Astro2020 APC White Paper

Spectrum Management: A State of the Profession White Paper

Type of Activity: ☐ Ground Based Project ☐ Space Based Project
☐ Infrastructure Activity ☐ Technological Development Activity
☒ State of the Profession Consideration ☐ Other

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Abstract (optional):

This Astro2020 APC white paper addresses state of the profession considerations regarding spectrum management for the protection of radio astronomy observations. Given the increasing commercial demand for radio spectrum, and the high monetary value associated with such use, innovative approaches to spectrum management will be necessary to ensure the scientific capabilities of current and future radio telescopes. Key aspects include development of methods, in both hardware and software, to improve mitigation and excision of radio frequency interference (RFI). In addition, innovative approaches to radio regulations and coordination between observatories and commercial applications (including satellites) have the potential to expand protections for radio astronomy sites. However, implementation of effective spectrum policy requires a scientific work force that is trained in both astronomical techniques and spectrum management. Budgets for current and future radio astronomy facilities should include funding for technology development related to RFI mitigation and excision and for personnel to engage in national and international radio regulatory processes, including training future generations of spectrum managers. It is also important that all evaluations of project feasibility for Astro2020 include an understanding and evaluation of the spectrum requirements for successful completion.

Introduction: The Value of Spectrum Management for Radio Astronomy

Radio astronomers are engaged actively in spectrum management activities in order to ensure access to the radio spectrum for scientific uses. Radio astronomy was born in the 1930s, out of Karl Jansky's effort at Bell Labs (commissioned by AT&T) to identify the origin of radio frequency interference (RFI) to transatlantic short-wave communications. The science progressed rapidly after the end of World War II, with the availability of new electronic technology and events such as the detection of the HI line by Ewen and Purcell, in 1950. Efforts to protect radio astronomy observatories from RFI commenced shortly after these developments. It was soon recognized that in order to be successful, protection efforts required the participation of radio astronomers in the national and international regulatory bodies set up for the management of the radio spectrum. Jan Oort, as the President of the International Astronomical Union (IAU), emphasized the need for astronomers to attend the meetings of the International Telecommunication Union (ITU). Oort himself addressed the 1959 Administrative Radio Conference (ARC), requesting frequency allocations of transmission-free passive bands for radio astronomy. He said that: "In order to go forward we need absolute quiet, but only in a few narrow bands." At Oort's behest, the Inter-Union Committee for the Allocation of Frequencies (IUCAF) was set up under the umbrella of the International Council of Scientific Unions (ICSU). In the United States, at the urging of Bernie Burke, the National Science Foundation (NSF) Radio Spectrum Management Office was established, following the creation of the National Radio Astronomy Observatory (NRAO). The Committee on Radio Frequencies (CORF) of the National Academy of Sciences was established in the early sixties. Two relatively recent reports by the National Academy of Sciences summarize the current status of scientific use of the radio spectrum and approaches to spectrum management and RFI mitigation and excision for passive (receive-only) scientific applications: *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses*[1] and *Spectrum Management for Science in the 21st Century.*[2]

Early protection efforts were directed to limiting interference to single dish radio telescopes by fixed and mobile transmitters operating at frequencies up to a few hundred MHz. Beginning in the mid-1960s, with the advent of artificial satellites, protection efforts began to be directed to minimize RFI by geostationary satellites that blocked access to the sky at some frequencies in a belt centered on the geostationary orbit. After the launch of the first GLONASS satellites, efforts shifted increasingly towards limiting the impact of non-geostationary satellite (NGSO) systems, particularly those larger systems that blocked access to the radio sky for large fractions of the time and at particular frequencies of interest, such as the OH lines near 1610 and 1660 MHz or the redshifted HI line below 1400 MHz. At the same time, technological

[1] National Academies of Sciences, Engineering, and Medicine. 2015. *Handbook of Frequency Allocations and Spectrum Protection for Scientific Uses: Second Edition*. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/21774/handbook-of-frequency-allocations-and-spectrum-protection-for-scientific-uses

[2] National Research Council. 2010. *Spectrum Management for Science in the 21st Century*. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/12800/spectrum-management-for-science-in-the-21st-century

progress, stimulated in part by the need of satellites to operate in the most transparent portion of the atmosphere, made radio observations vulnerable at frequencies up to ~ 20 GHz.

During the past three decades, mass market devices that require only type licensing, and may be easily carried everywhere, became the new threat to radio astronomy. An example of this type of device is the variety of vehicular radars now being installed in most cars, which are a valuable safety feature but have the potential to impact radio astronomy observations negatively.[3] Once again, this development was simultaneous with the march of radio technology towards higher frequencies; vehicular radars operate at ~ 76 GHz and it is expected that unlicensed devices will be operating soon at even higher frequencies (c.f., *FCC's Spectrum Horizons Report and Order*[4]). As another example, smartphones were introduced in the mid-1990s with the ability to provide a wealth of information at any time. The pressing desire for greater bandwidths and improved coverage for these increasingly ubiquitous phones has pressured the Federal Communications Commission (FCC) to increase the frequency allocations to mobile devices. Current 4G networks operate between 600 MHz and 6 GHz. The next generation of 5G networks will extend this to 24-86 GHz and also place even greater demand on frequencies below 6 GHz. Left unchecked, clever engineering approaches to mobile communications could eliminate wide swaths of frequency for any other use. Still more recently, proposals have been made to provide internet and related services by non-geostationary-satellite systems that are comprised of thousands of satellites (c.f., Starlink,[5] OneWeb,[6] Telesat,[7] and other similar constellations). Such systems would, in all likelihood, make the sky inaccessible not only in portions of the radio spectrum, but could interfere with optical observations as well.

Spectrum management for the benefit of radio astronomy has been, and continues to be, carried out by a relatively small number of members of the community. Some of the notable successes achieved over the approximately 60 years of spectrum management efforts for radio astronomy include:

- Allocation of approximately 2% of the spectrum below 50 GHz for exclusive passive (receive-only) uses;
- Defining protection criteria for passive and primary radio astronomy bands from 13 MHz to 275 GHz;
- Rearrangement of spectrum allocations between 70 GHz and 275 GHz for the benefit of radio astronomy and remote sensing;
- Development of Memoranda of Understanding to notify astronomers of the L3 signal calibrations near 1380 MHz;[8]

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[3] https://library.nrao.edu/public/memos/edtn/EDTN_219.pdf
[4] https://www.fcc.gov/document/fcc-opens-spectrum-horizons-new-services-technologies-0
[5] https://www.fcc.gov/document/fcc-authorizes-spacex-provide-broadband-satellite-services
[6] https://www.fcc.gov/document/fcc-grants-oneweb-us-access-broadband-satellite-constellation
[7] https://www.fcc.gov/document/fcc-grants-market-access-telesat-canada-ngso-constellation
[8] The L3 signal of GPS is used for the notification of the detection of nuclear explosions around the planet. Calibrations of this system are performed periodically by the US Air Force. The MOU assures notification of

- Agreement with the GLONASS Administration to limit emissions of that system to below the frequencies of interest to radio astronomers;
- Establishment of the National Radio Quiet Zone (NRQZ) for the protection of Green Bank Observatory and the Puerto Rico Coordination Zone for the protection of Arecibo Observatory;
- Organization of several successful summer schools of spectrum management for radio astronomers.

These achievements, and others, are critical to maintain relatively interference-free access to the radio spectrum, as is required for astronomical observations of faint cosmic sources. However, radio frequency interference is likely to increase during the next decade, even into frequency bands currently allocated as passive use-only, as technological advances make radio frequency technology not only common-place, but an integral component of day-to-day life for many people in the United States. To protect the future of radio astronomy, the astronomical community must not only work to protect the frequency bands allocated to radio astronomy, but also enhance and develop innovative approaches both to RFI excision and to effective sharing of the radio spectrum that will enable astronomical observations for frequencies up to 3 THz.

Key Issue and Overview of Impact on the Field: Current Challenges for Spectrum Management

Current spectrum allocations for the Radio Astronomy Service (RAS) are designed to protect small spectral regions deemed essential for specific spectral line transitions, such as the 21 cm spin flip of neutral hydrogen, or to sample radio continuum at approximately octave separations (see, *FCC Table of Frequency Allocations*[9]). However, the recent development of broad bandwidth receivers enables astronomers to observe well outside of these protected bands on a regular basis. Science drivers for these broadband observations include both increased sensitivity for continuum observations and the red-shifting of spectral lines associated with the expansion of the Universe. Indeed, one of the key design goals for the Jansky Very Large Array was to provide access to nearly continuous spectral coverage from 1 – 50 GHz. Future spectrum policy must take into account both the need to protect existing passive-only spectral bands and also the ability to obtain data in non-protected bands, as the science requires.

Additional challenges for spectrum allocations are faced by new technology developments at 20 GHz and above. To enable further commercial use of such high frequencies, the Federal Communications Commission (FCC) has initiated two major initiatives to allocate high frequency spectrum for commercial uses: Spectrum Frontiers[10] (Above 24 GHz) and Spectrum

astronomical observatories of the schedule for this transmission, as it is a significant source of radio frequency interference.

[9] https://transition.fcc.gov/oet/spectrum/table/fcctable.pdf

[10] https://www.fcc.gov/document/spectrum-frontiers-ro-and-fnprm

Horizons[11] (Above 95 GHz). One concern for these high frequency bands is that new commercial applications will result in increasing radio frequency interference, from out-of-band and spurious emissions, or from in-band emissions. Indeed, just this year, in the *Spectrum Horizons Report & Order*, the FCC authorized requests for experimental licenses using any frequency between 95 GHz to 3 THz. While there is currently a stipulation that any applicants that propose to use spectrum allocated exclusively for passive use(s) in this frequency range must provide an explanation for why nearby bands are not adequate, this stipulation provides only a modest response to the concerns of radio astronomy. Indeed, at the same time, commercial interests[12] are urging the FCC, at these higher frequencies, to remove the existing protections provided by footnote US 246 to the *US Table of Frequency Allocations*, which states that "No station shall be authorized to transmit in the following bands:" The list includes high frequency bands appropriate for observations of CO, CN, SO, NO, H_2CO, CS, and other complex organic molecules in our Galaxy. Should the FCC decide to follow through with this recommendation, millimeter-wave radio telescopes in the United States are likely to experience higher rates of radio frequency interference even in bands allocated specifically to radio astronomy.[13] Of particular concern is that unlike the microwave allocations, where radio astronomy is allocated only a small percentage of the spectrum (radio astronomy has co-primary allocations for only 1.65% of the spectrum below 11 GHz and frequency bands protected by footnote US 246 are only 0.75% of the spectrum below 11 GHz), 65% of the frequency range between 94 – 275 GHz is allocated to radio astronomy on a co-primary basis (18.4% of this frequency range is protected by footnote US 246). Given the high monetary value of spectrum for commercial uses, it is likely that there will be additional pressure to reconsider spectrum allocations as ultrawide-bandwidth applications are developed in these frequency ranges. Furthermore, since radio frequency devices developed in the United States are likely to proliferate internationally (and vice-versa), our international assets, such as the Atacama Large Millimeter/submillimeter Array (ALMA) will be at risk as well.

As mentioned above, the new generation of NGSO satellite constellations also provides a challenge for spectrum policy, as traditional coordination agreements become more complex with thousands of satellites in each constellation and multiple satellites above the radio horizon at all times. Not only are there concerns about the direct transmissions of these satellites downwards (into radio astronomy receivers), but leakage from transmission between satellites in the constellation (for example, for communication between satellites to maintain their orbital configuration) may introduce additional radio frequency interference when the satellites pass within the beam or sidelobe of a radio telescope. As the next generation of satellite

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[11] https://www.fcc.gov/document/fcc-opens-spectrum-horizons-new-services-technologies-0

[12] See, e.g., https://ecfsapi.fcc.gov/file/10305742817568/mmWC%20FCC%20Comments%20on%20Draft%20R%26O%20FINAL.pdf

[13] Notably, it is difficult to justify implementation of nation-wide regulations and restrictions when only a few geographic locations have radio telescopes capable of astronomical observations in these frequency bands. The recent closure of several millimeter-wave radio telescopes in the United States may be perceived as further weakening the justification for national protection of these high frequency radio astronomy allocations, as even fewer sites are now operating at these frequencies.

constellations are likely to increase the number of objects in orbit around Earth exponentially, probably to tens of thousands of satellites, the likelihood of a satellite crossing through a radio telescope field-of-view while actively transmitting will also increase. Furthermore, while coordination of dedicated transmission-free times for geographical areas around radio observatories may provide adequate protection in some cases, such arrangements have traditionally required sufficiently long lead time as to be of little use for transient phenomena, recent discoveries, or other rapid-response proposals. Developing coordination agreements that meet the needs of both the satellite operators and radio astronomy observatories will be a challenge in the coming decade.

Mobile phones, the internet of things (IoT), smart roads,[14] and any future digital technology that requires communication between multiple devices are all possible sources of radio frequency interference for radio astronomy observatories. Furthermore, while individual devices may be low power, the proliferation of electronic devices means that their emissions in the aggregate may exceed the requirements for radio astronomy observations. At the present time, there are almost no regulatory approaches that appropriately account for the aggregate interference of unlicensed devices. Further, while it is impossible to predict the future, recent experience with vehicular radars, which are now common-place and leading to the self-driving automobile revolution, suggests that the number and utility of radio frequency emitting devices will continue to increase rapidly, and the feasibility of excluding RF-emitting devices from the vicinity or even the grounds of radio observatories will become more challenging as these devices become integrated into everyday life. Specifically, vehicle technologies as well as mobile communication devices, unlike many RFI sources, are not confined to urban areas and can be very easily brought near a radio observatory by someone completely unfamiliar with spectrum management or coordination agreements. As is the case with vehicular radars, if these devices have the potential to reduce the number of accidental deaths, traditional modes of geographic exclusion may no longer be possible to protect radio astronomy facilities. Careful consideration of radio quiet zones and the implications regarding safety-of-life innovations will be necessary as this technology develops and spreads throughout the United States during the next decade.

Strategic Plan: Spectrum Management for the Future

Effective implementation of spectrum policy is critical to the success of radio astronomy during the next decade. At the most basic level, maintaining existing national and international radio regulations that provide protections for narrow spectral regions throughout the radio spectrum is a cornerstone of spectrum management for radio astronomy, as these regulations are what gives the radio astronomy service a crucial seat at the table during international discussions of spectrum management and frequency allocation. Existing regulations include established radio quiet zones (e.g., the National Radio Quiet Zone around Green Bank Observatory); future spectrum management solutions may include updated and expanded quiet zones for dynamic

[14] http://integratedroadways.com

coordination at these and additional observatory sites. In addition, developing coordination agreements between commercial applications (including satellites) and radio observatories is a critical step toward protecting radio astronomy receivers from direct transmissions that not only corrupt observations but could also damage equipment. Active participation by the radio astronomy community at both the national and international level are required to maintain these existing protections.

Currently, the NSF Electromagnetic Spectrum Management (ESM) staff, the National Academies' Committee on Radio Frequencies (CORF), and the NRAO spectrum manager are active participants in various national and international spectrum management activities. In addition, every radio astronomy facility monitors its own RFI environment and attempts to identify (and remove) sources of interference. This small cadre of spectrum-interested astronomers and engineers has been effective at protecting current radio astronomy facilities through both radio regulations and coordination agreements, nationally and internationally. However, one potential concern for the future of spectrum management is that there are only a small number of radio astronomers that have both the technical and policy training needed to continue this work.

Increasing the number of astronomers that can actively and effectively advocate for scientific use of the radio spectrum is a crucial step towards protecting current and future radio astronomy facilities from incapacitating levels of radio frequency interference. Spectrum management training can take the form of professional development workshops, service on existing committees, such as CORF, or temporary appointments as NSF-rotators assigned to the ESM group. Expanding the number of radio astronomers with expertise in both astronomy and spectrum policy will increase the number of advocates for passive use of the radio spectrum and, most importantly, provide strong scientific justification for continued protection of the frequency bands allocated to radio astronomy. Furthermore, ensuring and demonstrating that spectrum management is an attractive career path for newly-minted radio astronomers provides the possibility of seeding the FCC and other government agencies with technically trained spectrum managers with radio astronomy backgrounds.

New approaches to spectrum management are also necessary to protect the interests of radio astronomy and to maximize the scientific potential of current and future radio observatories. Specifically, while broad bandwidth observations are becoming routine, the radio spectrum is increasingly becoming more crowded. There are three approaches to opening up more spectrum for observation: (1) developing hardware and software approaches to mitigate RFI, (2) developing hardware or software for effective RFI excision, and (3) dynamic frequency coordination between radio facilities and commercial applications. The first method, RFI mitigation, involves methods such as steering a null in the telescope response toward the location(s) of RFI, or measuring the RFI signal characteristics and removing them from the observations. However, these methods may not be practical for a given telescope.

For the second approach, effective RFI excision requires both software to identify unnatural signals and also sufficient time- and frequency- sampling of the data such that removal of short-duration bursts of narrow frequency emission do not degrade the observations significantly. Thus, enabling effective RFI excision may require more time- and spectral- resolution than required based on astronomical considerations alone and will likely increase the required data rate and, therefore, data storage requirements for all such observations. Nonetheless, the technological challenges for such RFI excision are well within the expected development trends for data recording and storage over the next decade. More challenging, however, is the development of software that can accurately identify and remove pernicious low-level radio frequency interference that can subtly corrupt the observational data.

For the third approach, coordinated times of radio quiet are the most effective method to achieve relatively interference-free observations. Dynamic frequency allocations and coordination between radio observatories and commercial applications provide a new approach to spectrum management. For example, in their recent Notice of Proposed Rulemaking on Unlicensed Use of the 6 GHz Band,[15] the FCC proposed use of automated frequency coordination for all outdoor and some indoor devices at 6.525-6.687 GHz (amongst others), which would potentially enable coordination between radio observatories conducting observations of the methanol line (rest frequency at 6.668 GHz) and unlicensed devices within the local geographic region such that their transmissions would be shifted to a frequency not in conflict with the astronomical observations.[16] Given the remote, low population-density, location of most radio astronomy sites, this localized coordination, both geographic and temporal, enables efficient spectrum sharing and maximizes the scientific capabilities of the radio telescope while having minimal effect on the commercial application. Dynamic spectrum assignment has the potential to significantly reduce the instances of radio frequency interference and has the potential to open new frequency bands for time-shared use by radio astronomers, but requires the capability of coordination, through similar software/technology as the automated frequency coordination proposed by the FCC for 6 GHz unlicensed devices. While this may seem, at first glance, to put the burden on radio astronomy facilities, it is even more likely that large swaths of the radio spectrum will be entirely lost if dynamic spectrum sharing is not implemented. Thus, while implementation of such dynamic spectrum assignment throughout the radio spectrum will be a challenge, doing so will improve significantly the scientific capabilities of future radio facilities, such as the Next Generation Very Large Array (ngVLA).

In addition to active coordination agreements for satellite transmissions, one of the future challenges for radio astronomy will be conducting observations while multiple satellites that are RFI threats are above the radio horizon. In the future, orbit tracking and avoidance calculations may be required as part of all observatory scheduling software to prevent radio telescopes from pointing toward satellites with transmission strengths potentially high enough to damage sensitive radio astronomy instruments. Dynamic scheduling to minimize direct

[15] https://www.fcc.gov/document/fcc-proposes-more-spectrum-unlicensed-use-0
[16] See CORF's Comments on the FCC's 6 GHz Unlicensed Devices NPRM: https://ecfsapi.fcc.gov/file/10214821727667/01284111.PDF

observations of satellites may require additional consideration of effective observing modes at radio facilities and innovative approaches to spectrum allocations.

Given the considerations above, it is important that all evaluations of project feasibility for Astro2020 include an understanding of the spectrum requirements for successful completion. For example, all space-based projects will require both uplinks (to point the telescope) and downlinks (to retrieve data products). Even if the plan is to use existing frequency allocations for space-based projects, data rates and band congestion must be considered. For ground-based radio astronomy projects, consideration of spectrum access – are the planned frequency bands currently protected or are there realistic approaches to arrange coordination agreements to create access on a time-shared basis – must be factored into the evaluation. While radio astronomers can always attempt to observe at frequencies allocated to other services, and some compelling science cases require such observations, there must be an appropriate plan in place to ensure that the observations will be obtained with a noise level consistent with the science goals based not only on telescope design but also the expected level of radio frequency interference. Overall, it is critical for radio astronomers to understand whether they have any frequency protection for the proposed science, and if they do not, to find ways to advocate for the protection they need.

Recommendations

In summary, implementation of effective spectrum policy requires a scientific work force that is trained in both astronomical techniques and spectrum management. During the next decade, professional development of the next generation of spectrum managers is at a critical point both here in the United States and internationally, as many of the current cadre of spectrum managers are reaching retirement age. Spectrum management workshops for radio astronomers and RFI excision workshops may help achieve this goal; another possibility is to create opportunities for members of the astronomical community to second active spectrum managers to develop expertise in spectrum policy and procedures (such as rotator positions in the NSF Spectrum Management group or temporary appointments as additional spectrum managers at radio observatories). In addition, to protect the future of radio astronomy, current and future radio astronomy observatory budgets must include sufficient funding to support spectrum management at both the local level and to enable participation in the national and international regulatory process. Such budgets are non-negligible, as the effort required to resolve complex regulatory issues requires the time and dedication of multiple personnel, sometimes including those with legal training, and potentially extensive travel to participate in international regulatory processes.

In addition, innovative approaches to spectrum management, such as dynamic spectrum assignment in newly created coordination zones, and funding for investigations into interference mitigation and excision techniques will be necessary during the next decade to enable astronomical observations over the wide bandwidths that are required for observations of faint radio continuum sources and for redshifted spectral lines. Development of RFI excision hardware and software and standardization of observational procedures with sufficient time- and frequency- sampling, such that short duration bursts of radio frequency interference can be identified and removed, will increase the capabilities of radio observatories. Furthermore, with the proliferation and globalization of radio frequency emitting technology, spectrum management efforts should also include cultivation and maintenance of relationships with organizations, manufacturers, and other interests, for the purpose of addressing and removing emissions for licensed and unlicensed devices that malfunction, or were improperly designed or produced, as well as for illegal transmitters. While radio astronomy has benefited from effective spectrum management in the past, continued vigilance and innovative approaches are critical to enable effective sharing and future access to the radio spectrum for scientific uses.