frontiers | Frontiers in Astronomy and Space Sciences

TYPE Review
PUBLISHED 16 November 2023
DOI 10.3389/fspas.2023.1184171

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OPEN ACCESS

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RECEIVED 11 March 2023
ACCEPTED 08 September 2023
PUBLISHED 16 November 2023

CITATION
Frissell NA, Ackermann JR, Alexander JN, Benedict RL, Blackwell WC Jr., Boedicker RK, Cerwin SA, Collins KV, Cowling SH, Deacon C, Diehl DM, Di Mare F, Duffy TJ, Edson LB, Engelke WD, Farmer JO, Frissell RM, Gerzoff RB, Gibbons J, Griffiths G, Holm S, Howell FM, Kaeppler SR, Kavanagh G, Kazdan D, Kim H, Larsen DR, Ledvina VE, Liles W, Lo S, Lombardi MA, MacDonald EA, Madey J, McDermott TC, McGaw DG, McGwier RW Jr., Mikitin GA, Miller ES, Mitchell C, Montare A, Nguyen CD, Nordberg PN Sr., Perry GW, Piccini GN, Pozerski SW Jr., Reif RH, Rizzo JD, Robinett RS, Romanek VI, Sami S, Sanchez DF, Sarwar MS, Schwartz JA, Serra HL, Silver HW, Skov TM, Swartz DA, Themens DR, Tholley FH, West ML, Wilcox RC, Witten D, Witvliet BA and Yadav N (2023), Heliophysics and amateur radio: citizen science collaborations for atmospheric, ionospheric, and space physics research and operations.
Front. Astron. Space Sci. 10:1184171.
doi: 10.3389/fspas.2023.1184171

Heliophysics and amateur radio: citizen science collaborations for atmospheric, ionospheric, and space physics research and operations

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The amateur radio community is a global, highly engaged, and technical community with an intense interest in space weather, its underlying physics, and how it impacts radio communications. The large-scale observational capabilities of distributed instrumentation fielded by amateur radio operators and radio science enthusiasts offers a tremendous opportunity to advance the fields of heliophysics, radio science, and space weather. Well-established amateur radio networks like the RBN, WSPRNet, and PSKReporter already provide rich, ever-growing, long-term data of bottomside ionospheric observations. Up-and-coming purpose-built citizen science networks, and their associated novel instruments, offer opportunities for citizen scientists, professional researchers, and industry to field networks for specific science questions and operational needs. Here, we discuss the scientific and technical capabilities of the global amateur radio community, review methods of collaboration between the amateur radio and professional scientific community, and review recent peer-reviewed studies that have made use of amateur radio data and methods. Finally, we present recommendations submitted to the U.S. National Academy of Science Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 for using amateur radio to further advance heliophysics and for fostering deeper collaborations between the professional science and amateur radio communities. Technical recommendations include increasing support for distributed instrumentation fielded by amateur radio operators and citizen scientists, developing novel transmissions of RF signals that can be used in citizen science experiments, developing new amateur radio modes that simultaneously allow for communications and ionospheric sounding, and formally incorporating the amateur radio community and its observational assets into the Space Weather R2O2R framework. Collaborative recommendations include allocating resources for amateur radio citizen science research projects and activities, developing amateur radio research and educational activities in collaboration with leading organizations within the amateur radio community, facilitating communication and collegiality between professional researchers and amateurs, ensuring that proposed projects are of a mutual benefit to both the professional research and amateur radio communities, and working towards diverse, equitable, and inclusive communities.

KEYWORDS

amateur radio, ham radio, citizen science, HamSCI, ionosphere, space weather, heliophysics

1 Introduction

Amateur radio, also known as ham radio, is a non-commercial radio service for individuals interested in wireless communications, experimentation, engineering, and science. Since its establishment in 1912, the United States (US) amateur radio service has made significant contributions to radio technology and science. In the 1920s, radio propagation experiments known as the trans-Atlantic tests were coordinated by the American Radio Relay League (ARRL) and the Radio Society of Great Britain (RSGB). The experiments led to a greatly improved understanding of the ionosphere and directly contributed to the development of the field of atmospheric science (Yeang, 2013). The International Geophysical Year (IGY) of 1957/1958 included both formal and informal amateur radio citizen science activities, including experiments jointly coordinated by the U.S. Air Force and the ARRL (Duquet, 1959; Southworth, 1959; Southworth, 1960; Dora, 2023). The study of Long Delayed Echos (LDEs), including magnetospheric ducting of high frequency radio signals, is another early example of amateur-professional collaborations (Størmer, 1928; Villard et al., 1969; Villard et al., 1970; Muldrew, 1979). The US Federal Communications Commission (FCC) rules require this work continue today: Part 97 of the FCC rules states that a primary purpose of the amateur radio service is the "Continuation and extension of the amateur's proven ability to contribute to the advancement of the radio art." Recent advances in computing and software defined radio provide potent and novel opportunities to meet this mandate.

Throughout the previous solar cycle, the amateur radio community has risen to this task. Using software defined radios, high speed personal computers, and the Internet, amateurs have voluntarily built multiple networks that automatically monitor and log global amateur radio communications. Many of the signals observed by these systems use frequencies that propagate through and are directly affected by the ionosphere. Thus, the data from these networks can be used to study the upper atmosphere and the coupled geospace system. Over the past decade, these networks' data, along with other amateur radio data, have led to multiple peer-reviewed studies. These include studies of the ionospheric impacts of solar flares and geomagnetic storms (Frissell et al., 2014; Witvliet et al., 2016b; Frissell et al., 2019), traveling ionospheric disturbances (TIDs) (Frissell et al., 2022c), Sporadic E (Deacon et al., 2021; Deacon et al., 2022a), near vertical incidence skywave (NVIS) propagation (Walden, 2012; Witvliet et al., 2015a; Witvliet et al., 2015b; Witvliet et al., 2016b; Walden, 2016; Witvliet and Alsina-Pagès, 2017), greyline propagation (Lo et al., 2022), 160 m band propagation (Vanhamel et al., 2022), solar eclipses (Frissell et al., 2018), plasma cutoff and single-mode fading (Perry et al., 2018), and the development of new instrumentation (Collins et al., 2021; Collins et al., 2023).

This paper will summarize the peer-reviewed contributions of the amateur radio community to heliophysics since 2014 and discuss the scientific and technical capabilities of today's amateur radio community. It will also explain the current structure of the amateur radio community and how it can collaborate with the professional heliophysics community. This review paper includes and expands upon the material from two white papers submitted to the US National Academy of Sciences Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033: Frissell et al. (2022b) discusses the scientific and technical capabilities and contributions of the amateur radio community, while a companion white paper, Frissell et al. (2022a), discusses ways of fostering a collaborative relationship between the professional heliophysics and amateur radio communities.

Following are five sections: Section 2 describes the amateur radio community and the qualities that make it ideal for citizen science. Section 3 describes the basic physics that make it possible for amateur radio to be used for ionospheric remote sensing. Section 4 reviews recent amateur radio citizen science studies published in peer-reviewed journals. Section 5 provides the recommendations and discussion in the original white papers for advancing the technical capabilities for heliophysics and further fostering amateur radio - professional heliophysics collaborations over 2024–2033. Section 6 summarizes the paper. Table 1 presents a summary of selected scientific and technical amateur radio/citizen science publications presented in this review paper.

2 Amateur radio as a community for citizen science

2.1 The amateur radio service

Amateur radio is a non-commercial radio service with almost 770,000 US licensed operators (FCC License Counts, 2023) and over 3 million licensed worldwide. Amateurs can be any age and range in experience from novice to those with advanced Science-Technology-Engineering-Math (STEM) degrees. Each amateur is required to hold an amateur radio license issued by a national government. The licensing process ensures that each licensee demonstrate appropriate knowledge of radio science, electrical engineering, and amateur radio rules and practice.

While the amateur radio service is controlled by the national government of each individual's country, the interests of radio amateurs worldwide are represented by the International Amateur Radio Union (IARU, iaru.org) and its 172 member national societies. Member societies include the US American Radio Relay League (ARRL, arrl.org), the Radio Society of Great Britain (RSGB, rsgb.org), Radio Amateurs of Canada (RAC, rac. ca), the Japan Amateur Radio League (JARL, jarl.org), and others. Each society engages their country's amateurs through Internet platforms, membership journals, and local radio club affiliations. The IARU societies, independent publishers, websites, e-mail groups, social media sites, podcasts, "hamfests", equipment manufacturers, and special interest amateur radio organizations engage, coordinate, and promote amateur radio worldwide.

Because they rely on signals that are refracted back to Earth by the highly variable ionosphere (Figure 1), many popular amateur radio activities are affected by space weather. These space weather impacts are part of the hobby's allure. Many amateurs enjoy the challenge of space weather prediction and use that knowledge to make contact with distant stations (DXing). Amateurs also enjoy "contests", events during which they amass points by contacting as many other stations and locations as possible. DXers and contesters

10.3389/fspas.2023.1184171

TABLE 1 Summary table of amateur radio and citizen science research cited in this review paper. The upper section is organized by science topic; the bottom section is organized by instrumentation type. "Professional Studies" have been published in peer-reviewed professional journals or are technical reports written by professional scientists. "Amateur Radio Publications" are publications that have appeared in amateur radio magazines, journals, or books. Only references that explicitly use amateur radio or citizen science techniques are included in this table. See the referenced sections(s) for more detailed discussion on a topic and references that do not explicitly discuss amateur radio/citizen science.

Topic	Professional studies	Amateur radio publications	Sections
Organized by Science Topic			
Dawn/Dusk Terminator Effects	Collins et al. (2022), Collins et al. (2023) Frissell et al. (2019) Lo (2022); Lo et al. (2022)		§4.7, §4.8
Geomagnetic & Ionospheric Storms	Frissell et al. (2019) Malkotsis et al. (2022)		§4.1
Greyline Propagation	Lo. (2022); Lo et al. (2022)	Callaway. (2016) Greyline. (1924) Hoppe and Dalton (1975) Nichols (2005)	§4.7
Lightning HF Signatures	Fung et al. (2020)		
Long-Delayed Echos	Goodacre. (1980a) Muldrew (1979) Vidmar and Crawford (1985)	Goodacre. (1980b) Holm (2009) Martinez (2007) Villard et al. (1969, 1970)	§5.1
Near-Vertical Incidence Skywave	Walden. (2012), Walden. (2016) Witvliet et al. (2014), Witvliet et al. (2015c), Witvliet et al. (2015a), Witvliet et al. (2015b), Witvliet et al. (2016b), Witvliet et al. (2016a); Witvliet and Alsina-Pagès (2017); Witvliet et al. (2019); Witvliet (2021); Witvliet et al. (2023)	Witvliet and Van Maannen (2005) Witvliet and Van Maannen (2006a) Witvliet and Van Maannen (2006b)	§4.6
Plasma Cutoff and Single-Mode Fading	Perry et al. (2018)		
Radio Propagation (General)	Vanhamel et al. (2022)	Luetzelschwab et al. (2022) Serra (2022)	§4.5
Solar Eclipses	Bamford. (2000) Frissell et al. (2018)	Frissell. (2019)	§4.2
Solar Flares	Collins et al. (2023) Frissell et al. (2014); Frissell et al. (2019) Malkotsis et al. (2022) Witvliet et al. (2016b)		§4.1, §4.8, §5.1
Sporadic E	Deacon et al. (2021), Deacon et al. (2022a); Deacon et al. (2022b)	Bacon. (2021)	§4.4
Transequatorial Propagation	Ferrell. (1951) Southworth (1960)	Southworth. (1959) Tilton (1947)	§5.1
Traveling Ionospheric Disturbances	Collins et al. (2023) Frissell et al. (2022c)		§4.3, §5.1
Organized by Instrumentation Type			
Amateur Radio Spotting Networks	Collins et al. (2021a) Deacon et al. (2021), Deacon et al. (2022a); Deacon et al. (2022b) Frissell et al. (2014), Frissell et al. (2018), Frissell et al. (2019), Frissell et al. (2022c)	Collins et al. (2021b) Frissell (2019) Griffiths et al. (2020)	§3.1, §5.1

(Continued on the following page)

TABLE 1 (*Continued*) **Summary table of amateur radio and citizen science research cited in this review paper. The upper section is organized by science topic; the bottom section is organized by instrumentation type. "Professional Studies" have been published in peer-reviewed professional journals or are technical reports written by professional scientists. "Amateur Radio Publications" are publications that have appeared in amateur radio magazines, journals, or books. Only references that explicitly use amateur radio or citizen science techniques are included in this table. See the referenced sections(s) for more detailed discussion on a topic and references that do not explicitly discuss amateur radio/citizen science.**

Topic	Professional studies	Amateur radio publications	Sections
	Lo (2022); Lo et al. (2022) Perry et al. (2018) Vanhamel et al. (2022)	Taylor and Walker (2010)	
GNSS Scintillation	Rodrigues and Moraes. (2019)		§3.2, §5.1
HF Doppler Shift	Collins et al. (2021a), Collins et al. (2022), Collins et al. (2023) Gibbons et al. (2022)	Collins et al. (2021b)	§3.2, §5.1
HF Elevation of Arrival		Serra. (2023)	§3.2, §5.1
LF/VLF Receivers	Malkotsis et al. (2022)		§3.2, §5.1

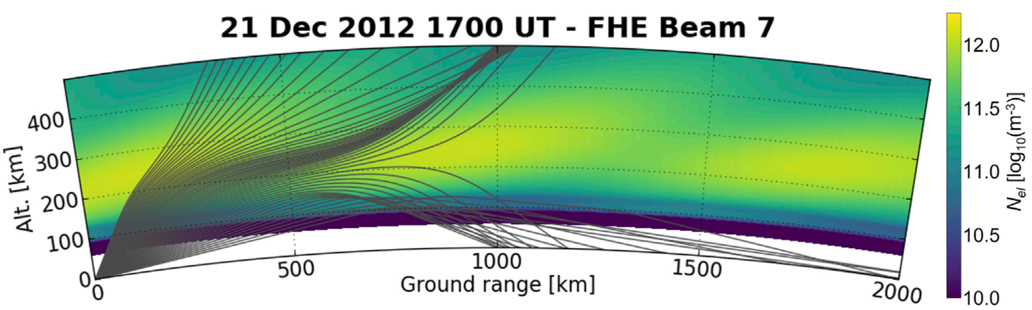

FIGURE 1
Illustration showing how radio amateurs using HF frequencies can remote sense the ionosphere. This raytrace simulation shows 14.5 MHz radio waves transmitted from Fort Hays, Kansas propagating toward the northeast through the IRI model perturbed with a Medium Scale Traveling Ionospheric Disturbance. 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. (2016a).

can win certificates, awards, and public recognition. Serious participants build elaborate stations and antenna systems and actively study radio propagation and space weather (e.g., Donovan, 2021; Nunés, 2021; Luetzelschwab et al., 2022). To effectively fulfill their duties, amateurs engaged in public service and emergency communications also need to understand space weather and its effects on radio propagation.

2.2 Ham radio science citizen investigation (HamSCI)

The amateur radio and professional heliophysics communities share many common goals and interests, but the cultural and structural differences between the communities is such that effective collaboration is not automatic. Amateurs may make new discoveries or technological advances but not be able to report them in the peer-reviewed literature. Conversely, professional scientists may make important discoveries that amateurs do not immediately appreciate or can access. Continuing in the long tradition of amateur radio citizen science efforts like the ARRL Transatlantic Tests (Yeang, 2013) and the ARRL-Air Force IGY experiments (Duquet, 1959; Southworth, 1960; Dora, 2023), the Ham Radio Citizen Science Investigation (HamSCI, https://hamsci.org) was founded in 2015 with a mission to bring together both the amateur radio and professional communities (Frissell et al., 2015; Frissell et al., 2016b; Silver, 2016). HamSCI's objectives are to 1) advance scientific research and understanding through amateur radio activities, 2) encourage the development of new technologies to support scientific research, and 3) provide educational opportunities for the amateur community and the general public. HamSCI's founders and core leadership team are amateur radio operators and professional scientists. Today, HamSCI has multiple projects supported by the U.S. National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), the Amateur Radio Digital Communications (ARDC) foundation, and is recognized as an official NASA Citizen Science project. HamSCI is highly collaborative and structured such that it can promote multiple projects from different institutions, and projects led by the amateur radio community. Thus, HamSCI is extremely adaptable, scalable, and ideally suited for novel and creative projects.

2.3 Exchange between amateur and professional communities

A key tenet of citizen science is the ability for amateurs and professionals to connect with each other and freely exchange ideas. Bi-directional exchange is important because the amateur and professional communities often have different but complementary skills, experience, and perspectives. For instance, an amateur might have excellent practical expertise in selecting the best operating frequencies and modes for effective communications under a variety of geophysical conditions. However, they may not have the necessary academic background to understand the physics underlying why their choices are effective. Trained scientists may have extensive experience using different data sets to explain a particular phenomenon, but may lack a practical understanding of how this impacts actual operations.

In a variety of ways, HamSCI facilitates bi-directional communications, including e-mail lists, weekly teleconferences, and the annual HamSCI workshop (HamSCI Get Involved, 2023). Currently, the HamSCI Google Group has over 850 amateur and professional global members. Many are members of both communities. The Google group allows anyone to post questions, announcements, or begin a discussion. While posting is open, moderators do monitor the group to ensure posts follow the HamSCI Community Participation Guidelines. (2022). Similar idea exchanges occur on the multiple Zoom teleconferences held each week.

HamSCI also connects amateurs and professionals at in-person conferences. Since 2018, HamSCI has hosted an annual workshop for amateurs and professionals to meet and give presentations (HamSCI Meetings, 2023). The HamSCI workshop is now a hybrid workshop, allowing for the benefits of an in-person meeting combined with the accessibility of a virtual workshop. The meeting is announced through multiple outlets that reach both amateur and professional audiences. Each year, leaders from communities are selected as invited speakers.

In addition to its own meeting, HamSCI members also participate in professional and amateur conferences. Professional conferences include the NSF Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) workshop and the fall American Geophysical Union (AGU) meeting. Amateur radio conferences include the ARRL-TAPR Digital Communications Conference and the Dayton Hamvention. Research funding supports the meeting travel of volunteers, students, and professionals. The regular participation by both amateurs and professionals at these meetings builds trust and facilitates collaboration between the groups.

2.4 Education and training

Education and training are critical to citizen science. Amateur radio has long provided training in electrical engineering, communications systems, antenna and information theory, space weather, and programming. Training starts with licensing, but life-long education is strongly encouraged. Amateur radio topics are closely aligned with heliophysics research needs. Citizen science collaborations with the amateur community should support and enhance existing training programs and add new opportunities that delve even deeper into heliophysics.

Opportunities for developing and delivering heliophysics educational materials are available by collaborating with established providers of amateur radio content. The ARRL, other national radio societies, and independent publishers produce books and media for amateur radio education (e.g., ARRL Store, 2022; CQ Store, 2022). The ARRL already has excellent in-person and virtual training programs established and routinely works with independent and school-affiliated amateur radio clubs across the country. Other groups with established radio educational programs include scouting (Radio Merit Badge, 2022; K2BSA, 2022) and Youth on the Air (YOTA, 2022). Besides working with established groups, independent creation of education and training programs and materials is effective. Instructors can create courses that use amateur radio to introduce space physics, like Reiff (2008) at Rice University and Frissell et al. (2022d) at The University of Scranton. Amateur radio contests can be used to introduce space weather concepts. Shortwave listening contests that make use of free, internet connected radios can be used by unlicensed participants (Sarwar et al., 2021).

Current school-based learning emphasizes modeling concepts and investigations that follow UDL (Universal Design for Learning) principles (CAST, 2018). Amateur radio offers an established, externally-supported, and multifaceted educational canon that is uniquely suited to supporting UDL goals. Amateur radio training naturally incorporates UDL principles because concepts are presented in multiple ways (mathematically, with models, verbally, and through building or using a radio). This results in a highly accessible way to understand math, science, engineering, or even writing (Collins et al., 2017) for people who may find these subjects challenging.

3 Amateur radio as a tool for ionospheric remote sensing

Amateur radio's power 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). 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. With few exceptions, citizen scientists without a license can use radio receivers across all of these frequencies to study signals of opportunity and natural radio sources. Amateur radio operators have additional privileges that permit them to transmit signals on select bands.

3.1 Global scale amateur radio observational networks

The amateur radio community has voluntarily built and currently run several automated networks that routinely monitor amateur radio communications in near-real time and report these observations to central databases. The major operational 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/). An older, manual reporting network is the DX Cluster. Each system has a different architecture and primarily monitors different 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 various digital amateur communication modes, and WSPRNet initially reported only on the WSPR mode (Taylor and Walker, 2010) that was designed specifically to probe weak signal HF propagation paths. Reporting of a similar mode, FST4W, was added to WSPRnet in 2022. Since 2019 the WSPRDaemon service (WD, http://wsprdaemon.org) makes available all WSPR reports since 2008 via client applications that dramatically speed queries (among others, http://wspr.rocks and https://wspr.live), while also relieving load on the WSPRnet server.

The RBN, PSKReporter, and WSPRNet have operated since 2008. While primarily built for the internal use of the amateur radio community, the operators of these networks have graciously allowed the science community to access the data for research. Frissell et al. (2014) first demonstrated the use of this data for space weather and space physics research by showing a solar flare HF radio blackout observed by the RBN. Numerous additional studies have since been published in both the amateur literature (e.g., Bacon, 2021; Serra, 2022), and in the professional literature reviewed in Section 4. WD, used with certain Software Defined Receivers (SDRs), uses two algorithms in time and frequency domains to estimate local noise, a measurement of interest in its own right, and useful to convert signal to noise ratio from WSPR and FST4W to signal level. Insights gained from noise estimates in conjunction with WSPR have been published in professional and amateur journals (Griffiths et al., 2020; Lo et al., 2022). Since 2022 WD has also accepted spectral spreading estimates from FST4W reception reports enabling attribution of each observation to a propagation mode, e.g., one- and two-hop F layer refraction, side scatter, and ionosphere-ionosphere.

Since the observations of these networks extend back to 2008, great potential exists for large scale statistical investigations. For example, Sanchez et al. (2022) and Engelke et al. (2022) are currently conducting Large Scale Traveling Ionospheric Disturbance (LSTID) climatologies. These networks can be expanded by encouraging amateurs and professionals to field more receivers. Additionally, all of these amateur radio networks provide real-time web-based displays and data streams. Although the real-time capabilities are not currently used in any official capacity, the global nature of these systems and direct applicability to real-time HF communications makes their use compelling for operational purposes.

3.2 Purpose-built citizen science instrumentation

The existing large-scale, amateur radio networks offer tremendous capabilities in terms of geospatial coverage, wide-scale amateur adoption, real-time reporting, and duration of historical archives. However, these systems have been designed to monitor radio propagation path openings, not for making finely-calibrated ionospheric physics measurements. These networks 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 between 1 and 2 min. Recent technological advances can overcome many of these limitations 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 (±50 ns) and frequency (down to parts in 10^{-10} using 1 s averaging) measurements (Frissell et al., 2021). Such low cost precision was not available just a few years ago, nor was the need for such precision recognized widely by the amateur radio community.

The development of novel instruments and techniques targeted at citizen science study of the ionosphere and space has been made possible due to 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. These new instruments can be broadly separated into two categories. The first category consists of passive instruments that rely on receiving signals-of-opportunity, such as GNSS signals, government-run beacons and radars, and broadcast radio stations. These passive instruments typically do not require a license and are unlikely to cause interference to other equipment. Thus, they allow for broad citizen science participation (see Section 3.2.1). The second category, in contrast, consists of active instruments that generate radio signals that can be used for remote sensing and generally requires a license. These instruments can take advantage of the amateur radio community's unique transmitting privileges (see Section 3.2.2).

3.2.1 Passive observations of signals of opportunity

Novel systems, capable of making and reporting precision passive ionospheric measurements automatically, easily, and at low cost are now being developed. One example is the NSF-funded HamSCI Personal Space Weather Station (PSWS). Its aim is to create a network of ground-based space weather sensing instruments to advance scientific understanding and improve propagation nowcast/forecast capabilities for radio operators (Collins et al., 2021; Frissell et al., 2021). The PSWS uses a modular approach to integrate various instruments including an HF radio receiver, GNSS TEC receiver, ground magnetometer, and VLF receiver. A low-cost variant (≲US$300) of the HF receiver known as the "Grape" can make precision Doppler measurements (Collins et al., 2022; Gibbons et al., 2022; Collins et al., 2023), with recent Grape results by Collins et al. (2023) reviewed in Section 4.8. A wideband software defined radio (SDR) for the performance-based HamSCI

PSWS known as the "TangerineSDR" is being developed to take advantage of signals of opportunity such as oblique chirp ionosondes (Joshi et al., 2021; Vierinen, 2022) and oceanographic HF radars known as CODARs (Kaeppler et al., 2022). Another valuable 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 (Rodrigues and Moraes, 2019). Malkotsis et al. (2022) developed an amateur radio based VLF/LF receiver for lower ionospheric modeling. Serra (2023) developed amateur system for making HF elevation of arrival measurements.

3.2.2 Active sounding

Because licensed amateurs can 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, modes designed 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 (McGwier, 2018; Lloyd, 2019). 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, e.g., coherent CW, where computer-generated Morse code transmissions are synchronized using GNSS Pulse-Per-Second (PPS) timing, allowing for time-of-flight measurements of radio transmissions (Kazdan et al., 2022). Conceivably, similar timing measurements or coding for ionospheric measurement could be incorporated into amateur radio digital modes such as WSPR or FT8. Such measurements would be a boon for amateurs and scientists by providing more data to determine the exact propagation mode used for a particular exchange.

3.3 Relationship to professional observations and modeling

Observations provided by the larger and robust amateur radio citizen science networks are valuable because they 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 (Reinisch et al., 2009; Bullett and Mabie, 2018), SuperDARN radars (Greenwald et al., 1995; Chisham et al., 2007; Nishitani et al., 2019), Incoherent Scatter Radars (ISRs) (Evans, 1969; Evans, 1975; Goncharenko et al., 2018), GNSS TEC and scintillation receivers (Rideout and Coster, 2006; Coster and Komjathy, 2008; Deshpande et al., 2016), professional ground magnetometers, rockets, spacecraft, *etc.* Every amateur and professional technique has both limitations and advantages; thus they should be used in a complementary fashion to ensure accurate measurement and to help develop a complete understanding of the geospace environment.

A natural use of amateur radio observations would be to provide observations of the impact of space weather activity on actual communications systems (e.g., Section 4.1), or to link bottomside ionospheric observations to height-integrated GNSS TEC measurements (e.g., Section 4.3). Amateur Radio measurements have the potential to be a dominant dataset for operational and scientific data-model assimilation. They directly complement existing GNSS datasets, which currently cannot independently separate the topside and bottomside ionosphere reliably. In certain cases, amateur radio networks can be used directly with professional instrumentation. Fallen. (2018), Fallen. (2019) successfully demonstrated the use of amateur WSPRNet stations to receive WSPR signals transmitted by the High Frequency Active Auroral Research Program (HAARP) transmitter (National Research Council, 2014) in Gakona, AK to test ionospheric propagation models. HAARP, in conjunction with precision amateur receivers and modeling, may also prove useful in advancing the understanding of long delayed echos (LDEs, Section 5.1.1).

Modeling is another important tool through which amateur radio observations can be used for scientific purposes. HF raytracing using numerical ionospheric models (Figure 1) link even simple binary propagation path observations to potentially valid physical mechanisms. This is particularly powerful when hundreds of thousands of propagation paths are modeled, such as when HF radio communications were observed on multiple frequencies during the 2017 Great American Total Solar Eclipse (Section 4.2). Preparations to gather similar observations are now being made for the 2023 and 2024 American Solar Eclipses (Frissell, 2022). As advances in modeling, and other techniques such as data assimilation and ionospheric tomography, improve, so will the use of amateur radio observations to advance heliophysics.

4 Amateur radio: Recent science results

4.1 Ionospheric impacts of solar flares and geomagnetic storms

Solar flares and geomagnetic storms are space weather disturbances that immediately and profoundly impact both the ionosphere and HF radio communications. Solar flares suddenly enhance extreme ultraviolet (EUV) and X-ray energy that causes rapid increases in the D-region ionization. Collisional absorption due to this D-region enhancement can cause complete fading out of dayside HF radio communications for periods ranging from a few minutes to an hour or more. Because solar EUV and X-ray energy propagate at the speed of light, it takes ~8 min for flares to travel from the Sun to the Earth and no advanced warning of these impacts is possible (Dellinger, 1937; Benson, 1964; McNamara, 1979; Chakraborty et al., 2018; Chakraborty et al., 2019; Chakraborty et al., 2021; Chakraborty et al., 2022).

Solar flares generally erupt from Active Regions, and are often accompanied by Coronal Mass Ejections (CMEs) and Solar Energetic Proton (SEP) events. CMEs can generate radio bursts that can cause noise that arrives in minutes and lasts up to tens of hours. SEPs can lead to Polar Cap Absorption (PCA) events that arrive in tens of minutes and may last days, affecting radio signals in the high latitude ionosphere (Bailey, 1964; Reiner et al., 1998; Sauer and Wilkinson, 2008; Knipp et al., 2016).

When CMEs or high speed streams (HSSs)/co-rotating interaction regions (CIRs) are Earthward-directed and carry a southward Interplanetary Magnetic Field (IMF), the transfer of energy and momentum from the solar wind into the magnetosphere is maximized and can result in a phenomenon known as a geomagnetic storm (Gonzalez et al., 1994; Gonzalez et al., 1999). Geomagnetic storms further trigger ionospheric storms, which result in complex, global changes to the Earth's ionosphere. The changes vary as a function of geomagnetic latitude, local time, season, atmospheric composition, and time relative to storm onset (Matsushita, 1959; Fuller-Rowell et al., 1996; Rishbeth, 1998; Buonsanto, 1999; Thomas et al., 2016).

The impacts of solar flares (e.g., Joselyn, 1992) and geomagnetic/ionospheric storms (e.g., Ferrell, 1951) on HF communications and the ionosphere have been long appreciated by the amateur radio, space weather, and professional scientific communities. Advances on these topics continue today. Measurements by Witvliet et al. (2016b), Witvliet et al. (2023) during an X1.6 solar flare showed a 45 dB increase in attenuation of radio signals arriving via the ionosphere, but also a 12 dB drop of ambient electromagnetic noise (Figure 2). This proves that 94% of the background noise received in a remote rural area propagates via the ionosphere, which was not known previously.

The recently developed automated, global-scale amateur radio networks such as the RBN, WSPRNet, and PSKReporter now offer an unprecedented ability to both measure the impacts of these space weather phenomena on actual communications and use those communications to remote sense the ionosphere. Frissell et al. (2014) used the RBN to observe solar flare impacts on HF communications, and Frissell et al. (2019) used RBN and WSPRNet observations to study solar flare and geomagnetic storm impacts during the active period of 4–10 September 2017. Most recently, Collins et al. (2023) used the network of Grape low-cost Personal Space Weather Stations to observe solar flares impacting HF Doppler Shift (Section 4.8).

Figure 3 (from Frissell et al., 2019) shows the HF RBN and WSPRNet response over Europe for two X-class solar flares occurring on 6 September 2017, with geomagnetic and solar flare information data in the top two panels. Deep radio blackouts are observed across all displayed HF bands in response to the solar flares in the GOES data. Frissell et al. (2019) also shows the response of the North American sector, which was transitioning from night to dawn during the occurrence of these flares. Due to shielding by the Earth, few to no flare effects were observed in the North American observations.

The global response of RBN and WSPRNet observations to a geomagnetic storm are shown in Figure 4 (from Frissell et al., 2019). The beginning of the storm at 2100 Coordinated Universal Time (UTC) 7 September 2017 causes a brief enhancement of communications activity on the 7–28 MHz bands, followed by below-average radio activity on the 7–21 MHz bands until 1400 UTC 9 September. These observations are consistent with ionospheric storms occurring in the summer/equinoctial months (Thomas et al., 2016). In addition to the analysis of the period immediately around this geomagnetic storm, Frissell et al. (2019) shows a global suppression of HF propagation lasting 12–15 days after the storm. This is attributed to combined storm and flare effects during this period, and is shown to be correlated with a decrease in observed daily average GPS TEC over the continental U.S.

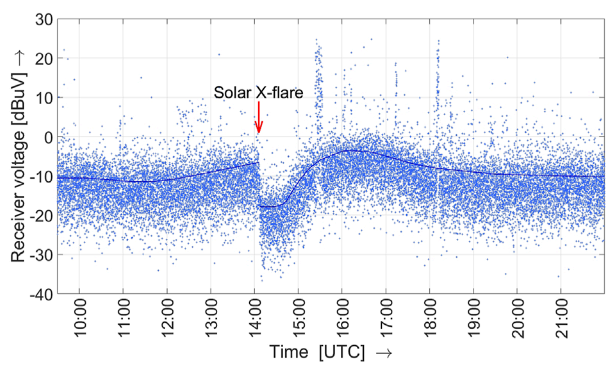

FIGURE 2
Measured background electromagnetic noise, dropping 12 dB at the impact of a X1.6 solar flare. This proves that 94% of the background noise in a remote rural area propagates via the ionosphere. From Witvliet et al. (2023).

4.2 Ionospheric response to solar eclipses

Solar eclipses, which occur when the Moon's shadow is projected onto the Earth, are not only stunning visual displays but also dramatically impact the ionosphere and ionospheric radio communications. A temporary reduction of insolation occurs and causes a corresponding reduction of photoionization and cooling that affects atmospheric structure and composition. Solar eclipses differ from the dawn-dusk transition. The eclipse shadow is highly localized, transient, supersonic, and often does not follow an East-West trajectory. Similarly, the exact conditions (such as trajectory and season) of every eclipse is unique. This uniqueness adds to the scientific value of studying each eclipse.

Solar eclipses are classified as total (solar disk is completely occluded), annular (lunar disk fits inside of the solar disk), and partial (only part of the solar disk is occluded). While some type of solar eclipse usually occurs somewhere on Earth two to three times each year, it is rare that a total solar eclipse occurs over regions that are well-instrumented for ionospheric study. Due to their predictability, solar eclipses are widely regarded as critical "controlled" ionospheric experiments and thus have received significant attention (e.g., Benyon and Brown, 1956; Evans, 1965a; Evans, 1965b; Anastassiades, 1970; Roble et al., 1986; Krankowski et al., 2008). Amateur radio operators and citizen scientists have also authored or contributed to solar eclipse ionospheric studies (Kennedy and Schauble, 1970; Kennedy et al., 1972; Bamford, 2000; Bamford, 2001).

On 21 August 2017, in just over 90 min, a total solar eclipse traversed the Continental United States (CONUS) from Oregon to South Carolina. It affected so many people in North America that it became popularly known as "The Great American Eclipse". Due to the eclipse's trajectory, it offered an unprecedented opportunity to study the ionosphere using a wide variety of instrumentation and models (Coster et al., 2017; Huba and Drob,

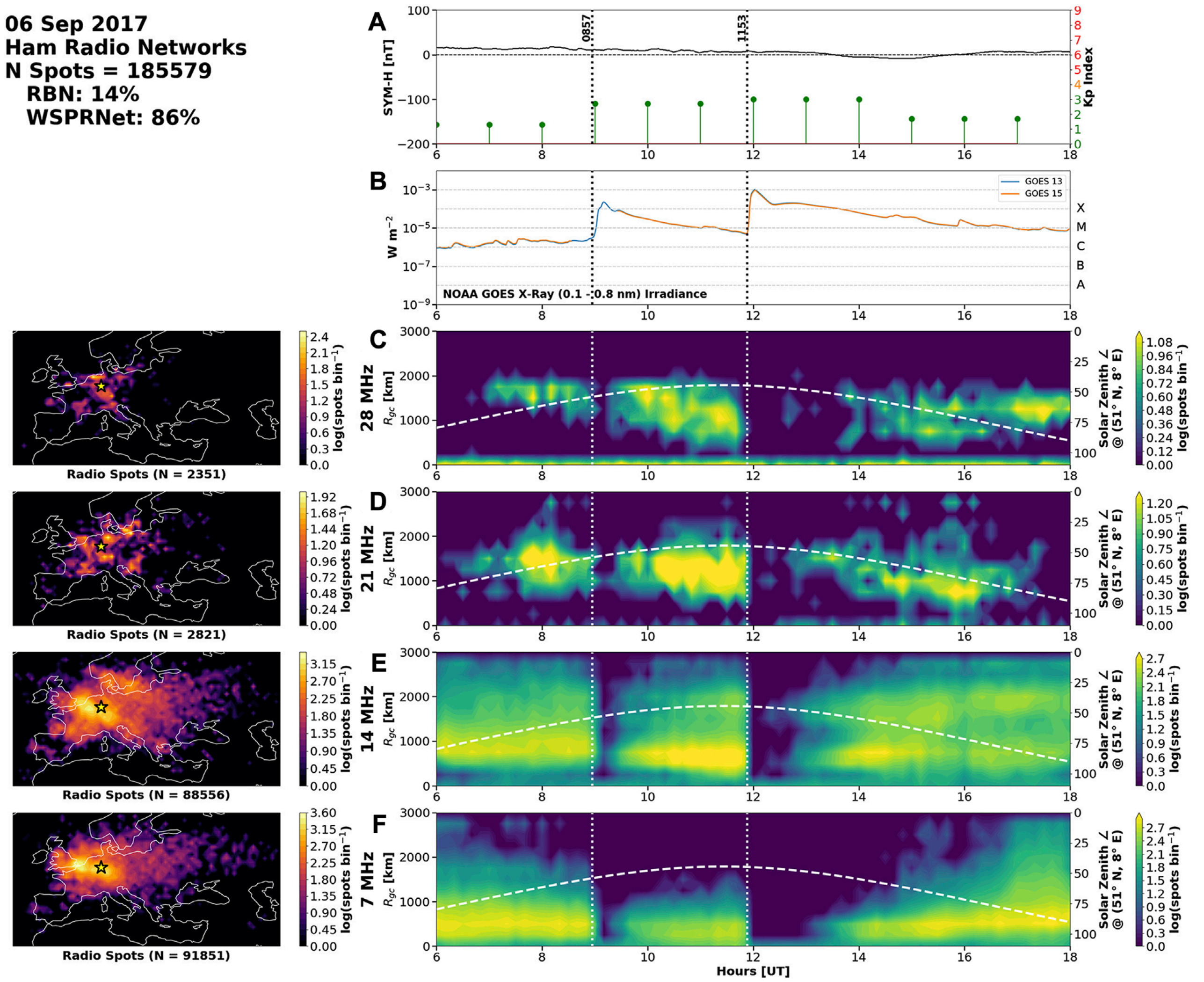

FIGURE 3
Example of solar flare ionospheric impacts observed by amateur radio observing networks over Europe on 6 September 2017. **(A)** SYM-H (black line) and Kp (colored stems). **(B)** GOES-13 (blue) and GOES-15 (orange) XRS 0.1–0.8 nm X-ray measurements. Flares are observed at 0857 UTC (X2.2) and 1153 UTC (X9.3) and indicated with dotted vertical lines. **(C–F)** Two-dimensional contour histograms of RBN and WSPRNet spot data for the 28-, 21-, 14-, and 7-MHz amateur radio bands, respectively. Bin size is 250 km × 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 in the GOES data. From Frissell et al. (2019).

2017; Zhang et al., 2017; Bullett and Mabie, 2018; Cohen et al., 2018; Goncharenko et al., 2018; Lin et al., 2018; Mrak et al., 2018; Yau et al., 2018). This was also the first solar eclipse for which the recently developed automated amateur radio reporting networks, including the RBN, PSKReporter, and WSPRNet, were leveraged. HamSCI organized the Solar Eclipse QSO Party (SEQP), a large-scale citizen science experiment structured like a traditional amateur radio contest. The event took place over 8 hours, from 1400–2200 UTC on 21 August 2017. It started 2 hours before first contact of partial eclipse in Oregon and ended 2 hours after the last contact in South Carolina. By structuring the experiment like an amateur radio contest, it was possible to leverage the amateur radio community's pre-existing capability to generate records of hundreds of thousands of radio communication paths on multiple frequencies over the entire CONUS.

Frissell et al. (2018) reported on the 2017 SEQP RBN observations and used the PHaRLAP HF raytracing toolkit (Cervera and Harris, 2014) to compare the observations to the predicted eclipsed ionosphere generated by the physics-based SAMI3 ionospheric model (Huba and Drob, 2017). Figure 5 (adapted from Frissell et al. (2018)) shows the results. RBN observations are presented in the left column; SAMI3/PHaRLAP modeling results are shown in the right column. Frissell et al. (2018) concluded that 14 MHz communications predominantly refracted off of the E region ionosphere during this event. Model results further show that these simulated rays all had mean takeoff angles $\theta < 10°$, suggesting that low angle 14 MHz signals were below the E region

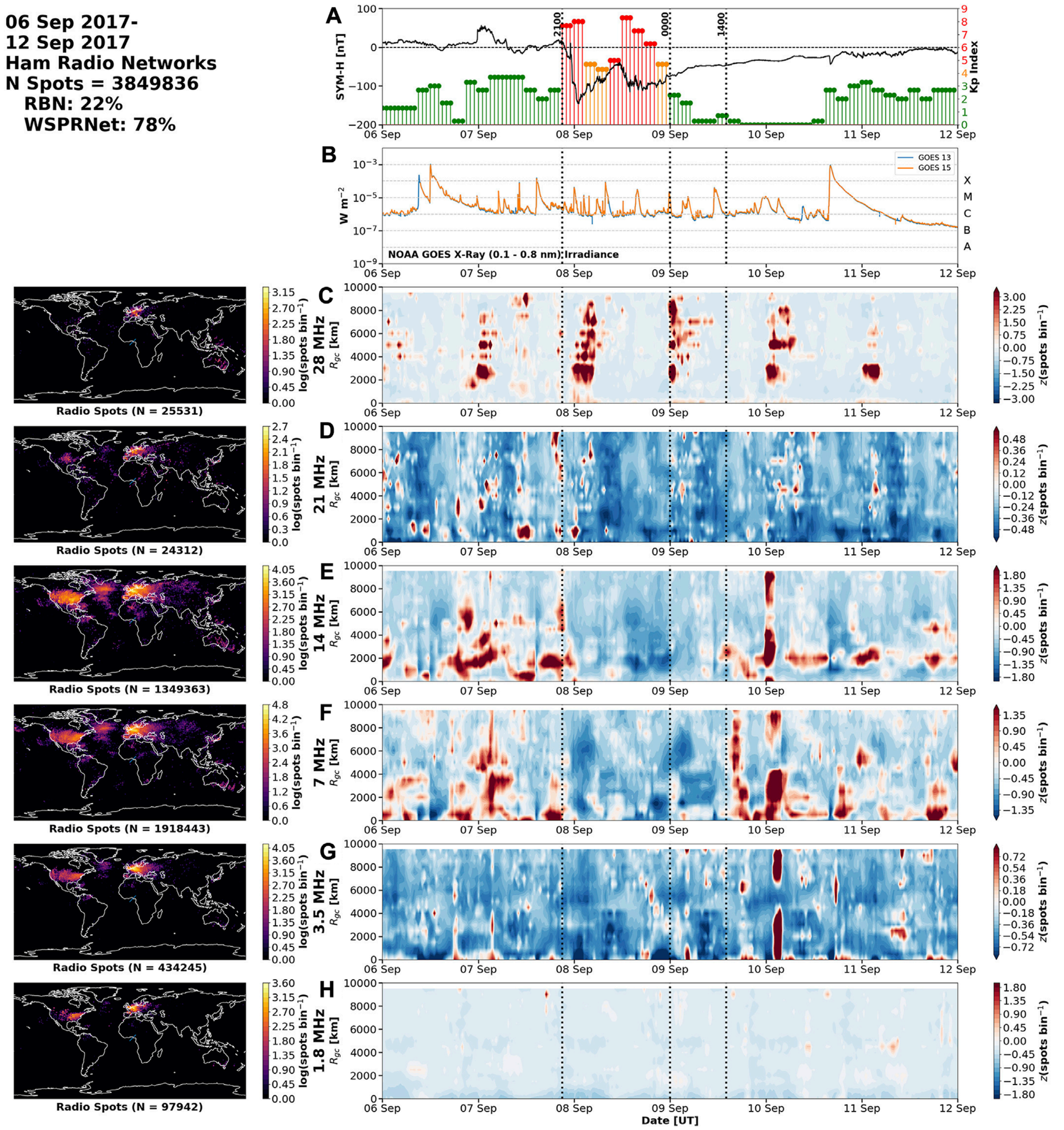

FIGURE 4
Observations showing the response of the high frequency amateur radio propagation to a geomagnetic storm occurring in the period of 6–12 September 2017. **(A)** SYM-H (black line) and Kp (colored stems). **(B)** GOES-13 (blue) and GOES-15 (orange) XRS 0.1–0.8 nm X-ray measurements. **(C–H)** Z-score of RBN and WSPRNet spot data relative to geomagnetically quiet days ($-25 < \mathrm{Sym-H} < 25$ nT and $Kp < 3$) from 2016 and 2017 for the 28-, 21-, 14-, 7-, 3.5-, and 1.8-MHz amateur radio bands, respectively. To the left of each time series is a map showing the TX-RX midpoints of all spots used in each histogram. Vertical dotted lines indicate (2100 UTC 7 September 2017) start of disturbed Kp (0000 UTC 9 September 2017) end of disturbed Kp, and (1400 UTC 9 September 2017) apparent high-frequency recovery. From Frissell et al. (2019).

cutoff frequency before and after the eclipse but escaped into space during the eclipse due to reduced ionospheric densities. Poor data-model agreement for $h \geq 125$ km refractions suggests ionospheric densities were never sufficient to support high angle 14 MHz rays.

In addition to publishing the 2017 SEQP results in the peer-reviewed scientific literature, they have also been reported in amateur radio community journals (Frissell, 2019). The 2017 SEQP results are important not only for their contributions to observations and understanding of the 21

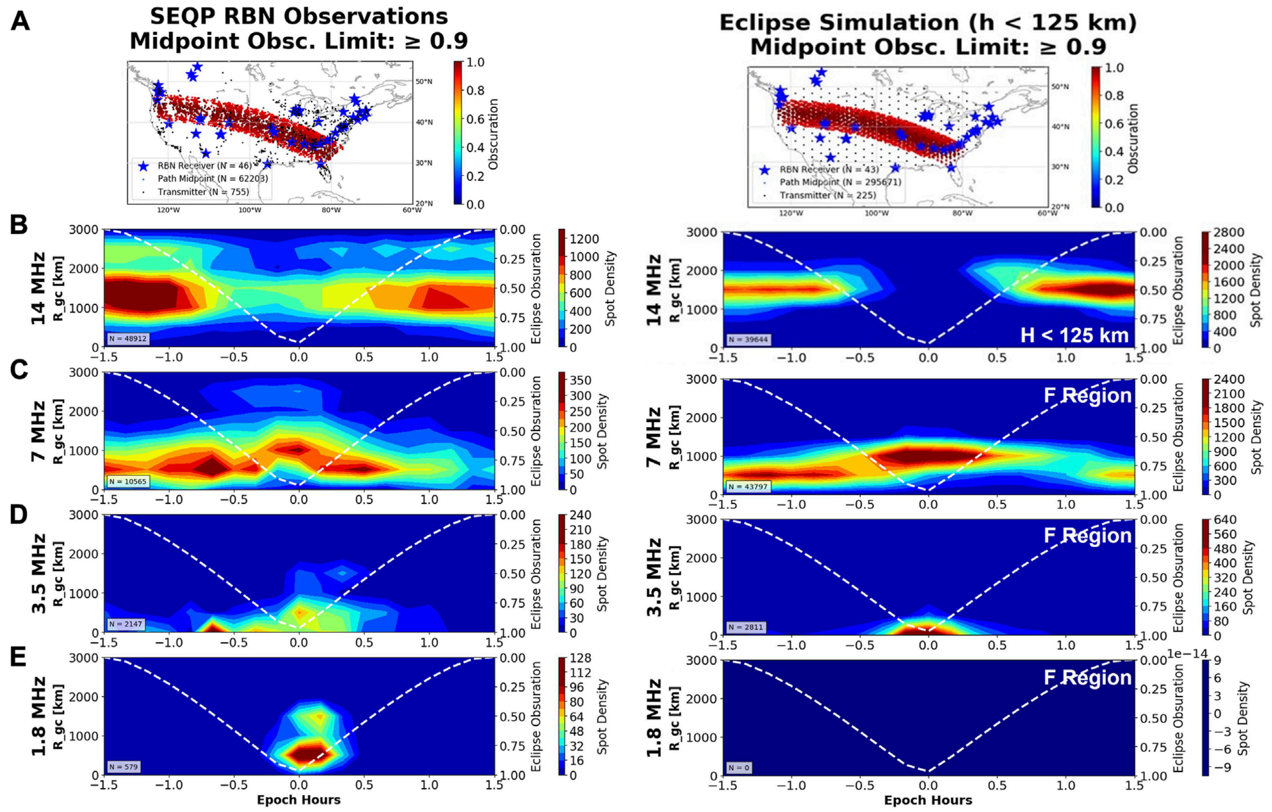

FIGURE 5
Solar Eclipse QSO Party Results from Frissell et al. (2018). RBN observations are presented in the left column; SAMI3/PHaRLAP modeling results are shown in the right column. (Row **A**) Maps depicting the locations of amateur radio transmitters (black dots), RBN receivers (blue stars), and TX-RX path midpoints of each reported or simulated signal (dots color coded by maximum eclipse obscuration). Observations in this figure have been restricted to midpoints that fall in the region of ≥90% maximum obscuration. (Rows **B–E**) Time series of ≥90% maximum obscuration RBN (left) or simulated (right) midpoints for the 14, 7, 3.5, and 1.8 MHz amateur radio bands, respectively. For each plot, the *x*-axis shows time in hours relative to eclipse maximum, the *y*-axis shows TX-RX great circle range R_{gc} in km, and the colorbar shows spot density contours on an underlying 500 km by 10 min grid. The white dashed line on each figure shows the eclipse obscuration curve at 300 km altitude for the point 40° N, 100° W (roughly in the center of the CONUS). Simulation results that are most consistent with observations are shown for each band: E region ($h < 125$ km) refractions for 14 MHz and F region ($h \geq 125$ km) refractions for 7, 3.5, and 1.8 MHz.

August 2017 solar eclipse, but they also provide a foundation for using amateur radio and modeling techniques for the study of future eclipses, including the upcoming 18 October 2023 annular and 8 April 2024 total solar Great American Eclipses.

4.3 Traveling ionospheric disturbances

Frissell et al. (2022c) demonstrated for the first time that automated amateur radio networks, including the RBN, WSPRNet, and PSKReporter, can observe large scale traveling ionospheric disturbances (LSTIDs). Traveling ionospheric disturbances (TIDs) are quasi-periodic variations of ionospheric densities. They are generally divided into two categories. LSTIDs have horizontal speeds between 400 and 1,000 m s^{-1}, periods between 30 min and 3 h, and horizontal wavelengths greater than 1,000 km. Medium Scale TIDs (MSTIDs) have horizontal speeds between 100 and 250 m s^{-1}, periods between 15 min and 1 h, and horizontal wavelengths of several hundred kilometers (e.g., Georges, 1968; Francis, 1975; Ogawa et al., 1987). LSTIDs are typically associated with atmospheric gravity waves (AGWs) generated by Joule heating and particle precipitation from auroral zone disturbances (Hunsucker, 1982; Lyons et al., 2019). These AGWs may propagate equatorward for long distances, transporting energy from the auroral zone to middle and low latitudes (Richmond, 1979). They can even reach the opposite hemisphere (Zakharenkova et al., 2016). Both MSTIDs and LSTIDs affect HF radio propagation by focusing and defocusing rays (Figure 1). As a TID passes overhead, the HF skip distance lengthens and shortens and will cause received radio stations to fade in and out with the same period as the TID.

Figure 6 from Frissell et al. (2022c) shows LSTID signatures observed by the RBN, PSKReporter, and WSPRNet in the 14 MHz amateur radio band (Figures 6A,B), along with coincident observations by the Blackstone (BKS) SuperDARN HF radar (Figures 6C,D) and Global Navigation Satellite System (GNSS) differential Total Electron Content (dTEC) (Figures 6E,F). Red

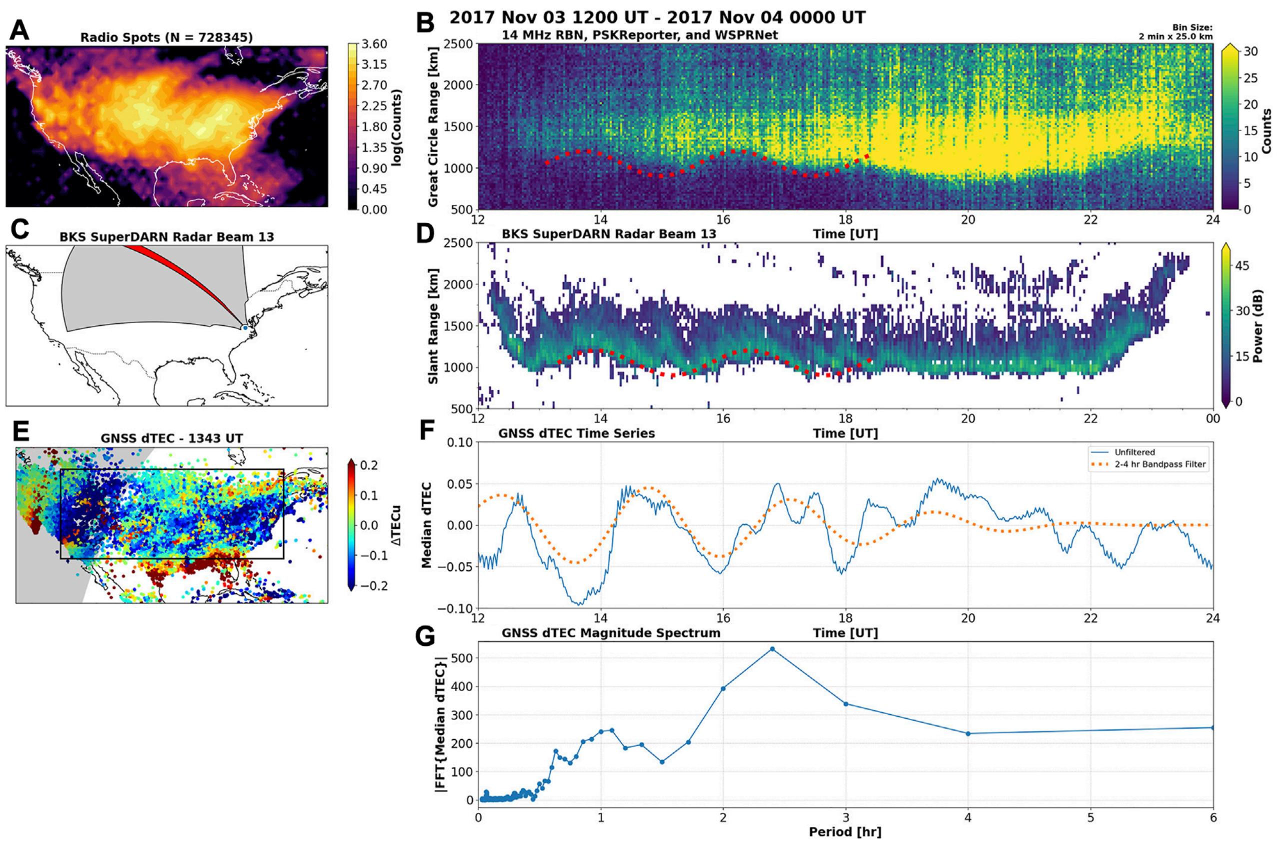

FIGURE 6
Example of Large Scale Traveling Ionospheric Disturbances (LSTIDs) observed using amateur radio networks, the Blackstone (BKS) SuperDARN radar, and GNSS dTEC. **(A)** Geographic distribution of TX-RX midpoints of amateur radio communications observed over the continental United States on 3 November 2017 from 1200 to 2359 UTC. **(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 UTC. **(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 h bandpass filter. **(G)** FFT Magnitude spectrum of the unfiltered data in **(F)**. Red dots overlaid on **(B)** and **(D)** show a sinusoidal 2.5 h oscillation in skip distance common to both the amateur radio and SuperDARN measurements. From Frissell et al. (2022c).

dots overlaid on Figures 6B,D show a sinusoidal 2.5 h oscillation in skip distance common to both the amateur radio and SuperDARN measurements. Figure 6G shows a Fast Fourier Transform (FFT) of the unfiltered data in Figure 6F that reveals a 2.5 h spectral peak, demonstrating remarkable consistency between the amateur radio, SuperDARN, and GNSS dTEC observations. The HF skip distance oscillation is inversely related to the dTEC oscillation, consistent with the hypothesis that increased ionization levels correspond with increased HF refraction and therefore shorter skip distances. Further analysis by Frissell et al. (2022c) shows the LSTIDs observed in the amateur radio data to have a propagation azimuth of ~163°, horizontal wavelength of ~1,680 km, and phase speed of ~1,200 km h^{-1}, all parameters consistent with the GNSS dTEC observations. SuperMAG SME index enhancements and Poker Flat Incoherent Scatter Radar measurements suggest the observed LSTIDs were driven by auroral electrojet intensifications and Joule heating. This novel measurement technique has applications in future scientific studies of LSTIDs and for assessing the impact of LSTIDs on HF communications.

4.4 Sporadic E

Sporadic-E (Es) is of great interest to radio amateurs, with many actively searching for intense Es events in order to extend their communications range at VHF frequencies via oblique reflection. This has enabled a number of scientific studies, including the detection and tracking of Es events, the exploration of the true nature of Es reflection, and the link between the occurrence of sporadic-E and lower atmosphere weather events.

Data from amateur radio reporting networks have been used to map intense sporadic-E events. This approach can provide an important supplement to other techniques, allowing the detection and tracking of Es where no suitable ionosonde or other measurements are available at the right time and place. The technique has been validated by reference to ionosonde data where there is overlap (Deacon et al., 2022a).

Figure 7A shows an example map of Western Europe, on which are plotted reception reports, on three frequencies, from a single 15-min period on 18 August 2018. Solid lines indicate the great

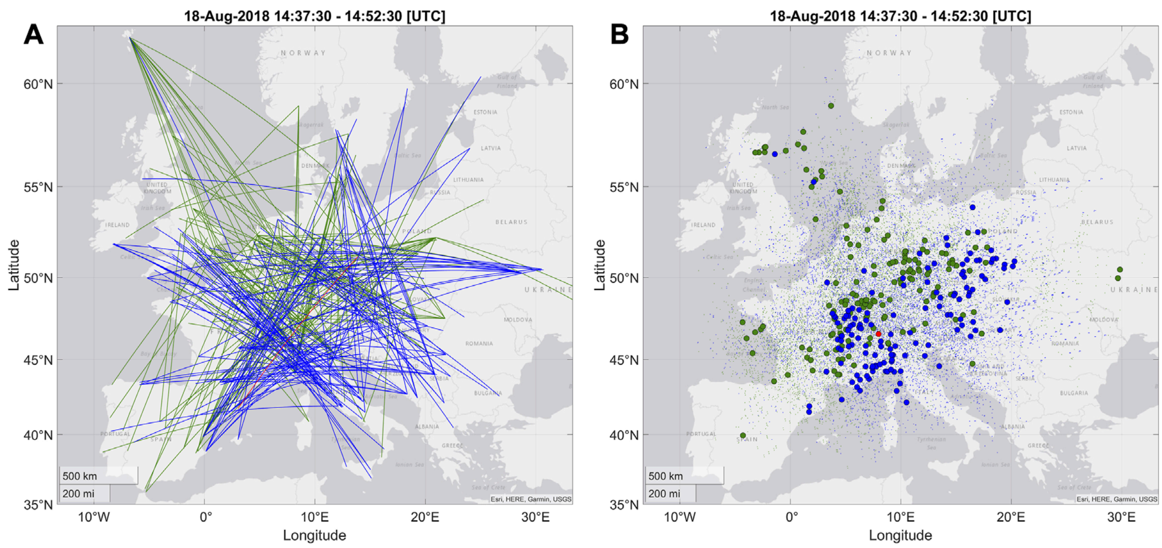

FIGURE 7
(A) Example map showing reception reports from a 15-min period centered on 14:45 UTC 18 August 2018. Solid lines indicate the great circle paths between the transmitting and receiving stations. **(B)** Example map showing the midpoints of reported signal paths from the same time period as in **(A)**, plus the estimated geographical coverage of the data. Solid circles represent the midpoints of reported great circle paths, and background dots indicate the estimated geographical coverage of the measurements. Green = 28 MHz, blue = 50 MHz, red = 70 MHz. From Deacon et al. (2022a).

circle paths between transmitting and receiving stations. It can be seen that there is clear triangulation, from multiple directions, of a number of concentrated areas of reflection. In order to show the pattern of estimated reflection points more clearly, Figure 7B represents the same reception reports as in Figure 7A but with solid circles indicating the mid-points of the great circle paths, with the paths themselves omitted for clarity. The very small dots show an estimated coverage plot. A clear gap can be seen between an Es cloud over central Europe and one over eastern France. This technique can be used to reveal the incidence, evolution and decline of a sporadic-E event in a way that is not possible with other techniques. A pseudo-real time video, included as supplementary material in Deacon et al. (2022a), has also been produced to show the evolution of this event over the course of several hours.

Amateur resources and equipment have also been used to investigate the process by which oblique VHF radio wave reflection from intense midlatitude Es clouds occurs, with specular reflection, scattering, and/or magnetoionic double refraction all previously proposed in the literature. The experimental approach uses the polarization behaviour of the reflected signals as an indicator of the true reflection mechanism, as described in Deacon et al. (2021).

In Deacon et al. (2022b), results are presented from a measurement campaign in the summer of 2018. The campaign gathered a large amount of data at a receiving station in the south of the UK using six European amateur radio beacon transmitters, received via sporadic-E reflection, as 50 MHz signal sources. In all cases the signals received were elliptically polarized, despite being transmitted with nominally linear polarization; there were also indications that polarization behaviour varied systematically with the orientation of the path to the geomagnetic field. This represents, for all the examples recorded, clear evidence that signals were reflected from midlatitude Es by magnetoionic double refraction.

The analysis approach seeks to establish an overall picture of polarization behavior, and Figure 8 shows a representative example. The distribution of measured polarization ellipse parameters for a beacon in the Faroe Islands is shown in histogram form. Figure 8A shows measured axial ratio on the horizontal axis on a logarithmic scale, with circular polarization marked by the red line in the center. Left-hand elliptical polarization is to the left of the red line and right-hand elliptical polarization is to the right of the red line. Linear polarization, when present, appears as very high values to the far right or left of the center line. Figure 8B shows measured tilt angle, with the red line marking 0° (horizontal) and with negative angles to the left, positive angles to the right. In each case, the vertical axis is the percentage of the total measurements in each bin.

A clear result of the measurement campaign is that, for all six beacons, the signals received were elliptically polarized after reflection from the Es cloud. This was despite the fact that all the beacons were known to be transmitting with linear polarization. Received signals exhibited no evidence of depolarization, and there were indications that polarization behaviour varied systematically depending on the orientation of the wave normal to the geomagnetic field at the point of reflection. This represents convincing evidence that the mechanism for radio wave reflection was principally magnetoionic double refraction, rather than either scattering or “specular reflection”.

Referring now to what causes sporadic-E clouds to form, in a recent review article for an amateur radio audience (Bacon, 2021), the author, a professional meteorologist, describes the probable links between meteorological phenomena and the occurrence of

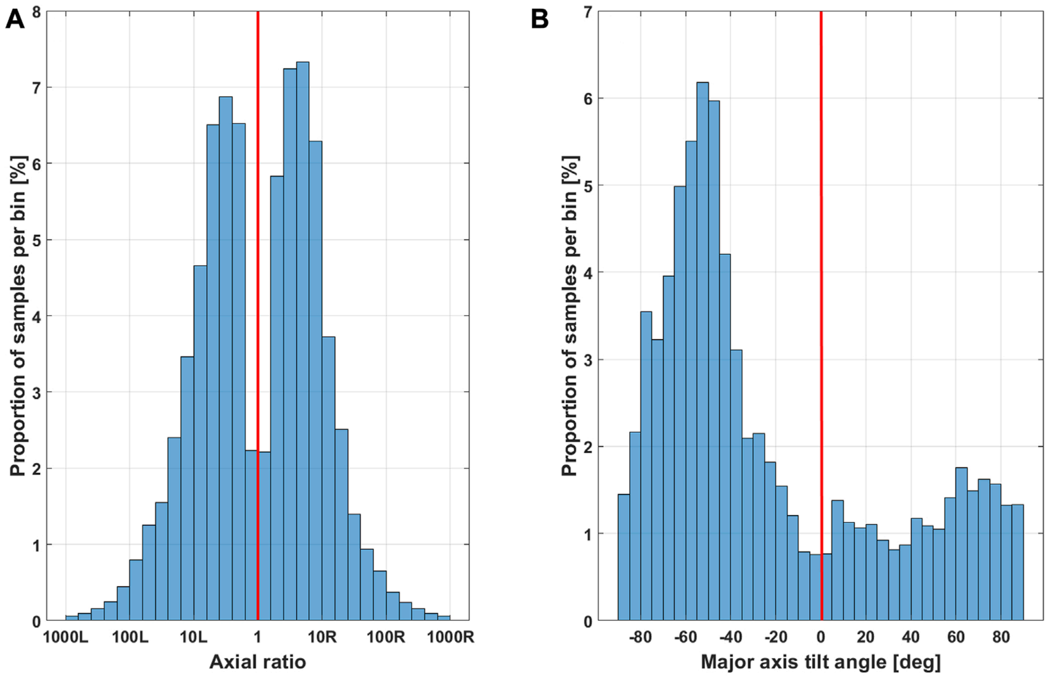

FIGURE 8
Example polarization analysis. Faroe Islands beacon, 8 August 2018, total 40 min at 6,000 samples s^{-1}. **(A)** Polarization ellipse axial ratio histogram. Horizontal axis: axial ratio (logarithmic scale). Red center line: axial ratio = 1 (circular polarization). Left of center line: left-hand elliptical polarization. Right of center line: right-hand elliptical polarization. Vertical axis: proportion of samples per bin. **(B)** Polarization ellipse tilt angle histogram. Horizontal axis: tilt angle (linear scale). Red center line: tilt angle = 0° (horizontal). Left of center line: negative tilt angle. Right of center line: positive tilt angle. Vertical axis: proportion of samples per bin. From Deacon et al. (2022b).

sporadic-E layers. Although the wind-shear theory for the creation of Es is well established, and the important role of diurnal and semi-diurnal atmospheric tides is clear, there is good evidence from radar studies of the mesosphere/lower thermosphere region that there is additional wave activity interacting with the tidal components. These are upward-propagating atmospheric gravity waves (AGW) produced by weather systems in the troposphere. These features are often localized to specific regions associated with weather events, tending to move as the weather systems move.

If successful prediction of the localized incidence of intense sporadic-E is to be achieved, these lower-atmosphere phenomena must be taken into account. An online prediction tool is under development (Bacon, 2023) which incorporates jet streams, mountain waves, upper wind patterns and atmospheric vorticity, along with atmospheric tides, meteor rates and the geomagnetic field as well as geographical factors. A real-time map is automatically produced indicating the relative probability of the occurrence of intense Es, both geographically and temporally. The model is currently being tested and refined, using input both from practical amateur radio experience and by comparison with ionosonde data.

4.5 Plasma cutoff and single-mode fading

The utility of amateur radio enthusiast's transmissions for science activities has been demonstrated in several different experiments, including those in which fundamental plasma and magnetoionic properties of the terrestrial ionosphere were studied. One experiment in particular, reported in Perry et al. (2018) conducted on 28 June 2015, involved amateur radio users participating in the 2015 ARRL Field Day and the Radio Receiver Instrument (RRI; James et al. (2015)) which is part of the Enhanced Polar Outflow Probe (e-POP; Yau and James (2015)) onboard the Cascade, Smallsat and Ionospheric Polar Explorer (CASSIOPE) spacecraft in low-Earth orbit.

RRI is a digital radio receiver comprised of 4, 3-m monopole antennas and accompanying receiver electronics. RRI's science targets include artificial and natural radio emissions, including HF transmissions, and is able to measure radio waves from 10 Hz to 18 MHz, sampling at 62.5 kHz, and providing in-phase and quadrature measurements of incident signals. RRI's monopoles can be electronically configured into a crossed-dipole configuration in which both dipoles sample the same frequency, which allows for polarization information; or, the dipoles can be "tuned" to sample separate frequencies.

For the 28 June 2015 experiment, the RRI was configured such that one of RRI's dipoles was tuned to 7.025 MHz to monitor the 40 m amateur radio band, while the other was tuned to 3.525 MHz to monitor the 80 m amateur radio band. RRI was activated for 117 s, beginning at 01:16:14 UTC, while the CASSIOPE spacecraft was at 386 km altitude, just north of Milwaukee, Wisconsin, heading in a southeasterly direction. During the experiment the spacecraft moved along the western shore of Lake Michigan, ending southeast of Nashville, Tennessee, at 358 km altitude.

A spectrogram of signals received on the RRI dipole monitoring the 40 m band (tuned to 7.025 MHz), reproduced from Perry et al. (2018), is shown in Figure 9 panel a. For approximately the first 30 s of the pass, the amateur's CW emissions are easily identified by the strong, narrow, and syncopated emissions. Perry et al. (2018) identified the call signs of these amateurs aurally, and confirmed their geodetic locations during the 2 minute experiment. Each identified (and confirmed) call sign is marked in the figure. Dramatically, the amateur emissions disappeared about the first 30 s of the experiment, as the spacecraft moved southeasterly. There were no identifiable emissions on the other dipole, which was tuned to monitor the 80 m band (at 3.525 MHz).

Supplementary data from other passive ground-based receiving networks (not shown here) indicated that the amateurs continued to transmit throughout the 2 minute RRI experiment. Accordingly, Perry et al. (2018) attributed the disappearance of amateur radio signals to plasma cutoff. As CASSIOPE moved south, the amateur transmissions became internally reflected by the ionosphere because the product of the transmissions' frequency and their angle of incidence with respect to the ionosphere dropped below the ionosphere's critical frequency–an effect described by the Secant Law and plasma cutoff.

Numerical ray trace modeling, constrained by ionosonde measurements in the continental United States and an empirical model of the ionospheric plasma density, shown in panel b of Figure 9, support the plasma cutoff hypothesis. In the ray trace simulation for the 25 June 2018 experiment, HF rays were traced from the positions of the identified hams in Figure 9 panel a, through an ionosphere with a critical frequency of 6.9 MHz in the region—just below RRI's tuned frequency. As the results show, rays propagated up to the spacecraft in a region where CASSIOPE was passing through in the first 30 s of the experiment. As the spacecraft moved south, the rays corresponding to the transmissions observed in the first 30 s of the experiment became internally reflected and could no longer propagate through the ionosphere to RRI. Amateur transmissions were not observed for the remainder of the experiment because CASSIOPE had moved into an ionosphere whose critical frequency was above that of the 40 m band. A close inspection of the simulation results indicate that the simulated signal cutoff—when the rays became internally reflected—occurred approximately 15 s after it was observed in the RRI data. These results demonstrated the ability to use amateur radio transmissions to remotely sense fundamental properties of the ionosphere, such as its critical frequency, to a high-degree of accuracy.

In their analysis of the same 28 June 2015 RRI dataset, Perry et al. (2018) also reported evidence of single-mode fading. Figure 10 shows an extract of the 'ESV', a portion of the 'K9ESV' call-sign, formed by Morse code 'dits' and 'dahs', received by RRI. An inspection of the peaks of each pulse shows a periodic oscillation of the order of 30 Hz that is remarkably coherent. Perry et al. (2018) ruled out any instrumental effect, such as an unstable transmitting system.

Additional ray trace analysis performed by Perry et al. (2018) showed that only the ordinary mode (O-mode) transmitted wave would have been incident on RRI during this portion of the experiment. The O-mode one is of two modes of propagation for radio waves at these frequencies; the other is the extraordinary mode (X-mode). The O-mode has an index of refraction that is closer to unity than the X-mode; therefore, at transmitting frequencies close to the ionosphere's critical frequency, which—as discussed earlier—was the case during the 28 June 2015 experiment, a range of frequencies exists that would allow for the O-mode to propagate up to RRI but not the X-mode, which would undergo cutoff. This is illustrated in Figure 9, which shows only O-mode traces propagation to CASSIOPE altitudes.

Because the transmitting frequency of the O-mode rays incident on RRI are so close to the ionosphere's critical frequency they are heavily refracted. This is indicated in Figure 9, which shows that the rays propagating up to RRI are not parallel to one another, and several exhibit strong refraction. As a result, an interference pattern is established with the non-parallel O-mode rays, complete with peaks and nulls in terms of intensity. As the CASSIOPE spacecraft moved southward, it transited the pattern, which registered as peaks and nulls in K9ESV's transmission. This is referred to as a single-mode fade (the mode here is the O-mode) (James, 2006), and it is a magnetoionic effect—a manifestation of the birefringent properties of the terrestrial ionosphere. Additional calculations performed by Perry et al. (2018) showed that a fading-rate of the order of 30 Hz is plausible for the case of K9ESV's signal geometry and CASSIOPE's trajectory during the experiment. This result is a compelling case, and demonstrates the capacity to study fundamental plasma and magnetoionic properties of the ionosphere using amateur radio signals and with the cooperation of amateur radio operators.

4.6 Near Vertical Incidence Skywave propagation

In remote areas where no telecommunication networks exist, or where such networks have been disabled by natural disasters or hostilities, Near Vertical Incidence Skywave (NVIS) propagation can be used to quickly restore information transfer and coordination (Witvliet and Alsina-Pagès, 2017). This is done with radio waves emitted at steep angles, which are reflected by the ionosphere to cover a contiguous area with a radius of 200 km or more.

To support work from humanitarian organizations that deliver basic healthcare in low and middle income countries (LMIC), such as Médecins sans Frontières, a group consisting of radio amateurs and scientists established the optimum NVIS antenna height through simulation and measurement (Witvliet and Van Maannen 2005; Witvliet and Van Maannen 2006a; Witvliet and Van Maannen 2006b; Witvliet et al., 2015a). It was shown that the use of mobile whip antennas will result in a Dead Zone between 30 and 60 km of the transmitter due to suppression of high-angle waves (Witvliet, 2021).

The same group showed that the magneto-ionic propagation phenomenon discovered by Appleton and Builder (1933) and described in detail by Ratcliffe (1962) and Rawer (2013) produces two fully isolated radio channels on the same frequency, if complementary left- and right-hand circular polarization antennas are used (Witvliet et al., 2015b; 2016b). This knowledge can be used to create more effective HF Multiple Input Multiple Output (MIMO) systems with compact antennas (Witvliet et al., 2014) or to mitigate the multipath fading typical for ionospheric radio

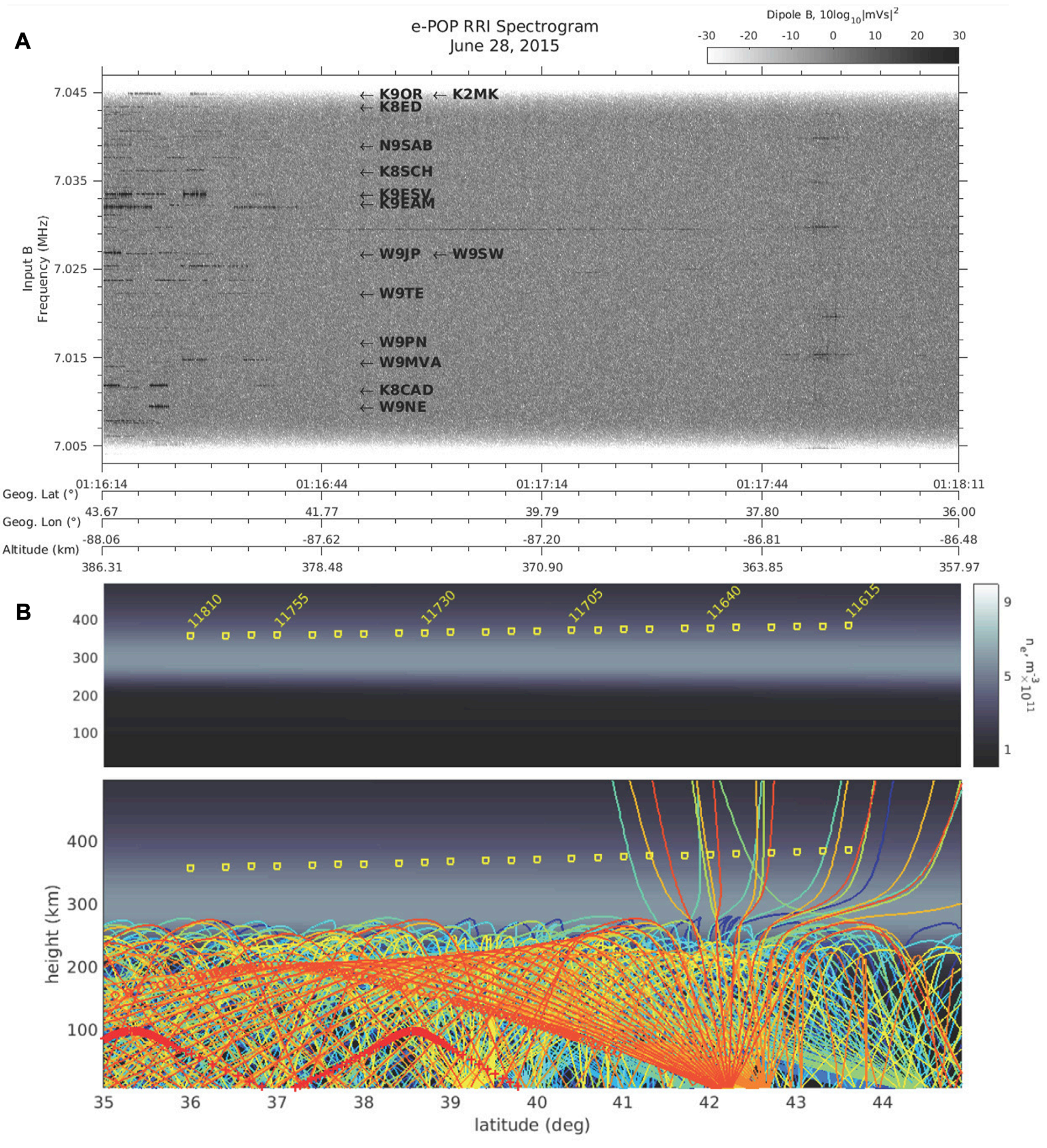

FIGURE 9
(A) A spectrogram of data collected during the 28 June 2015 experiment by the RRI dipole tuned to monitor the 40 m amateur band (tuned at 7.025 MHz), reproduced from Perry et al. (2018). CASSIOPE's position during the experiment is provided on the horizontal axis. Amateur operators whose transmissions could be aurally identified and whose locations could be confirmed are marked with their respective amateur radio call signs. Plasma cutoff is marked by the cessation of amateur signals after the first 30 s of the experiment. **(B)** The results of the numerical ray trace simulations, supporting the plasma cutoff hypothesis. The top portion shows CASSIOPE's altitude track with respect to geodetic latitude, descending from right to left, overlaid on an empirical ionosphere. The origin of the rays were the geodetic positions of the identified amateur operators denoted in **(A)**. The lack of rays penetrating through the ionosphere south of approximately 41° is due to plasma cutoff.

(Witvliet et al., 2015c). They also discovered the Happy Hour-propagation interval, in which only circularly polarized waves are received (Witvliet et al., 2015b). This phenomenon is simulated in Figure 11A, measurements are shown in Figures 11B,C.

For their research they created compact hybrid transmit antennas to produce waves with digitally programmable polarization (Witvliet et al., 2016a). NVIS propagation is very efficient: these small 1-W probe transmitters produce 57 dB

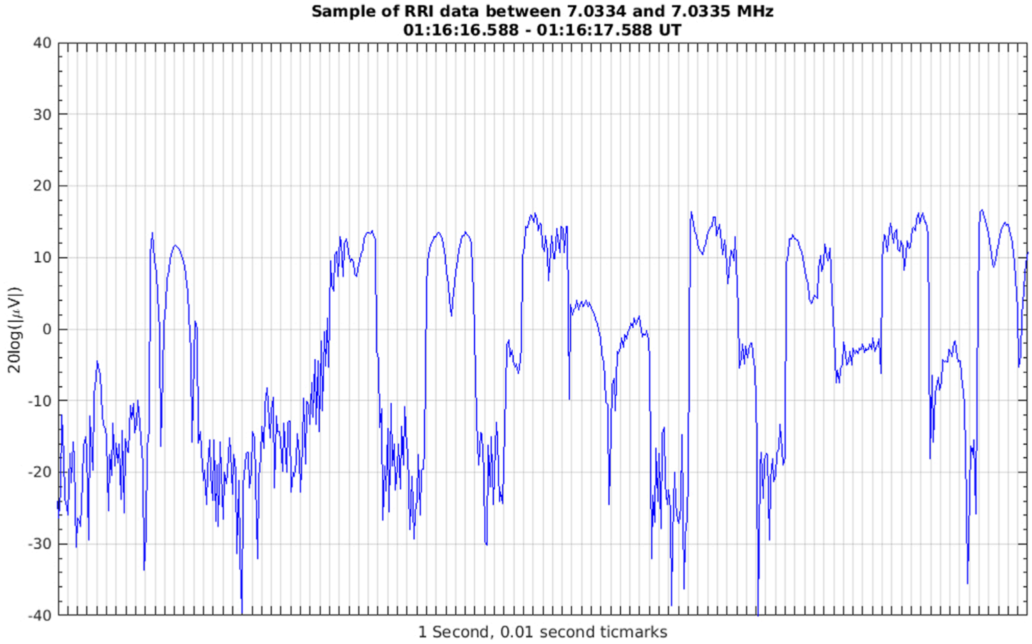

FIGURE 10
Reproduced from Perry et al. (2018), Morse coded pluses—'dits' and 'dahs'—spelling out the 'ESV' portion of the 'K9ESV' call-sign, received by RRI during the 28 June 2015 experiment. A coherent oscillation on the peaks of the pulses was identified as a manifestation of single-mode fading, a product of the CASSIOPE spacecraft passing through a self-interference pattern established by the O-mode component of K9ESV's transmissions.

signal-to-noise ratio in a 10 Hz bandwidth at 100 km distance (Witvliet et al., 2019).

4.7 Greyline propagation

Greyline propagation is a phenomenon where HF radio signals start and end at locations close to the terminator line at sunrise or sunset. This was first reported in the Amateur Wireless magazine in 1924, where it was noted that the propagation on wavelengths of 80 m and 95 m between the UK and New Zealand was best between 6.30 a.m. and 7 a.m. (Greyline, 1924). This early reference noted that this was thought to be because of the overlap of dawn and dusk. Hoppe and Dalton (1975), Nichols (2005), and a recent publication by Callaway (2016) all provided further evidence for terminator enhancement of HF propagation.

It should be noted that there are different propagation paths which can be classified as greyline propagation. While the transmitter and receiver locations are known, the path in between them is not measured. Therefore there are two possible interpretations of the term greyline propagation - one being a case where the propagation is continuously along the terminator and the other where only the start and end points (i.e., the transmitter and the receiver) are at the terminator and the propagation in between might be along the terminator or it might not be (i.e., other paths are possible).

Although there have been consistent reports of greyline propagation throughout the history of amateur radio, there have been relatively few reports in the scientific literature. Ponyatov et al. (2014) reported super long-distance and round-the-world propagation and noted preferential take off azimuths in relation to the terminator for the achievement of successful propagation links between Australia and Russia. Such HF studies historically required either experimental scientific equipment to be deployed or they relied on regular observation and documented reporting from dedicated radio amateurs. This has changed over the past few years, with the new opportunities offered by the Weak Signal Propagation Reporter (WSPR) network (Taylor and Walker, 2010). There are now more than a decade of automatically recorded world-wide radio links in the WSPR database that allow investigations to be conducted on a statistical basis.

Lo et al. (2022) undertook a systematic study of radio propagation at 7 MHz between New Zealand (NZ) and the United Kingdom (UK) and other long-distance locations. They found that there was a clear preference for links to be made around the terminator times, thus providing statistical evidence that the terminator time was indeed preferred for propagation to be supported. An example figure summarising the UK to Australia propagation during the year 2017 is shown in Figure 12. Lo et al. (2022) also found some interesting results from ray-tracing through the International Reference Ionosphere (IRI) model that indicated that the paths were not necessarily traveling along the terminator even though they started and ended at it. They noted the preference for nighttime propagation where the absorption of the signals would be reduced.

The research in the PhD thesis of Lo (2022) provided some useful lessons about the use of WSPR data for scientific study of

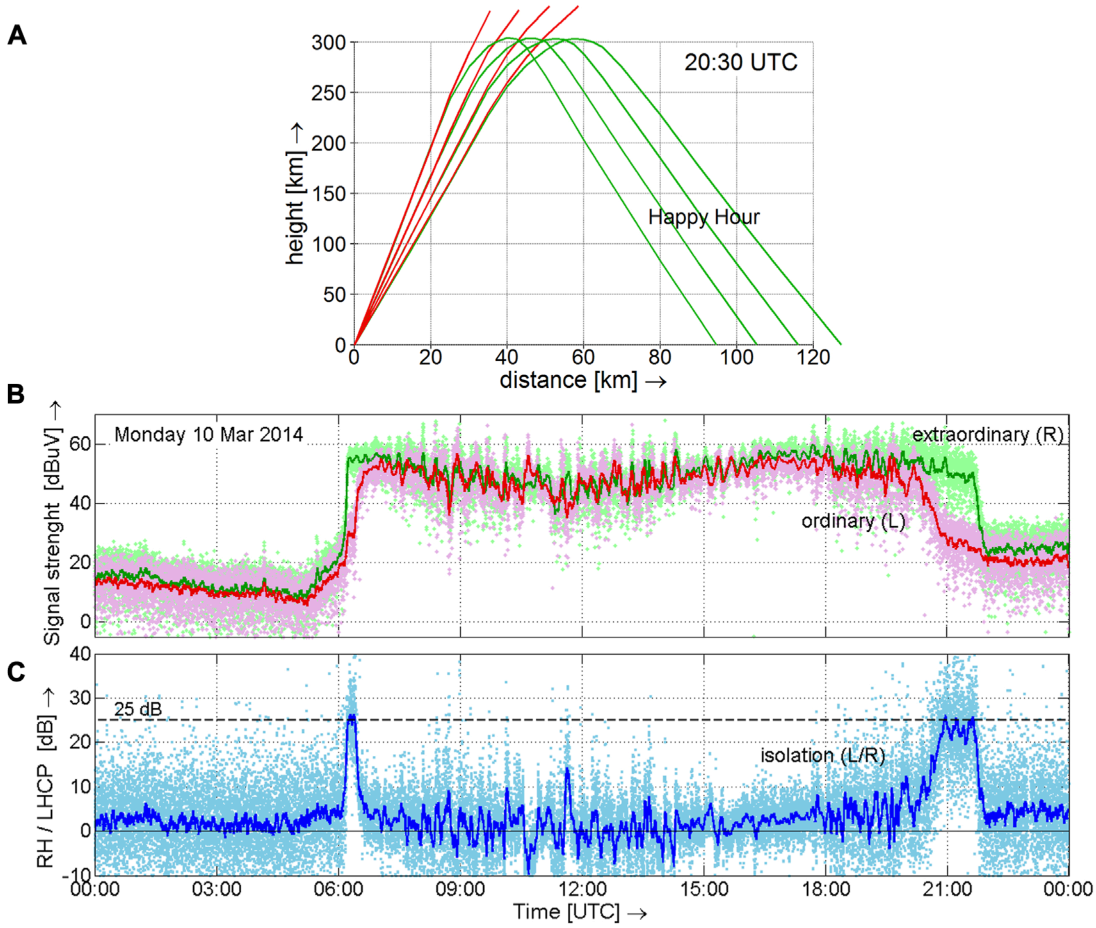

FIGURE 11
(A) During Happy Hour, an interval at sunrise and just after sunset, only the extraordinary wave propagates. This results in the reception of purely right-hand circular polarized waves (Northern hemisphere). **(B)** The measured signal strength of the two independently propagating characteristic waves and **(C)** the isolation between them. Local noon is 13:00 UTC. During Happy Hour, an interval at sunrise and just after sunset, only right-hand circular polarized waves (R) are received (Northern hemisphere). From Witvliet et al. (2015b).

the ionosphere. The first was that accurate observations to provide a realistic global specification of the ionosphere at a given time would be needed to allow high confidence in the use of ray-tracing to determine the full propagation path. Lo et al. (2022) suggests a number of ways that the amateur radio data itself could be used to improve models. Model electron density could be iteratively adjusted until a best fit to the observed propagation paths is found. This is similar to the non-linear inversion to fit oblique HF observations by Heitmann and Gardiner-Garden (2019) and Psiaki (2019). It is important to note that models such as the IRI are smoothed monthly medians and do not include plasma irregularities and small-scale structures. Using more advanced and realistic models may produce better results; additionally, the amateur observations may help to validate or constrain such models. While fitting a 3D model that includes such small-scale features is extremely challenging due to the large possible solution space, Mitchell et al. (2017) successfully demonstrated this in a localized region for TIDs using a Monte Carlo forward ray-trace approach to finding a best-fit to solve the inversion problem. With continued improvements to raw computational power, advancements in modeling techniques, and increased data quality and coverage, it is conceivable that this type of approach could eventually be extended to global scales in near-real time.

The second lesson is that the lack of a distinct local noise channel at the receiver sites hampered the separation of variations in the local noise pattern from that of the propagation reception - essentially a lack of reception of a signal could be either because its propagation was not supported or because the local noise was preventing a decoding of the WSPR signal. Therefore a resulting recommendation was to include a noise channel recording facility on WSPR receivers. The third recommendation was that a direction of arrival measurement at some receivers would be very beneficial with interpretations of the propagation paths. In particular for the super long-distance propagation there are multiple feasible paths that the signal can take to the antipode and these could be distinguished if there were angle of arrival (azimuthal) capabilities at some of the receiving sites.

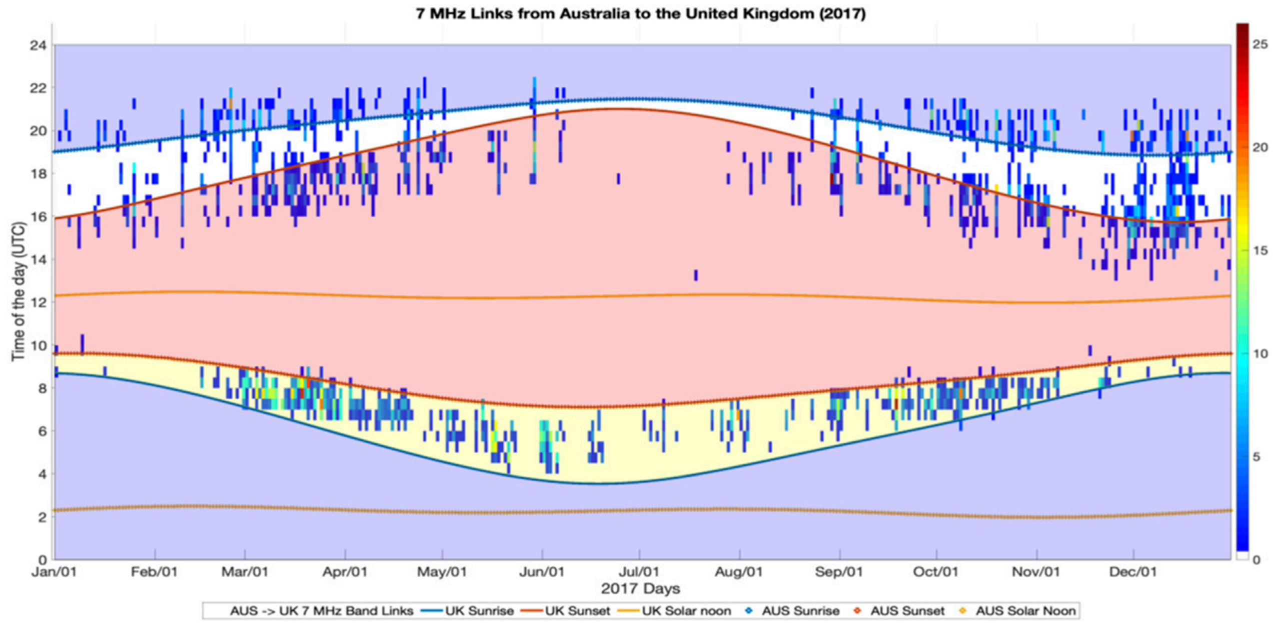

FIGURE 12
7 MHz radio links made from the UK to Australia in 2017. The blue shaded area is the Australian daytime hours. The red area is the UK daytime hours. The yellow shaded area is the common daytime hours, and the white shaded area is the common night hours. The colors indicate the number of links available in each half-hour interval. From Lo et al. (2022).

4.8 HamSCI personal space weather station observations

The HamSCI Personal Space Weather Station (PSWS) is a project to develop and deploy ground-based instruments capable of remote sensing the geospace environment in a form useable by citizen scientists (Collins et al., 2021; Frissell et al., 2021; Collins, 2023). The low-cost PSWS version (≲ US$300 for all hardware), known as the "Grape", is a low intermediate frequency (IF) receiver capable of making precision frequency measurements by mixing received HF signals with outputs from a GNSS Disciplined Oscillator (Gibbons et al., 2022). By measuring the Doppler shifts of signals emitted by high-stability transmitters such as US National Institute of Standards and Technology (NIST) standards stations WWV (Fort Collins, Colorado) and WWVH (Kekaha, Hawaii), or Canadian standards station CHU (Ottawa, Ontario), it is possible to measure ionospheric variability imparted on the received signal. The observed Doppler shifts may be attributed to changes in ionospheric peak layer height, peak layer electron density, and/or layer thickness that can cause changes in the propagation path. Positive Doppler shifts indicate decreasing path lengths (blueshifts), while negative Doppler shifts indicate increasing path lengths (redshifts) (Lynn, 2009). Frequency stability of WWV and WWVH was recently reviewed by Lombardi (2023) in the amateur radio journal *QST*.

Gibbons et al. (2022) describes the Grape Version 1 hardware, while Collins et al. (2023) describes the Grape data collection, processing, and presents examples. Figure 13 from Collins et al. (2023) shows almost 2 years (27 July 2020 through 30 May 2022) of Grape 10 MHz WWV observations received using a Grape Version 1 receiver located in Macedonia, Ohio (near Cleveland). Figure 13A shows a time series of Doppler shift measurements; Figure 13B shows a time series of received power measurements. Each column of pixels represents 1 day; solar mean time calculated for the midpoint between Fort Collins and Cleveland is shown on the *y*-axis. Positive Doppler shifts at dawn (blues) and negative Doppler shifts at dusk (reds) along with seasonal variations in the dawn/dusk times are clearly evident. A new antenna and preamplifier were installed on 26 August 2021, resulting in higher received power. Data is aggregated by the WWV Amateur Radio Club via FTP at the end of each UTC day.

Figure 14 (from Collins et al., 2023) shows the response of a network of Grape Personal Space Weather Stations to X-ray solar flares on 28 October 2021. The response is a Doppler "flash", similar to the signature observed by SuperDARN radars (Chakraborty et al., 2018; Chakraborty et al., 2021; Chakraborty et al., 2022). Figure 14A presents NOAA GOES-17 0.1–0.8 nm band X-ray flux measurements showing an X1 class flare at ~1535 UTC and a C4.9 class flare at ~1738 UTC. Figure 14B shows Grape Doppler shift and 14c shows Grape Doppler received power for a network of Grapes distributed across the continental US monitoring the 10 MHz WWV signal transmitted from Fort Collins, CO. The data from each Grape station is color-coded by longitude. Grapes show a sudden increase in Doppler shift for both flares and decrease in received power in response to the X1 flare. Station response varies with longitude, indicating propagation paths closer to the flare impact point observe a stronger response. The response to the X1 flare at 1535 UTC is quite large; but the Grape receivers are also sensitive to the orders-of-magnitude less powerful C4.9 class flare at 1738 UTC.

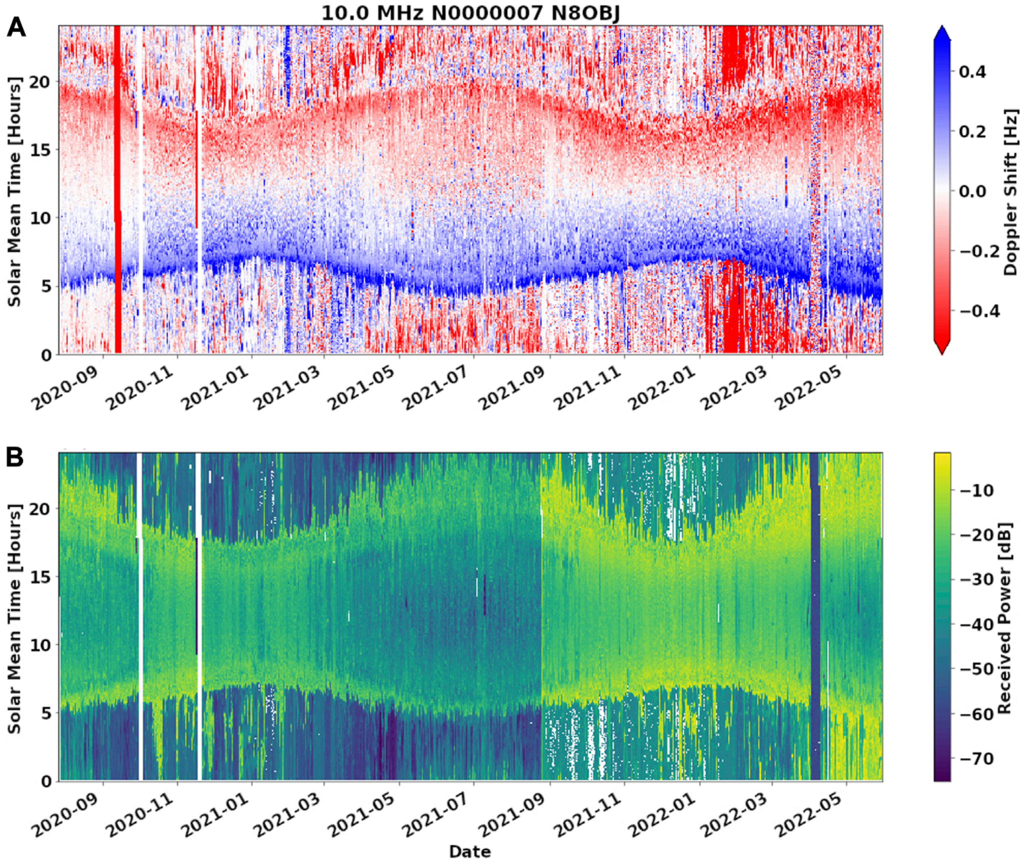

FIGURE 13
(A) Doppler shift and **(B)** Received power measurements of the 10 MHz signal produced by the WWV transmitter near Fort Collins, Colorado received with a Grape Version 1 Low-Cost Personal Space Weather Station located near Cleveland, Ohio for the period 27 July 2020 through 30 May 2022. Each column of pixels represents 1 day; solar mean time calculated for the midpoint between Fort Collins and Cleveland is shown on the *y*-axis. Positive Doppler shifts at dawn (blues) and negative Doppler shifts at dusk (reds) along with seasonal variations in the dawn/dusk times are clearly evident. A new antenna and preamplifier were installed on 26 August 2021, resulting in higher received power. From Collins et al. (2023).

In addition to the seasonal, dawn-dusk, and solar flare signatures demonstrated in Figure 13, Figure 14, Collins et al. (2023) also demonstrates that the Grapes are sensitive to MSTID-band ($15 < T < 60$ min) variability. Although the Grape Version 1 observations presented here track only a single frequency bin with time, newer versions of the Grape software can record at least 4 Hz of bandwidth around the WWV carrier allowing for multi-hop mode splitting and Doppler spread measurement.

5 Discussion

Here, we present the recommendations relating to amateur radio and heliophysics that were submitted to the U.S. National Academy of Science Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033. Section 5.1 presents the technical recommendations for advancing heliophysics proposed by Frissell et al. (2022b), while Section 5.2 presents the recommendations for fostering a collaborative relationship between the professional heliophysics and amateur radio communities. Proposed by Frissell et al. (2022a). We note that amateur radio citizen science also dovetails with other citizen science projects on aurora (MacDonald et al., 2015) and radio waves from Jupiter as well as other sources (Arnold, 2014; Fung et al., 2020). However making these connections requires effort to align data and communities. All of these topics could also be expanded and encouraged with satellite mission opportunities to do citizen science at a larger scale more akin to environmental projects like iNaturalist, as discussed by MacDonald et al. (2022) Decadal Survey White Paper, Science for all: The case for Citizen Science in all NASA missions.

5.1 Amateur radio and the advancement of heliophysics

5.1.1 Scientific advancements

Amateur radio and citizen science networks show great promise in addressing open questions within heliophysics, radio science, and space weather. Figure 3 shows how these networks can be used to measure the ionospheric impacts of solar flares and their direct effects on HF radio communications (Frissell et al.,

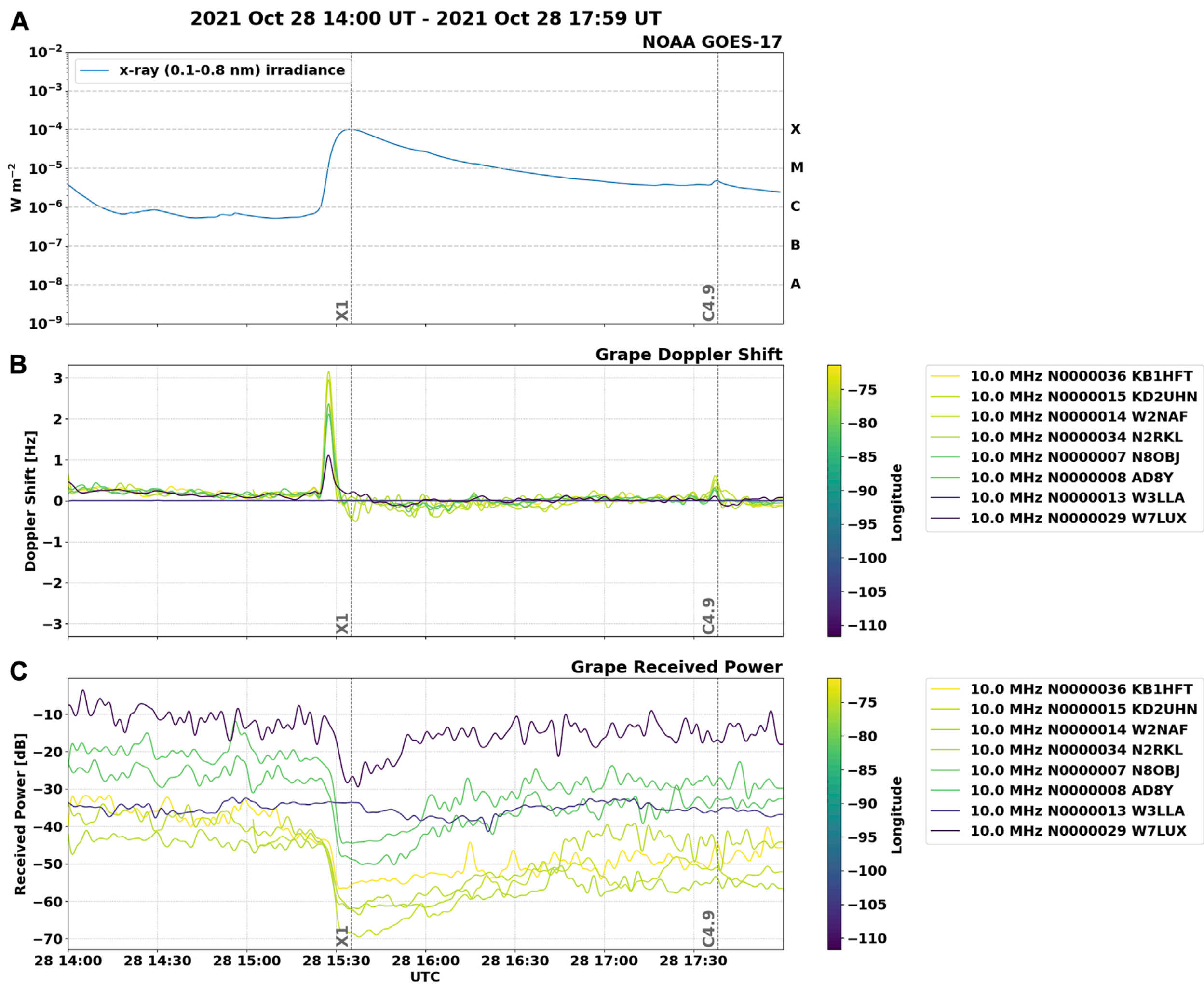

FIGURE 14
Response of a network of Grape Personal Space Weather Stations to X-ray solar flares on 28 October 2021. Grape stations shown are receiving the 10 MHz WWV signal transmitted from Fort Collins, CO and are color-coded by longitude. **(A)** NOAA GOES-17 0.1–0.8 nm band X-ray flux measurements showing an X1 class flare at ~1535 UTC and a C4.9 class flare at ~1738 UTC. **(B)** Time series of Grape 10 MHz Doppler shift measurements. **(C)** Time series of Grape 10 MHz received power measurements. Grapes show a sudden increase in Doppler shift and decrease in received power in response to both flares. Station response varies with longitude, indicating propagation paths closer to the flare impact point observe a stronger response. From Collins et al. (2023).

2019). Systems such as the RBN, WSPRNet, and PSKReporter can provide timing measurements of HF absorption and recovery relative to solar flare occurrence as a function of frequency and geographic location. Precision HF Doppler receivers such as the Grape (Section 3.2.1) can also provide measurements of flare-induced Sudden Frequency Deviation (SFD) and provide insights on the mechanism causing these deviations (Collins et al., 2023). In addition to these, amateurs are continuously developing novel approaches to making low-cost scientific measurements, such as the elevation angle of arrival system developed by Serra (2023). These measurements, especially when made over large geographic regions, can be used in conjunction with physics-based models such as WACCM-X (Liu et al., 2018) or TIME-GCM (Siskind et al., 2022) to address open questions about 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 (Chakraborty, 2021).

Figure 1, Figure 6 show 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., Hines, 1960; Bossert et al., 2022) or electrodynamic processes (e.g., Kelley, 2011; Atilaw et al., 2021) and can propagate large horizontal distances (even to the opposite hemisphere) (Zakharenkova et al., 2016). Advanced physics-based models such as SD-WACCM-X/SAMI3 (McDonald et al., 2015) and HIAMCM (Becker and Vadas, 2020) coupled with raytracing tools such as PHaRLAP (Cervera and Harris, 2014; Calderon, 2022) provide the ability to link TID observations with theoretical models. TIDs are 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. (2022) and Engelke et al. (2022), and the development of HF Doppler sounding techniques to determine TID parameters such as period, wavelength, and direction (Crowley and Rodrigues, 2012; Romanek et al., 2022) will undoubtedly advance TID understanding.

Mid-latitude Sporadic E, i.e., intermittently occurring patchy, thin layers (few kilometers thick) of enhanced ionization between ~90–130 km altitude (Haldoupis, 2011), continues to be an active interest area for both professionals and amateurs. Interesting propagation conditions that occur for amateur radio operators in the Very High Frequency (VHF, 30–300 MHz) and high HF bands remain unexplained, 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 formation of Sporadic E is unresolved. Wind shears play a role, but some dispute remains about how localized the shears need to be. Deacon et al. (2022a), Deacon et al. (2021) are working to identify and characterize Sporadic E patches with amateur radio data, and Bacon (2021) is developing a model for predicting Sporadic E and its effects on amateur radio propagation.

There are numerous additional scientific topics that can be advanced with amateur radio. Transequatorial propagation (TEP), first reported in *QST* by amateur Tilton (1947), is unusually long-distance radio propagation that occurs across the equator, particularly on the HF and VHF bands. TEP became an important subject of the early amateur-professional studies (Ferrell, 1951), including the ARRL-US Air Force Radio Propagation Project (Southworth, 1959; Southworth, 1960). Explanations include chordal hops between the equatorial ionospheric anomaly (EIA) enhancements and propagation off of the unique structures associated with Spread F and equatorial plasma bubbles (Nielson and Crochet, 1974; Flaherty et al., 1996; Maruyama and Kawamura, 2006). Because of TEP's sporadic nature and the requirement to have transmitters and receivers on opposite sides of the equator, it can be challenging to make observations that advance understanding of TEP and its underlying plasma dynamics. However, the long-term, multi-frequency, global observations of the RBN, PSKReporter, and WSPRNet are well suited for such studies.

Long delayed echos (LDEs) (Muldrew, 1979) in the 1–30 MHz range have regularly been heard since the first observations by an amateur in 1927. Størmer (1928) presented the first observations and this led to a 2-year test program with transmissions on 9.55 MHz from the Netherlands and where simultaneous observations of delays from 3 to 30 s were reported both there and in Norway. Vidmar and Crawford (1985) gives five likely explanations, but since the 1970s, the only mechanism that is well understood is ducting in the magnetosphere combined with ionospheric reflection, which only gives echos up to 0.5 s (Ellis and Goldstone, 1987; Martinez, 2007; Holm, 2009). The others are 2) travel many times around the world (Goodacre, 1980; Goodacre, 1980), 3) mode conversion involving coupling to mechanical waves in the ionosphere with delays up to tens of seconds (Crawford et al., 1970; Muldrew, 1979), 4) reflection from distant plasma clouds, 5) non-linearity in addition to mode conversion to account for observations at VHF and UHF.

Major advancements in instrumentation and modeling during recent decades provide compelling reasons to re-visit these LDE hypotheses using carefully designed professional-amateur campaigns. High-powered professional transmitters, such as HAARP, can provide signals that may trigger LDEs. The echos can then be received by GNSS-disciplined amateur radio receivers capable of making precision time and frequency measurements. These measurements, in conjunction with modern, high-resolution magnetospheric-ionospheric models to suggest where wave mode conversion may occur, provides a plausible path forward in understanding LDE generation.

5.1.2 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, 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) (PROSWIFT, 2020), has been formalized as the Space Weather Research-to-Operations and Operations-to-Research Framework (SWR2O2R, 2022). The amateur radio networks, which provide real-time and historical observations of actual communications systems, speak directly to this mandate. These systems can provide data for nowcasting, 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 (Akmaev et al., 2010). The amateur radio community and its measurements represent a yet-to-be activated asset for the validation and improvement of existing and future Space Weather operational products through their access 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.

5.1.3 Recommendations for advancing the technical capabilities of amateur radio in heliophysics

Amateur radio is being utilized in space physics and space weather in many ways. Existing networks built by the amateur radio community such as the RBN, PSKReporter, and WSPRNet and purpose-built networks and instrumentation such as the HamSCI Personal Space Weather Station provide global-scale data that can be used on its own or in conjunction with measurements from other instruments and model outputs to address open questions in heliophysics. Amateur radio data are available in near real-time and are from actual communications systems. Thus, they represent an important part of the R2O2R loop. To maximize the benefit of amateur radio capabilities for heliophysics, we recommend the following.

- 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 (Nelson et al., 2005), U.S. Navy chirp sounders (Headrick and Thomason, 1998; Bernhardt et al., 2017), CODAR oceanography radars (Kaeppler et al., 2022), and U.S. Navy VLF transmitters (Gross and Cohen, 2020; Richardson and Cohen, 2021).
- 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.
- Develop methods for continuous cross-calibration among instrumentation, both amateur and professional.
- 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.

5.2 Fostering collaborations with the amateur radio community

5.2.1 Driving co-design and collaboration in amateur radio science

To maximize broader impacts in the areas of learning and equity, Pandya and Dibner (2018) provide a comprehensive resource for the design of citizen science projects (*cf.* Section 5.2.2). HamSCI embraces a model of citizen science where volunteers are engaged in every stage of an investigation, from formulating questions to building tools and engaging in analysis. This co-design concept is critical for participant engagement, project success, making the best use of skills and talents, and ensuring the project benefits all involved. In these collaborations, all participants should be fully credited and have rights to use the materials and ideas they help develop. Open hardware (TAPR, 2022) and open software (GNU Project, 2022) licenses are used for all projects. HamSCI volunteers are encouraged to set up ORCIDs, use callsigns as FAIR identifiers (Stall et al., 2019), and are given co-authorship or acknowledgment in papers and presentations.

As discussed in Section 2.3 and Section 2.4, amateur radio operators have a powerful combination of advanced technical skills and strong avocational initiative. They are, thus, well-positioned to participate in hardware and software development. For instance, the NSF-funded HamSCI Personal Space Weather Station (PSWS) project is developing a network of novel ground-based instruments for ionospheric remote sensing that can be used by citizen scientists and professionals alike (Collins et al., 2021; Frissell et al., 2021; Gibbons et al., 2022). In developing the PSWS proposal, HamSCI joined with Tucson Amateur Packet Radio (TAPR, tapr.org), a volunteer amateur radio electrical engineering organization with a global presence and almost 40 years of experience.

5.2.2 Diversity, equity, and inclusion (DEI)

The current demographic landscape of the amateur radio community as well as the projected demographic changes in the United States present significant challenges and opportunities to increase diversity. Barriers to entry include exam and equipment costs, asymmetric mentorship opportunities, and a lack of support for some community newcomers. Demographic statistics are not readily available, but informal surveys (Thomas, 2019) and the authors' lived experience indicate that the population of active amateur radio operators is generally White, overwhelmingly male, and over the age of 55. Instances of implicit and explicit bias are common and expected for Black, Indigenous, and people of color (BIPOC), female, and LGBTQ + hams, leading to a "leaky pipeline" of talent within the hobby (Howell and Wright, 2021) and thereby reducing the pool of possible citizen science volunteers. It would seem that much of this bias is "baked in" to the hobby (Haring, 2003; Wills, 2021); however, it is also true that members of underrepresented groups were innovators in radio (Fikes, 2007; Blue, 2008) and that inclusion is as much a task of "remembering" as it is opening space. The ARRL has signaled willingness to address current Diversity, Equity, Inclusion (DEI) issues (Minster, 2022), but much more can and should be done.

Targeted efforts to include more women, young people, and underrepresented groups into the hobby will have an outsized impact. The benefits of these efforts will be twofold: they will introduce to the participants a valuable technical skillset, while simultaneously growing the ranks of amateur radio operators to keep the community strong and maintain open source, noncommercial access to the electromagnetic spectrum (EMS) for future generations. In short, increasing the ranks of amateurs will help the community maintain citizen access to the EMS natural resource.

To do this, the science community must leverage best practices in diversity, equity and inclusion, as well as proven educational practices tuned for minoritized communities. The authors recommend a three-prong strategy: supporting amateur radio organizations that welcome diverse cohorts in training and exams, encouraging the inclusion of amateur radio in existing STEAM curricula of formal and informal programs (Derickson et al., 2019) with strong DEI components, and working with demographically focused amateur clubs such as OMIK, Young Ladies Radio League, and Rainbow Amateur Radio Association, to help those underrepresented find supportive and sustaining communities in the hobby.

The authors acknowledge that long-term, substantive change—beyond tokenism—will be required to build sustainable, inclusive communities of radio amateurs and scientists. Fundamental shifts in the way scientists and amateur radio operators see themselves and how others see them are required. The question "what does a scientist or amateur radio operator look like?" needs answers that reflect the changing demographics of the US and the demographics of the world.

Further support may be needed to help amateur radio and scientific communities welcome minoritized people and help them hold space in the community. Amateur radio operators often struggle with the "Curse of Knowledge": a cognitive bias where an expert assumes something that they are intimately familiar with must be widely known and/or inherently easy (Weiman, 2007). Hams must remember that mentoring ("Elmering") in the form of open source education, "teaching to learn", and the ethos of sharing knowledge are part of being an amateur. Everyone comes with some knowledge or experience that they can contribute to the collective–indeed the cliché "the smartest person in the room is the room" is truism in the amateur radio community. The challenge for "more seasoned" hams working in DEI is to meet newcomers at their level of knowledge, and be willing and patient enough to help support these "new" cohorts in developing a "room" in which everyone increases their knowledge (Freire and Macedo, 2005).

5.2.3 Giving back to the amateur radio community

All amateur radio citizen science projects need to address research questions and advance the scientific field, but it is also crucially important that the projects also benefit the amateur radio community. It is important that project participants receive appropriate acknowledgment. This will often be in the form of co-authorship and/or acknowledgment in publications and presentations. They should also have the ability to retain intellectual property rights (at least in the open source sense) on ideas and designs. When data collection is involved, amateurs want feedback to know that their data has been received and is being used. Interviews with HamSCI participants indicate that web-based, real-time displays of participant data are an important way to provide this feedback. As new scientific discoveries are made or operational products are developed using amateur radio resources, those discoveries and products should be made available back to the amateur community in a way that is understandable and useful to them. Finally, it is important to listen to the amateur radio community to identify ways in which the scientific community can provide the greatest service to the amateurs.

5.2.4 Recommendations for Fostering Collaborations with the amateur radio community

- Provide funding resources for amateur radio-based citizen science projects. The amateur radio community is a highly technical, engaged community that has a proven track record of making substantial contributions to heliophysics science and technology. Support should be provided for collaborative amateur radio-professional research projects, infrastructure for the collection, storage, and distribution of citizen science datasets and analytical tools, conferences and workshops that bring professionals and amateurs together in-person and virtually, and personnel support to help manage these projects.
- Develop research and educational programs in collaboration with organizations already established in the amateur radio community. Many organizations, including the ARRL, TAPR, CQ Communications, Scouts, and HamSCI already have established means of engaging with the amateur radio community. By having citizen science projects collaborate with these groups, it is possible to broaden participation.
- Develop international collaborations to solve global-scale science problems. Heliophysics problems extend beyond the regulatory boundaries of the United States. Global scientific collaborations, coordinated with the help of the IARU and its member societies, should be established.
- Recognize volunteers as colleagues that have important skills and insight. Many amateurs have years of experience and/or advanced degrees in fields relevant to Heliophysics research. Volunteers that do not are highly enthusiastic and are willing to learn. Volunteers should be respected and treated collegially.
- Encourage attendance of amateur radio citizen scientists at professional conferences and provide funding for relationship building with and between communities. This can be done through direct support and citizen science related discounted registration. It would encourage skilled and vested amateurs to foster relationships with scientists in a professional venue and allow them to learn how scientific papers are written and presented.
- Ensure open access to publications and software. Requiring all publicly funded research to publish open access and encouraging the use of open source software for analysis will make research more accessible to citizen scientists.
- Provide citizen scientists with routes to peer-reviewed publication. Citizen scientists working on independent research projects may lack funding to cover publication fees or knowledge of how to properly analyze data and prepare a manuscript for a peer-reviewed journal. We recommend resources be allocated and policies be established to help citizen scientists clear these hurdles.
- Ensure that collaborations have a clear benefit to the scientific and amateur radio communities. All amateur radio citizen science projects need to address research questions and advance the scientific field, but it is also important that the projects also benefit the amateur radio community.
- Encourage growth and diversity, equity, and inclusion in the amateur radio community. Support amateur radio organizations to welcome diverse cohorts in training and exams, while also encouraging the inclusion of amateur radio in existing STEAM curricula with strong DEI components.

6 Summary

The amateur radio community is a global, highly engaged, and technical community with an intense interest in space weather, its underlying physics, and how it impacts radio communications. The large-scale observational capabilities of distributed instrumentation fielded by amateur radio operators and radio science enthusiasts offers a tremendous opportunity to advance the fields of heliophysics, radio science, and space weather. Well-established amateur radio networks like the RBN, WSPRNet, and PSKReporter already provide rich, ever-growing, long-term data of bottomside ionospheric observations. Up-and-coming purpose-built citizen science networks, and their associated novel instruments, offer opportunities for citizen scientists, professional researchers, and industry to field networks for specific science questions and operational needs.

In this paper, we discussed the scientific and technical capabilities of the global amateur radio community, reviewed methods of collaboration between the amateur radio and professional scientific communities, and summarized recent peer-reviewed studies that have made use of amateur radio data and methods. Finally, we presented recommendations submitted to the U.S. National Academy of Science Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 for using amateur radio to further advance heliophysics and for fostering deeper collaborations between the professional science and amateur radio communities. Technical recommendations include increasing support for distributed instrumentation fielded by amateur radio operators and citizen scientists, developing novel transmissions of RF signals that can be used in citizen science experiments, developing new amateur radio modes that simultaneously allow for communications and ionospheric sounding, and formally incorporating the amateur radio community and its observational assets into the Space Weather R2O2R framework. Collaborative recommendations include allocating resources for amateur radio citizen science research projects and activities, developing amateur radio research and educational activities in collaboration with leading organizations within the amateur radio community, facilitating communication and collegiality between professional researchers and amateurs, ensuring that proposed projects are of a mutual benefit to both the professional research and amateur radio communities, and working towards diverse, equitable, and inclusive communities.

Author contributions

NAF is the primary author of this paper. CD, GWP, SL, CM, BAW, LE, and KVC contributed sections to the paper. Substantial editing and comments were provided by RMF, MLW, and RBG. All other authors are active members of the HamSCI, TAPR, and/or Aurorasaurus projects and have contributed through contributing to instrument design and engineering, experiment design, data collection and analysis, and editing of the paper. All authors contributed to the article and approved the submitted version.

Funding

NAF acknowledges the generous support of NSF Grants AGS-2045755, AGS-2002278, AGS-1932997, AGS-1932972, AGS-2230345 and AGS-2230346, NASA Grants 80NSSC23K1322 and 80NSSC21K1772 and Amateur Radio Digital Communications (ARDC). VEF is supported by NSF Graduate Research Fellowship grant 2235201. KVC is supported by NSF grant ANT-2218996. BAW was funded by INFRAIA-02-2020, grant number 101007599, as part of the project "Plasmasphere Ionosphere Thermosphere Integrated Research Environment and Access services: A Network of Research Facilities (PITHIA-NRF)," (https://www.pithia-nrf.eu/). The Ham Radio Project (JNA/NRAO) is supported through a generous grant from ARDC. We also thank the American Radio Relay League (ARRL) for donating license manuals and other learning materials and acknowledge the Tuscon Amateur Packet Radio and the Young Amateurs Radio Club for their administrative and technical support.

Conflict of interest

WL is employed by Liles Innovations, LLC. EM is employed by STR. TD is employed by DX Engineering.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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