University of Missouri, Columbia, MO 65211, USA*
[12] *Predictive Science Inc., San Diego, CA 92121, USA*
[13] *National Institute of Standards and Technology, Boulder, CO 80305, USA*
[14] *Dartmouth College, Hanover, NH 03755, USA*
[15] *Virginia Tech, Blacksburg, VA 24061, USA*
[16] *STR, Beavercreek, OH 45431, USA*
[17] *Millersville University, Millersville, PA 17551, USA*
[18] *University of Birmingham, Birmingham, UK*
[19] *University of New Brunswick, Fredericton, NB, Canada*
[20] *Montclair State University, Montclair, NJ 07043, USA*

Abstract

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, and the associated novel instruments, offer opportunities for citizen scientists, professional researchers, and industry to field instrument networks 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. Over 770,000 operators are licensed in the United States and over 3 million worldwide. They provide 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 the current technical and scientific capabilities of the global amateur radio community and the role they play in the advancing heliophysics and space weather operations. A companion white paper, Frissell et al. [23], gives recommendations on fostering a collaborative relationship between the professional heliophysics and amateur radio communities. 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 that 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.

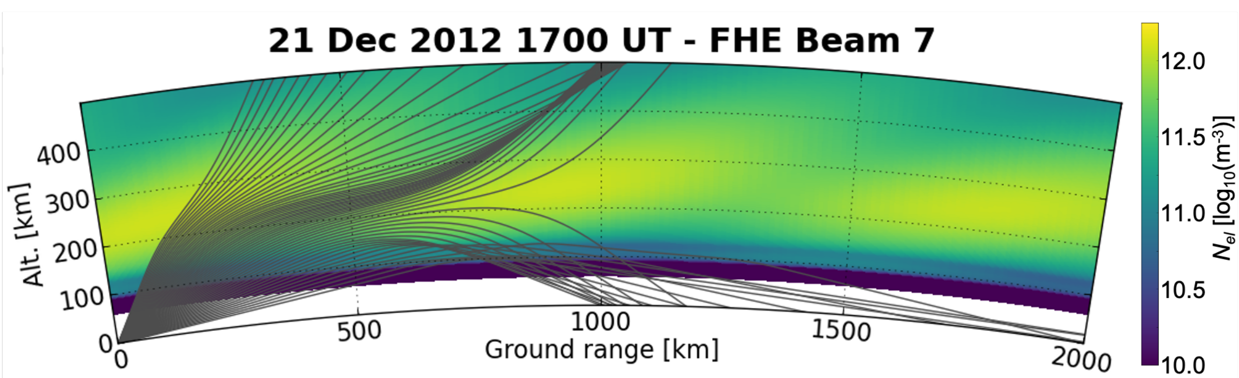

Figure 1: Illustration showing how HF radio amateurs can remote sense the ionosphere. This raytrace simulation shows 14.5 MHz radio waves transmitted from Fort Hays, Kansas propagating toward the northeast through the IRI model perturbed with a Medium Scale Traveling Ionospheric Disturbance. Radios located 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. [19].

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 reports these observations back to central databases. The three currently operational major networks 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 [46] that was designed specifically to probe weak signal HF propagation paths.

These near-global scale networks have been operational since 2008. While they 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. The use of such data for space weather and space physics research was first demonstrated by Frissell et al. [18], 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) [24], characterization and prediction of Sporadic E [15, 14, 3], asymmetries in ionospheric greyline propagation [34], 160 m band propagation [47], geomagnetic storm and solar flare ionospheric impacts [21], plasma cutoff and single-mode fading [38], solar eclipse ionospheric impacts [20], and understanding of localized radio propagation anomalies [43].

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. [21] 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. [24], Figure 3 shows an example of Large Scale Traveling Ionospheric Disturbances (LSTIDs) observed in the RBN, PSKRe-

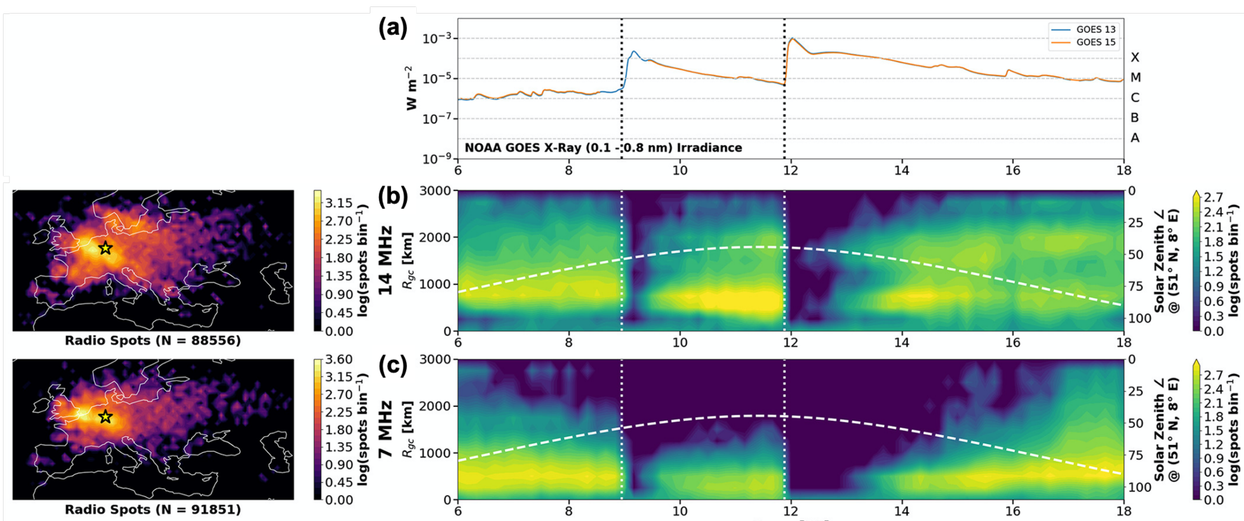

Figure 2: Example of solar flare ionospheric impacts observed by amateur radio observing networks over Europe on 6 September 2017. (a) GOES-13 (blue) and GOES-15 (orange) XRS 0.1–0.8 nm X-ray measurements. Flares are observed at 0857 UT (X2.2), 1153 UT (X9.3) and indicated with dotted vertical lines. (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. [21].

porter, 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, great potential exists for large scale statistical investigations with the existing data, such as the LSTID studies currently being conducted by Sanchez et al. [42] 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 web-based displays and can provide real-time data streams. Currently, the real-time capabilities are not used in any official operational capacity; however, the global nature of these systems and direct applicability to real-time HF communications is 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 to monitor radio propagation path openings, not for making finely-calibrated ionospheric physics measurements. These systems are limited by temporal uncertainties on the order of ±1 s, frequency uncertainties on the order of ± 1 Hz, spatial uncertainties on the order of kilometers, and uneven sampling cadences on the order of 1 to 2 minutes. Recent technological advances can overcome many of these limitations with orders of magnitude improvement. For

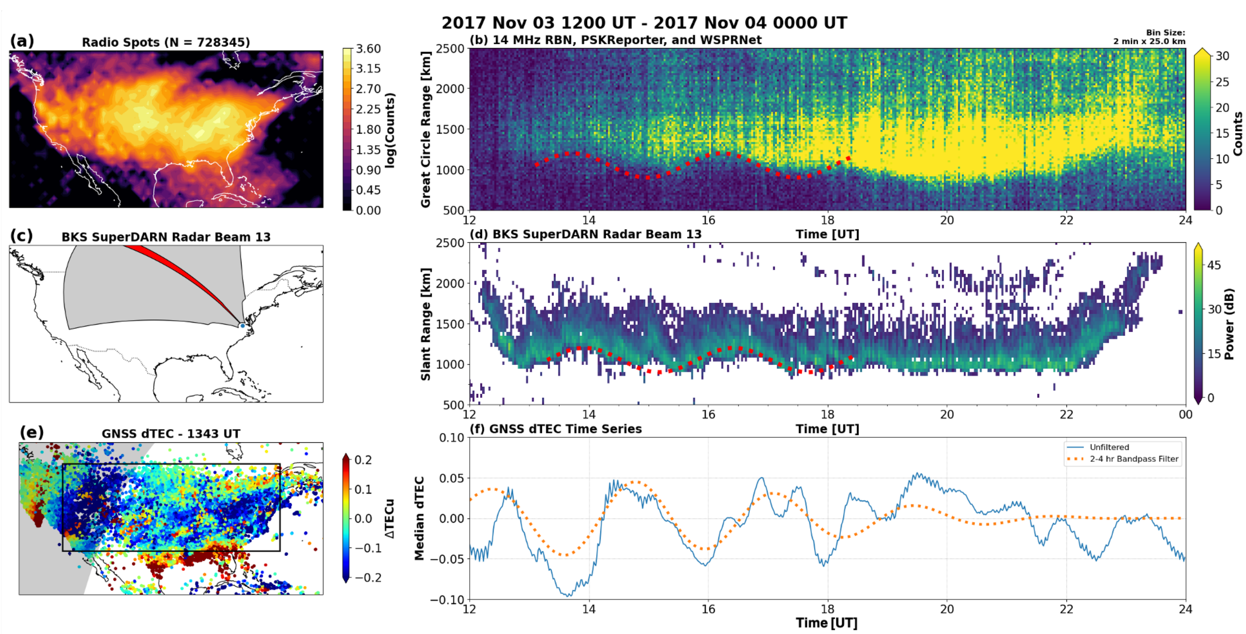

Figure 3: Example of Large Scale Traveling Ionospheric Disturbances (LSTIDs) observed using amateur radio networks, the Blackstone (BKS) SuperDARN radar, and GNSS dTEC. (a) Geographic distribution of TX-RX midpoints of amateur radio communications observed over the continental United States on 3 Nov 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. [24].

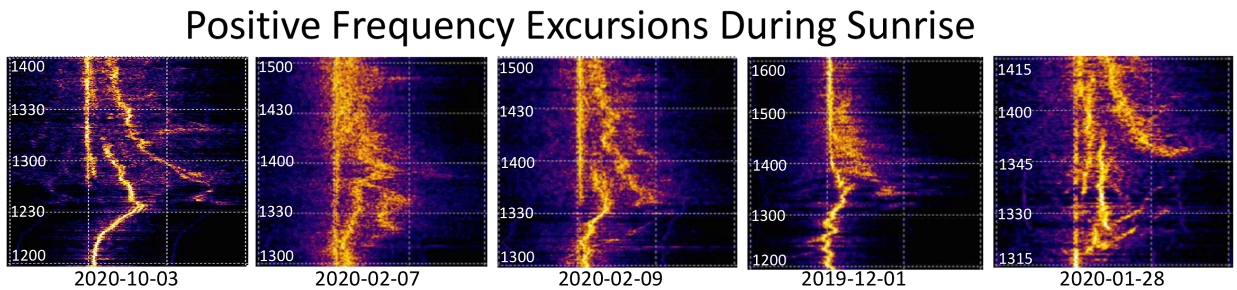

Figure 4: WWV spectra received at WA5FRF (Mico, TX) on 5 MHz during five sunrises showing Doppler shifts, mode splitting, and abrupt mode manifestation and extinguishment. Horizontal scale is 1 Hz/div. From Collins et al. [10].

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 (± 50 ns) and frequency (down to parts in 10^{-10} using 1 s averaging) measurements [22]. Such 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 instruments and techniques specifically targeted at citizen science study of the ionosphere and space. These new instruments can be broadly separated into two categories. First, are passive instruments that rely on receiving signals-of-opportunity, such as GNSS signals, government-run beacons and radars, and broadcast radio stations. Passive instruments typically do not require a license and are unlikely to cause interference to other equipment. This lack of licensing and interference allows for broad citizen science participation. The second type, in contrast, are active instruments that generate radio signals that can 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 [35].

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 [22, 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, 25], 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

[48, 28] and oceanographic HF radars known as CODARs [29]. Another important Citizen Science project is the ScintPi, a low-cost way to measure ionospheric scintillation using a GNSS receiver coupled with a RaspberryPi single-board computer [40].

3.2 Active Sounding

A unique trait of collaborating with the amateur radio community is that licensed amateurs have permission to transmit radio signals. The community can develop active ionospheric sounding modes and equipment (within the constraints set by Federal Communications Commission Rules Part 97 that govern the amateur radio service). Within these guidelines, mode designs for the purpose of ionospheric sounding may be possible, such as the development of a limited capability, low-cost, low-power ionosonde designed to work within the amateur radio bands [33, 37]. However, as amateur radio is primarily a radio service for two-way communications rather than scientific research, techniques that simultaneously allow for communications and improved ionospheric sounding are particularly valued. An example of this would be 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 [30]. 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 by giving 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 because it is 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 scientists. 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 has both limitations and advantages, and thus should be used in a complementary fashion to develop a complete understanding of the geospace environment. In this regard, a natural use of amateur radio observations 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 is another important tool using amateur radio observations for scientific purposes. HF raytracing through numerical ionospheric models (Figure 1) link even simple binary propagation path observations to potentially valid physical realities. This is particularly powerful 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. The paths were raytraced through an eclipsed version of the first-principles physics-based SAMI3 ionosphere model [20]. Preparations for similar activities are now being made for the 2023 and 2024 American Solar Eclipses [17]. As advances in this type of modeling, and other techniques such as data assimilation and ionospheric tomography, improve, so will the use of amateur radio observations to advance the field of heliophysics. Amateur Radio measurements have the potential to be a dominant dataset for operational and scientific model data assimilation. They directly complement existing GNSS datasets, which currently cannot independently separate the topside and bottomside ionosphere reliably.

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 [21]. 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 [32] or TIME-GCM [44] 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. They may be associated with atmospheric gravity waves (AGWs) [e.g., 27, 5] or electrodynamic processes [e.g., 31, 2] and can propagate large horizontal distances (even to the opposite hemisphere) [49]. Advanced physics-based models such as SD-WACCM-X/SAMI3 [36] 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. [42] 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, 41] will undoubtedly advance TID understanding.

Mid-latitude Sporadic E, or intermittently occurring patchy, thin layers (few kilometers thick) of enhanced ionization between ∼90-130 km altitude [26], continues to be an active area of interest for both professionals and amateurs. Interesting propagation conditions that occur for amateur radio operators in the Very High Frequency (VHF, 30 – 30 MHz) and high HF bands, and numerous open questions regarding the formation of Sporadic E are unanswered. “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 unresolved. Wind shears play a role, but some dispute remains about how localized they need to be. 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 [45] 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) [39]. 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, 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]. The amateur radio community and its measurements represent a yet-to-be activated asset to the validation and improvement of existing and future Space Weather operational products through their sensitivity to a Space Weather domain inaccessible to many other instruments. Engaging with this community will further-enable R2O2R activities to build robust operational products and elucidate new Space Weather science.

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.
- Advocate for continued and novel transmissions of RF signals used in citizen science experiments, and, where appropriate, facilitate cooperation and technical exchange between the operators of those signals and the space physics research community. Examples include: NIST WWV and WWVH, U.S. Navy chirp sounders, CODAR oceanography radars, and U.S. Navy VLF transmitters.
- Develop receivers that make use of established professional transmitters for coordinated experiments. These receivers can be deployed by citizen scientists, professional researchers, industry, and government users alike.
- 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, and the associated novel instruments, offer opportunities for citizen scientists, professional researchers, and industry to field instrument networks 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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