ADDRESSING RADIO FREQUENCY INTERFERENCE

POLICY OPTIONS FOR THE FEDERAL COMMUNICATIONS COMMISSION

Applied Policy Project Final Report

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Glossary: Acronyms and Abbreviations

AAS:	American Astronomical Society
CBRS:	Citizens Broadband Radio Service
FAA:	Federal Aviation Administration
FCC:	Federal Communications Commission
GBT/GBO:	Green Bank Telescope/Observatory
ITU:	International Telecommunications Union
NOAA:	National Oceanic & Atmospheric Administration
NRAO:	National Radio Astronomy Observatory
NRQZ:	National Radio Quiet Zone
OET:	Office of Engineering and Technology (subsidiary of FCC)
RFI:	Radio-Frequency Interference
VLA:	Very Large Array
VLBA:	Very Long Baseline Array

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Disclaimer

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Honor Pledge

On my honor as a student of the University of Virginia, I have neither given nor received unauthorized aid on this assignment.

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Paul A. Cederoth April 7, 2022

Executive Summary

The electromagnetic spectrum is becoming overcrowded due to exponentially growing demand and outdated management practices.

Human beings use the spectrum for all forms of wireless communication, including Wi-Fi, AM and FM radio, and cellular telephony. However, growth in the number and variety of devices using this spectrum is starting to strain its limited space. As devices crowd onto specific areas of spectrum, they start to interfere with each other. This has caused devices as diverse as radio telescopes, airplane altimeters, and weather satellites to cease functioning properly.

The agency best equipped to address this problem is the Federal Communications Commission (FCC), which manages the use of spectrum and broadcasting more broadly across the United States. Therefore, this report identifies the following three potential policy options specifically for FCC:

1. Implement Dynamic Spectrum Sharing

2. Protect and Support American Radio Astronomy Installations

3. Increase Spectrum Allocations to Passive Services

Each alternative is evaluated according to its performance under the following criteria: (1) Cost-Effectiveness; (2) Equity; (3) Political Feasibility; and (4) Ease of Implementation. Based on this analysis, this report recommends FCC pursue Alternative 1: Implement Dynamic Spectrum Sharing due to its strong cost-effectiveness, equitable effects, and high political feasibility. By pursuing this alternative, FCC can ensure a sustainable and technology-friendly future for the electromagnetifc spectrum. Spectrum sharing allows passive radio services to continue accessing parts of the spectrum not strictly allocated to them without destructive interference while maintaining strong growth from other services.

The Problem: Electromagnetic Interference

There is too much terrestrial radio-frequency interference (RFI) on the electromagnetic spectrum.

Every device that wirelessly connects to the Internet, or which communicates with other devices via Bluetooth, or which sends a wireless transmission of nearly any kind, makes use of the electromagnetic spectrum. At a certain range of frequencies, electromagnetic waves are very effective at transmitting information across space rapidly. One of the most commonly-used ranges is the radio frequency range, and it is where the vast bulk of wireless communication takes place (examples include cellular telephones, car radios, satellites, and even remote garage-door openers).

As technological development spreads and accelerates, demand for devices that utilize the electromagnetic spectrum is growing at a rate of roughly 15% per year (ReportLinker, 2020). However, space on the radio range of the spectrum is limited, leading to increased competition and scarcity. All devices that use electromagnetic waves have a certain range where they are intended to broadcast. Like water spilling out of a pitcher that is poured too fast, however, these devices often emit waves that "spill" into other frequency ranges. Such events cause electromagnetic interference, and they can also take place when too many devices are using the same range at the same location simultaneously. When such interference occurs on the radio range, it called "Radio-Frequency Interference," or RFI.

Due to the very large number of devices broadcasting at all times globally, RFI is nearly ubiquitous on Earth. This causes a certain level of data loss on many devices, but generally not enough to hinder performance of the device. However, when the radio receiver encountering the interference is particularly sensitive, or the interference in question is very strong, massive data loss and even physical damage to the receiver can occur. Such interference generates significant direct costs to industries and individuals, and generates additional costs in the form of externalities and wasted time.

The government body best suited to address this problem is the Federal Communications Commission (FCC). This analysis, developed for the American Astronomical Society (AAS), will present three viable policy alternatives that FCC may choose to undertake to limit the impact of RFI on radio astronomy and the other passive services. Such policy steps would also benefit meteorology and aviation, two other industries heavily impacted by RFI, so their situation is also discussed here.

Client Overview: The American Astronomical Society

The American Astronomical Society, founded in 1899, represents the interests of all professionals involved with astronomy in any substantial way, including geologists, physicists, and others. It facilitates the sharing of resources between astronomy professionals, organizes conferences on astronomical issues, and manages several scholarly publications (AAS, "About the AAS," n.d.). Radio astronomy falls squarely into AAS' purview, as many objects in space are best observed in the non-visible parts of the electromagnetic spectrum. Radio telescopes can also be used almost continuously, whereas terrestrial telescopes generally are mostly useful during nighttime.

Importantly, AAS is also an advocacy organization. They engage in direct lobbying with executive and legislative policymakers on behalf of the astronomical sciences, and are frequent commenters on relevant regulatory actions (AAS, "How AAS Advocates," n.d.). AAS is, essentially, the key policy stakeholder representative for this issue. As such, it is among the best-prepared organizations to advocate on behalf of radio astronomy at the federal level.

The Radio Spectrum: Regulation and Industry Issues

Electromagnetic spectrum is regulated based on the different frequencies at which devices operate or observe. Currently, the federal and international norm is a system of allocations, whereby licenses are assigned or auctioned to different actors, who are then allowed to broadcast freely within that frequency band.

Regulation in the United States and Globally

The radio spectrum is regulated jointly by the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA). Together, they act to prevent the proliferation of destructive levels of RFI. NTIA has jurisdiction over the spectrum with regards to Federal activities, such as military and intelligence operations, while FCC takes responsibility for all other actors broadcasting in the United States (FCC, n.d.).

FCC's authorizing statute is the Communications Act of 1934. While it has been heavily amended since then, the Act does give the agency enforcement powers, which FCC carries out through criminal suits, fines, license revocations, and similar measures (Communications Act, 1934; FCC Enforcement Bureau, 2020). One major overhaul of telecommunications law in the United States took place with the 1996 Telecommunications Act, which was largely focused around encouraging competition of the sort seen with spectrum auctions, among other issues like cell tower construction (Telecommunications Act, 1996). Generally, the powers and responsibilities of FCC are summarized in Chapter 47 of the Code of Federal Regulations (CFR).

The many branches of FCC operate more or less independently, with the oversight of a five-member Board of Commissioners, each of whom serves a five-year term (FCC, 2010). The Commissioners are appointed by the President of the United States and are subject to Senate confirmation (FCC, 2010). Since only three Commissioners may be of the same party, FCC policy tend to avoid overt partisanship. The Board meets every month to vote on significant matters for the FCC; for example, the board's January 2022 meeting included discussion of a Notice of Proposed Rulemaking on transparency requirements for Internet service providers (FCC, 2022). Different offices are known to cooperate frequently given the many overlaps that occur with FCC's authority (NTIA, n.d.). The Office of Engineering and Technology (OET), one such branch of FCC, takes the most active role in spectrum management. They allocate specific ranges and bands of the radio spectrum to different industry players in order to avoid overlapping uses (FCC, n.d.). For example, all frequencies between 8.815 and 8.965 MHz are allocated to aeronautical mobile uses (FCC, 2021). FCC issues licenses for any actor wishing to broadcast within a given range.

OET often acts in cooperation with the International Telecommunications Union (ITU). While OET may make its own allocations for the United States, they are typically undertaken with international agreements at the World Radio Conferences, given the international nature of many radio broadcasts (FCC, 2015). Spectrum may be further subdivided at the discretion of member nations within the industry allocations set at the ITU Conferences, usually by giving out broadcasting licenses. FCC's normal policy for such allocation uses spectrum auctions, described below.

Spectrum Auctions

FCC has used auctions to issue broadcasting licenses in unassigned areas of the electromagnetic spectrum since authorized by Congress to do so in 1994 per an omnibus reconciliation act (FCC, 2006). Auctions are used when different bidders apply for licenses to broadcast in the same range, making the different applications mutually exclusive.

The agency announces auctions several months in advance and invites comment on the bidding and application procedures for the coming auction. For example, FCC opened the comment period on April 17, 2018, for one of its 5G frequency auctions to be held in November of that year, with comments due by May 9 (FCC, 2018). At the same time that they announce the auction, each of the five FCC commissioners will release a statement giving their thoughts on the coming auction, much in the style of a press release (Example: FCC, 2018).

The auction itself is usually a series of consecutive auctions for frequency bands within a certain range, meaning that several different companies in the same industry will bid. At the aforementioned 5G auction, known as "Spectrum Frontiers Auction 101," the 24 GHz and 28 GHz frequency bands were auctioned off. At the 28 GHz auction, 2,965 broadcasting licenses were awarded among 40 qualified bidders over 176 rounds held from November 14, 2018, to January 24, 2019 (FCC, 2019). While these auctions do create generally efficient allocations of broadcasting licenses and significantly reduce lag times between application and license approval (FCC, 2006), they can crowd out passive users of the spectrum. Meteorology is one industry particularly harmed by this process, as will be described below.

While RFI and its impacts are ubiquitous, three industries face critical threats to their survival: Radio Astronomy, Meteorology, and Aviation.

Industries Affected by RFI

Radio Astronomy

Radio astronomy uses extremely sensitive instruments since they scan for extremely radio-faint objects. While FCC specifically designates certain bands for the exclusive use of radio astronomy, the large and growing use of wireless communication has rendered RFI nearly universal, resulting in some data loss in virtually all observations taken.

This industry deserves special attention due to its status as a "passive" user of the electromagnetic band, which means that they access the spectrum but do not transmit. Other such passive services include parts of the space research and earth exploration research services (Gergely, 2014).

How does the industry currently interact with the radio frequency spectrum?

Radio astronomy is currently allocated a set of frequency bands per OET and ITU agreement (FCC, 2021). Such ranges are said to be particularly important because certain types of objects (such as quasars and pulsars) tend to emit energy in those ranges.

What is the impact of RFI?

Though transmitting is prohibited within protected radio bands, devices and broadcasters operating near to the protected range can "spill" over into the protected range when they transmit (NRAO, n.d.). Some devices also inadvertently, or illegally, broadcast within these ranges. Moreover, satellites flying overhead broadcasting information or using ground-scanning radar can transmit directly into the receiver of the radio telescope. Although in the United States there is a geographically remote area in West Virginia known as the National Radio Quiet Zone (NRQZ) where effectively *all* wireless transmissions are illegal, noncompliance has led to major RFI issues at the radio astronomy installations there (Kurczy, 2021). Similarly, the telescopes of the Very Large Array (VLA – pictured in **Figure 1**) and Very Long Baseline Array (VLBA), the two other main radio astronomy operations in the United States, are located in remote, but increasingly radio-noisy, areas. This prevents the industry from making scientific discovery and actually blocks astronomers from observing the vast majority of objects in the observable universe.

Figure 1: The Very Large Array in Socorro, NM. Facilities like this one are built in remote locations in the hopes of protecting the sensitive telescope from radio interference. Source: NRAO

How could future trends impact this industry?

Historically, radio astronomers have also opportunistically accessed virtually all unused radio frequency bands of the spectrum, since the celestial objects they observe (e.g. distant galaxies, stars, etc.) The upper reaches of the electromagnetic spectrum were traditionally unusable for other industries, allowing astronomers to observe in that range at will (National Academies, 2021a). However, like a parcel of undeveloped land on the edge of town, that unused spectrum is now being divided up and sold for the use of new technologies.

Meteorology

Similarly, RFI will soon cause major damage to meteorology, since FCC recently re-allocated a band traditionally used by NOAA to 5G cell development (Calma, 2019). While improvements in technology have allowed for greater data extraction even in the face of instrument noise and interference (Crockett et al., 2021), major action will be required in the coming decade.

How does the industry currently interact with the radio frequency spectrum?

Meteorology requires the use of ground-based radar to map weather patterns and storm systems, as well as some passive sensing from satellites (WMO-ITU, 2017). Such tracking allows forecasters to provide timely alerts for impending hurricanes, tornadoes, and similar natural disasters. To this end, many frequency bands are allocated internationally and domestically for the sole use of meteorologists (FCC, 2021).

What is the impact of RFI?

RFI is known to damage meteorological radar observations. The passive receivers on weather satellites are extremely sensitive since they "listen" for very low-power radiation, not unlike radio astronomy receivers. These satellites are estimated to increase forecast accuracy by 30 to 40% (English, 2019). However, since they are so sensitive, they are particularly vulnerable to RFI, and meteorologists have noticed corruption of their data in recent years.

How could future trends impact this industry?

Recently, the FCC auctioned off the use of a certain band of radio wave for 5G cell phone use that the National Oceanic & Atmospheric Association (NOAA) needs for its weather predictions (Calma, 2019). As a result, roughly 77% of the data collected by NOAA for weather predictions will be ruined by RFI, which will result in a decrease in forecast accuracy by about 30% (Jacobs, 2019) – effectively wiping out all the added accuracy from satellite observations. **Figure 2** demonstrates how accuracy can be lost when interfering signals damage a weather scan.

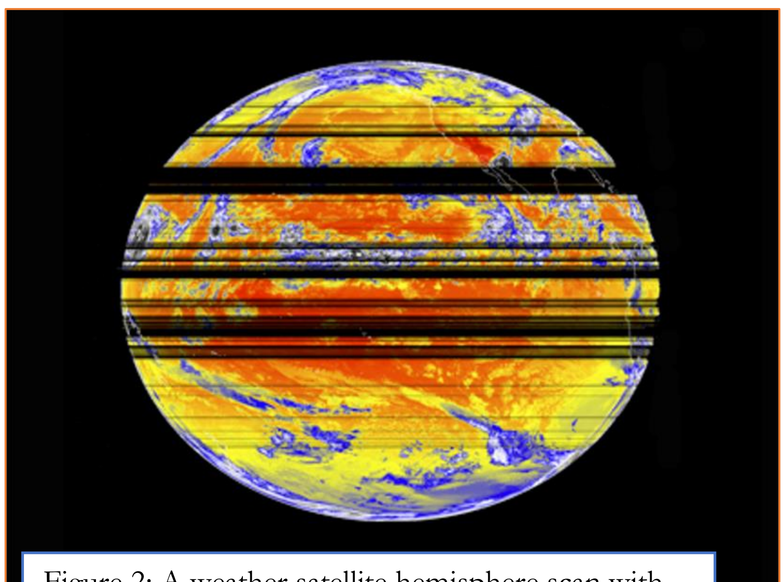


Figure 2: A weather satellite hemisphere scan with parts of the image totally ruined by RFI. Credit: CIMSS/SSEC (Gerth, 2018)

Aviation

Radio communication is essential in aviation. Airborne pilots have been communicating with each other and with the ground via radio since the 1910s, and the two technologies have developed hand-in-hand in the intervening decades.

How does the industry currently interact with the radio frequency spectrum?

During flight, airplane pilots rely on special devices such as altimeters to gauge crucial pieces of information, such as their real-time distance from the ground. Since pilots need to communicate with each other and with ground control, and many of these devices rely on the radio-frequency spectrum, aviation has many allocated frequency bands (FCC, 2021).

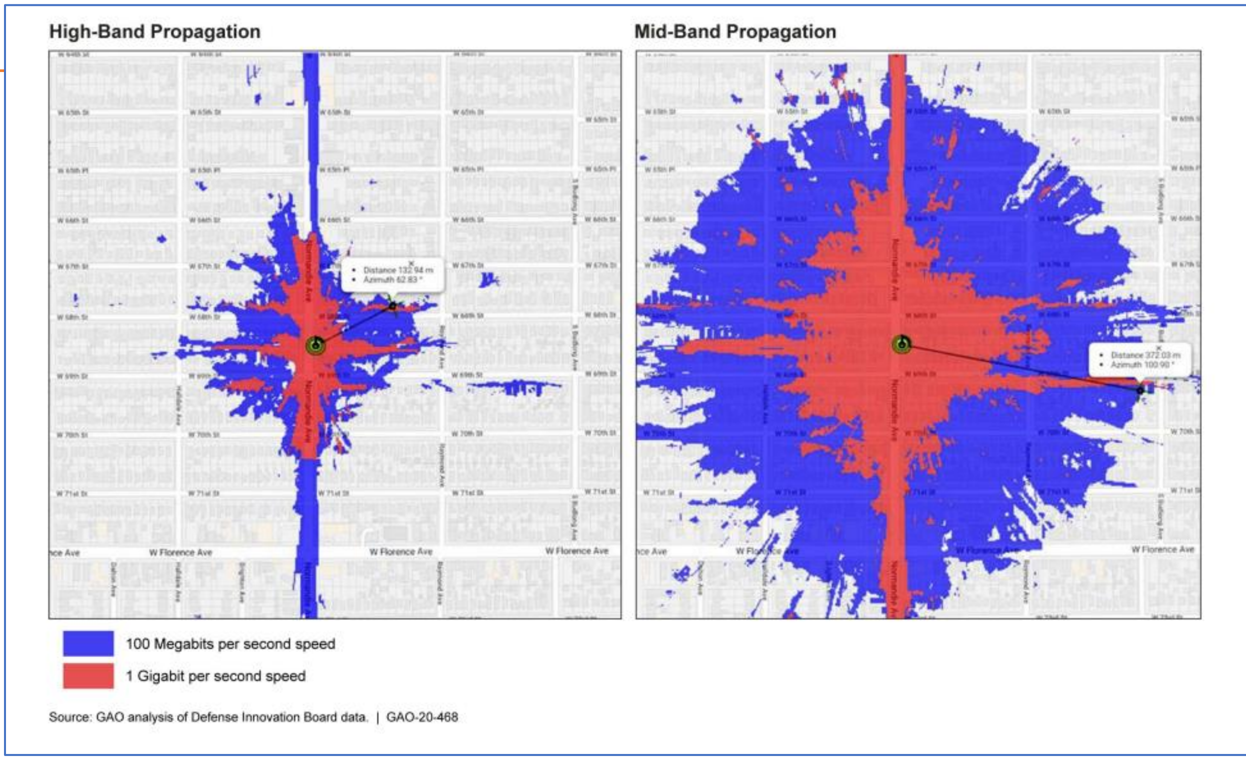
What is the impact of RFI?

Since altimeters and other in-plane devices are highly sensitive to radio interference, passengers are required to turn off personal electronic devices and why cell phones must be set to "airplane mode" during take-off and landing. Nevertheless, roughly a third of passengers do not comply with these federal regulations, generating interference inside the airplane (RTCA, 2020). Ground- and upper atmosphere-based radio sources (cell towers, satellites, etc.) also generate interference in more built-up areas, so commercial flights are increasingly exposed to RFI. In Europe, which has a similar level of interference to the U.S., roughly 5% of flights meet such bad interference as to require special assistance (Eurocontrol, 2021).

How could future trends impact this industry?

Still, the impact of RFI on aviation in the future is politically contested. The Federal Aviation Administration (FAA) and other allied groups argue that the impending U.S. rollout of 5G will present significant risks to their radar altimeters due to these technologies' proximity in frequency (FAA, 2021). 5G advocates counter that other countries, such as Japan, have successfully implemented 5G with no adverse effects on aviation, despite lower safety standards than comparable FCC rules (Bennett, 2021). **Figure 3** shows how 5G cell installations transmit across large areas of urban environments, potentially straying into areas where they can interfere with aviation operations.

Figure 3: High-Band versus Mid-Band 5G propagation in an urban environment. Mid-band 5G's wide reach and close proximity to the bands used by radar altimeters are a source of concern to the aviation industry. Credit: Defense Innovation Board (GAO, 2020)



Future Developments Materially Impacting this Analysis

Radio astronomers have proposed one technical solution to terrestrial RFI: building a radio telescope on the far side of the Moon. The facility would be constructed autonomously by robots deployed to the surface; after that, it would operate remotely on the totally radio-silent "dark" side of the Moon[1] (McFall-Johnsen, 2021). This would totally solve most Earth-based RFI problems, though it would be expensive and faces some threats due to Chinese lunar rover ambitions (NASA JPL, 2021). In such an event, the policy steps for FCC advocated by this analysis would no longer have the same urgency. Still, a Moon base of this type is unlikely to occur within the next two decades.

[1] The Moon is tidally locked with the Earth, which means that it *always* keeps the same side facing Earth. Because of this phenomenon, the far side of the Moon is shielded from Earthly radio transmissions.

The Costs to Society

Losses to Astronomy

Radio astronomy relies on highly sensitive passive receivers designed to identify signals from deep-space objects that emit radio waves very weakly. Since these instruments must operate at an extreme level of sensitivity, they are peculiarly vulnerable to RFI: if a radio telescope is pointed directly at a radio-emitting object such as a satellite, the receiver will be instantly and totally ruined (ITU, 2020). Even excluding such extreme cases, radio transmissions are (and have been for several decades) so widespread that *all* radio astronomy observations experience RFI (Davis, personal communication, 2021). Therefore, while data do not exist on the absolute number of observations marred to some degree by RFI, many hours are wasted annually filtering and attempting to repair damage done to radio observations.

Direct costs to the radio astronomy industry are small in absolute terms, but major within the industry. The International Telecommunications Union (ITU) has tentatively estimated that roughly 5% of radio astronomy observations are discarded due to overwhelming interference, and that such interference wastes about 5% of operating time for a telescope, through finding such observations, fixing any fried receivers, etc. (ITU, 2020). With a roughly $105 million total budget for radio astronomy facilities in the U.S, a 5% loss of operating time equates to a loss of $5.25 million (NSF, 2020b). Costs included in this estimate include an increased need for scientists and others working specifically to address RFI, as well as costs for items like receiver filters and the development of specialized software (Schinzel, personal communication, 2022).

Externalities for these issues in the astronomical field are not significant compared to other costs. However, there are other major indirect costs associated with RFI. For example, since all terrestrial radio observations are marred to some degree by interference, astronomers may be forced to construct radio telescopes in space to continue generating significant discoveries for humanity. The most practical proposal is that of the previously-mentioned Moon telescope, for whose research NASA recently contributed $500,000, though the final cost would easily exceed a billion dollars (McFall-Johnsen, 2021).

Losses to Aviation

Direct costs to aviation due to RFI are very high. 10% of U.S. flights are currently barred from landing in low-visibility conditions as of April 2022, because the radar altimeters used to help planes land in such conditions cannot be trusted to function properly in the presence of 5G cell towers (Dickson, 2022; Shepardson, 2022). At a 2022 hearing of the House Transportation Committee, airline executives and spokespeople argued that the 5G issues would take years to resolve. 5G interference, then, will likely continue to cause delays even among cleared altimeters, and the prevalence of this technology will only grow over the policy period. Over time, however, some of these altimeters will be cleared for use, while others will be phased out as planes are decommissioned. Therefore, it is assumed that 5% of flights will experience a delay for the first two years and 3% after that, with an average delay of one hour. Since roughly 16.4 million flights are handled by the FAA every year, this means that 820,000 flights are delayed by an hour annually (FAA, n.d.). The average cost for a U.S. passenger air carrier is $8,916 per flight-hour, so this translates to a direct cost to aviation companies of over $7.3 billion dollars every year (FAA, 2020).

The externalities for this situation would be the added emissions from 820,000 extra flight-hours every year. There are 25.5 million hours of flight and 185 million tons of CO2 produced from flying per year in the U.S., meaning 7.255 tons per flight-hour (FAA, n.d.; Tiseo, 2021). Using a social cost of carbon of $50, this equates to about $300 million in externalities. There are other indirect costs as well. 2.9 million people fly in the U.S. daily, adding to roughly 1 billion passengers per year (FAA, n.d.). If 5% of these passengers experience a 1-hour delay, there will be just under 53 million work-hours lost per year. Since median personal income in America is about $36,000 annually, ($19.33 per hour) this makes a conservative opportunity cost estimate of $1.023 billion (Census Bureau, 2021).[2]

Losses to Meteorology

Meteorology also relies on sensitive radio instruments and will be heavily impacted by the deployment of 5G technology. Because of a recent FCC frequency band auction, NOAA is anticipating a 30% forecast accuracy decrease since they will be losing most of their satellite data (Calma, 2019; Jacobs, 2019), as 5G technology will affect portions of the radio spectrum specifically needed by the National Weather Service to measure water vapor and precipitation totals.

Across the American economy, roughly $13 billion in revenue relies directly on accurate weather predictions, meaning that $3.9 billion will be lost annually due to 5G radio interference, assuming losses proportional to prediction accuracy (NWS, 2017). There is another direct cost created by this poorer accuracy: damage caused by severe weather. Currently, extreme weather imposes an average of $50 billion annually in the U.S (NOAA, 2021). Assuming a 30% decrease in forecast accuracy means a 30% increase in costs from extreme weather (since, for example, Jacobs testified that the forecast model will now get the average hurricane landfall wrong by roughly 2-3 days), the increased damage to society due to RFI with weather predictions yields a direct cost of about $15 billion.

Thus, there is a major approximate cost to society through externalities, direct costs, and opportunity costs: $5,250,000 + $7,300,000,000 + $300,000,000 + $1,023,000,000 + 3,900,000,000 + $15,000,000,000 = $27,528,250,000.

[2] This is a conservative estimate since the average income of Americans who fly is certainly higher than $36,000/year, implying that the true cost figure is far greater.

Policy Options and the Existing Evidence

Since demand for the electromagnetic spectrum can only be expected to grow, one or several policy options should be taken by FCC to protect radio astronomy, meteorology, and other fields highly vulnerable to RFI.

Criteria for Evaluation

Each policy alternative discussed will be evaluated according to each of the following criteria:

1- *Cost-Effectiveness* (40%)

This is the most important criterion in this analysis, given the major costs and disruption to society generated by RFI. Cost-effectiveness for this project will be expressed as the net present value total costs of radio interference to society divided by the change in the number of hours of radio observation ruined. This criterion will measure change in interference by estimating the hours of time using radio instruments (telescopes, altimeters, satellite scanners, etc.) that are effectively "wasted" by interfering signals. It is measured by the total cost to society under the policy under evaluation divided by the number of observation hours "saved" by that policy. Future costs are discounted using a social discount rate of 3%, as suggested by Cellini & Kee (2015).

The last year for which reliable data are available across industries is 2020, so this will be the policy base year. The cellular telephone industry rollout of new generations of wireless product is by far the most important technological innovation in this analysis, with a clear break in the data appearing in 2022, the year of 5G rollout. This analysis uses a range of 10 years, both for the simplicity of analysis and because, on average, the industry rolls out a new generation of cell phone every 10 years, rendering projected analyses beyond that point impractical (GAO, 2020).

2- *Equity* (20%)

There are two main considerations for the Equity criterion. First, policies will be evaluated for Equity by their ability to protect the interests of the comparatively much weaker scientific community relative to powerful, better-funded telecommunications firms. Second, and not necessarily aligned, is the equity consideration of the everyday telecommunications consumer. Policies that benefit the passive radio services at the expense of the American citizenry are not equitable, and so they will not be rated highly by this criterion.

3- *Political Feasibility* (30%)

Since most viable policies for this topic rely on federal rulemaking by FCC, this criterion will focus on the likelihood a given policy alternative will pass FCC muster. FCC is chaired by five commissioners, only three of whom may be of the same political party. This means that any policy alternative favored by the party holding a majority will be highly politically feasible. For example, during the Trump Administration, FCC's Board of Commissioners had five Republicans, headed by Commissioner Ajit Pai. Republican politics heavily favored speedy development and innovation in the 5G cell technology space, so FCC undertook many pro-5G policies from 2017 to early 2021. After each major rulemaking requiring a Board vote, each Commissioner will release a public statement offering their views on the issue. There is some nuance to these releases; after the vote on the Citizens Broadband Radio Service, for instance, Republican Commissioner Michael O'Reilly released a statement showing approval in part and dissent in part (FCC, 2016). This criterion, then, will weigh how Commissioners will ultimately vote against any nuance they may add. Analysis by this criterion will also consider the likelihood of gaining bipartisan or cross-party support.

4- *Ease of Implementation* (10%)

This criterion is weighted lower since all discussed policy alternatives involve rulemaking by FCC alone. That said, this criterion will examine the level of action required within FCC to accomplish a given alternative. If a policy requires multiple rules to be issued, for example, it may be harder to implement. Funding will also play a role here since some alternatives in this project involve increasing contributions to radio science facilities. This criterion also considers the extent to which FCC staff concur with the soundness of the policy, and whether it will demand technical expertise requiring the hiring of new staff.

Discussion of Policy Alternatives

Status Quo: No Protective Regulatory Action, Continued Spectrum Auctions

If no action is taken by FCC to reform the use of the electromagnetic spectrum, harmful interference will continue to spread throughout the American economy. In terms of lost hours of radio communication (through wasted sky observation time, radar altimeter reading, and satellite scanning time for radio astronomy, aviation, and meteorology, respectively), the situation will continue to deteriorate. Radio astronomy facilities in the U.S. will lose roughly 16,000 hours of observation time per year (out of a total of 24,020 operating hours annually). Aviation will face major losses during the first two years of 5G rollout (starting 2022), but over time this outcome will improve slightly as older, less resilient radar altimeters are phased out. Thus, it is assumed that they will lose roughly 4,560 hours of radio readings annually from 2022-2024, and 2730 hours annually after that. Finally, because NOAA's GOES-series satellites' numerous scans of the earth will be marred by 5G operations, the American meteorology industry will lose around 12,250 hours of scan time annually. In total, these three industries will lose nearly 370,000 hours of radio communication time between 2020 and 2030 (For more detailed tables and calculations, see Appendix).

Policy Alternative 1: Dynamic Spectrum Sharing (DSS)

Spectrum sharing, at its essence, is a technique whereby different users access the same frequency band at the same time. Sometimes, users opportunistically access a given radio frequency when it comes available. Versions of this policy have been implemented in recent years for the simultaneous use of 5G and 4G LTE technologies.

Existing Evidence

Dynamic Spectrum Sharing (DSS) evolved as a result of increasing demand for wireless communication, a problem which was exacerbated by the partial rollout of 5G technology onto infrastructure designed for 4G use alone. Its efficiency and fast reactivity (Massaro & Beltrán, 2020), as well as its ability to avoid critical data loss (Barb et al., 2021) make DSS an attractive technical solution to the RFI problem. Under DSS, two users (and *only* two users) are allowed to transmit at the same frequency as long as interference stays below a set limit, done by limiting the power output of the "secondary" user (Baby & James, 2016).

For radio astronomy specifically, Ramadan et al. developed a DSS paradigm that reduces the traditional need for remote (radio quiet) observation facilities, whereby a radio astronomy facility would coordinate sharing with nearby cell towers in a Shared Spectrum Access Zone (2017). Such a model would demand some technological innovation, but remains realistic: passive radio facilities will have secondary antennae measuring incoming RFI, and access the spectrum during the predictable times when such interference levels are low (Ramadan et al., 2017).

Most evidence examining spectrum sharing focuses on collaboration between *active* users of the spectrum. Services like astronomy, which are called passive radio services, still require the frequency to be open as an active user would, but they are not actually *broadcasting* on that frequency. This means that they are not detectable on the spectrum unless they have another means of communication with the spectrum manager. Some have argued that this makes spectrum sharing infeasible for radio astronomy (National Academies, 2021b); at the very least, spectrum sharing will be more complicated for these services than it has been for cell services. Another assumption that may fall flat is that spectrum users will comply with the rules of DSS; if more users attempt to "share" in the frequency, DSS is less effective (Baan, 2019).

Policy Steps

FCC has already instituted some limited sharing arrangements. For example, in 2015 the agency designated a band of radio spectrum which had long been allocated for federal use, but rarely actually used by the government, as the "Citizens Broadband Radio Service" (CBRS). They issued rules creating a two-tiered user hierarchy consisting of Priority Access and General Authorized Access users. General Authorized Access users are generally commercial actors, and under the FCC rule they can use that spectrum band as long as they do not generate harmful interference for government Priority Access Users (Citizens Broadband Radio Service, 2015).

This alternative would simply require FCC to authorize sharing on more bands of the radio spectrum, designating radio astronomy services as a priority access user. Like the CBRS, these authorizations would require rulemaking by the agency.

Policy Alternative 2: Protecting National Radio Quiet Zone & Strengthening Radio Astronomy Protections

The U.S. has one National Radio Quiet Zone (NRQZ), which was established in 1958 by FCC. Within the zone, special approval is needed for any new radio-frequency transmitting device (NRAO, n.d.). This means that, for example, there is no cell phone service in the vicinity of the Green Bank Telescope (the primary astronomy installation), and services such as Wi-Fi are technically banned. Since the actual telescope is located in a deep valley between tall mountains in the NRQZ, there is substantial physical shielding from terrestrial radio sources. Similarly, the VLA is located in a remote desert, while the VLBA's ten locations are spread across the U.S. These telescopes' sites, then, *should* be relatively uninhibited for radio observation.

This policy involves three main components: first, increasing funding by FCC for the National Radio Quiet Zone (NRQZ) where sensitive passive radio receivers for the defense and radio astronomy industries are located; second, strengthening the rules for broadcasting around the NRQZ (current rules are outdated and poorly enforced); and third, restricting satellite broadcasts above the NRQZ, since satellites can beam directly into radio receivers and negate the effect of existing protections. Comparable rules would be made for the remote regions surrounding the telescopes of the VLBA and VLA radio astronomy facilities.

Existing Evidence

Not all radio telescopes globally are protected by radio quiet zones. However, depending on the specialization of a specific radio astronomy facility, "separation distances" may be implemented by local or national governments to ensure limited or no commercial wireless uses in the area (CRAF, n.d.). In addition to the previously-mentioned limits on personal wireless technology, the U.S. NRQZ limits interference from larger transmitters by a "coordination" process for "all new or modified, permanent, fixed, licensed transmitters inside the NRQZ" per FCC and NTIA rules (Green Bank Observatory, n.d.).

Anecdotally, compliance with local regulations in the American NRQZ appears to have declined with the advent of wireless internet technology. One NRQZ official charged with enforcing the quiet zone encountered over 350 RFI-producing hotspots within 5 miles of the observatory, and 175 within 2 miles – including one from a Wi-Fi hotspot *across the street from the observatory* (Kurczy, 2021). As a result, radio astronomers are forced to abandon areas of the spectrum used by technologies like Wi-Fi, even though they should legally have access to the entire spectrum within the NRQZ. However, low funding and legal ambiguities render strict enforcement of these rules impractical (Kurczy, 2021).

Policy Steps

This policy alternative would involve three main steps by FCC:

1. *Begin contributing to NRQZ's and NRAO's budgets through yearly contributions*
   One major impediment to enforcement in the NRQZ is limited funding, which stems in part from the National Science Foundation's 2019 decision to decrease their contributions to Green Bank (NSF, 2020a). Thus, contributions from FCC would allow the facility both to enforce its rules more effectively and make the asset of the NRQZ more valuable. NRAO funding would also be increased by $3.5 million annually; this amount reflects how much was spent in FY2020 on a special spectrum innovation project designed to protect radio astronomy services from RFI (NSF, 2022).

2. *Issue clearer rules on personal and institutional broadcasting requirements in the NRQZ*
   The rules for broadcasting in the NRQZ are from 1958, long before the advent of cellular telephone technology or wireless Internet (NRAO, n.d.). Many of the rules governing wireless-transmitting devices inside the NRQZ are therefore poorly equipped to handle RFI from modern lifestyles. Poor compliance may be remedied by better articulation of the rules.

3. *Initiate rulemaking prohibiting satellite broadcasts above radio astronomy installations*
   Though physical isolation and legal restrictions protect passive radio services like astronomy within the NRQZ, there remains the threat of satellites. In recent years, thousands of small satellites such as from SpaceX's Starlink have begun a race to provide global satellite-based internet (Witze, 2019). Such satellites require transmissions in the radio spectrum (including in radio frequencies of scientific interest), rendering terrestrial protections useless (Clery, 2020). Already, the Green Bank Observatory has encountered significant satellite-based interference (Hall et al., 2019). This policy would therefore require rulemaking from FCC prohibiting broadcasts above radio quiet zones.

Policy Alternative 3: Increase Allocations to Passive Services, Protect Unallocated Spectrum

A final alternative is simply to escalate existing FCC commitments to protecting scientific research. There are already many protected frequency bands in the radio frequency spectrum, such as 13.36-41 GHz, which is protected both in the U.S. and internationally (FCC, 2021). This policy would increase the number of such allocated frequencies to ranges which were formerly unused but are now subject to development.

This policy would have two main steps: first, strengthening existing protections against out-of-band radio "spillage" into protected frequencies, which would protect radio astronomy; and second, giving protected frequency ranges currently used for 5G technology back to the meteorology industry. Politically, this second step would not be decided until the next World Radiocommunication Conference in 2023, when allocations are made internationally (FCC could act unilaterally, but typically does not do so in these cases), and so any benefit to meteorology would realistically have to wait until Year 5 of this analysis.

Existing Evidence

This policy shares with the status quo one major drawback: broadcast "spillover." Transmitters operating near protected bands virtually always "spill" into the protected range, intentionally or not (NRAO, n.d.). Newly allocated frequency bands would also experience this problem, which will likely grow over time as spectrum use increases.

Policy Steps

Frequency allocation is undertaken, as mentioned above, by FCC's Office of Engineering & Technology (OET). While OET could take unilateral action for U.S. radio astronomy, this policy would be more effective if the agency seeks international communication with ITU at a World Radio Conference. The next such Conference is in 2023 (ITU, n.d.), at which OET would have to advocate for allocations for radio astronomy, likely with the cooperation of the international astronomy community. Alternatively, OET could act unilaterally. In either event, upon reaching an allocation decision, this policy alternative would require FCC rulemaking to update their Table of Frequency Allocations as published in the Federal Register (2021).

Findings: Analysis of Alternatives, Outcomes Matrix, and Recommendation

A Note on Cost-Effectiveness Methodology

As mentioned above, cost-effectiveness is expressed as the net present value total costs of radio interference to society divided by the change in the number of hours of radio observation ruined. The policy base year (Year 0) from which estimates begin is 2020, and all projections are made up to and including 2030 (Year 10), based on the average length of time between adoption of cell phone technology "generations" (GAO, 2020).

Outcome Projections

The outcome estimated in these projections is the hours of time using radio instruments effectively "wasted" by interfering signals. For each industry, events that can reasonably be expected to grow or shrink this outcome materially over the next decade are given weight, along with an assumed impact. For example, the absence of 5G technology in the United States prior to 2022 means that for aviation, there are no hours lost in Year 0 or 2. For astronomy, by contrast, it is assumed that hours wasted will grow as the number of satellite constellations "beaming" transmissions into and around radio facilities will increase. When proposed policy alternatives are expected to change these projections, the change in outcome is expressed as the number of hours "saved."

Cost Projections

Cost estimates in this analysis are based on opportunity costs from wasted work-hours, externalities from pollution and weather damage, and direct costs such as instrument replacement. When possible, actual budget allocations and other concrete cost figures are used. These costs can be expected to grow and shrink over time, and future costs are discounted using a social discount rate of 3% (Cellini & Kee, 2015).

For both outcome and cost projections, as well as more detail on the analysis used, see the Appendix.

Analysis of Alternatives

Brief Discussion of Status Quo

The baseline cost-effectiveness of $511,820.25 gives the cost to society of every hour of electromagnetic observation that is ruined by radio interference. In contrast, each alternative is measured by the total cost to society divided by the number of hours *saved* – that is, how many fewer hours are wasted during the policy period? The status quo is considered "Very Low" for equity for two reasons: first, lower-funded passive services like radio astronomy are harmed, while major telecommunications companies benefit from their greater financial and political resources; second, as weather-related disasters occur with increasing frequency due to climate change, weather forecasters' inability to make accurate predictions will exacerbate existing racial disparities in the impact of natural disasters (EPA, 2021). The status quo requires no government action that is not simply reactive, so it is rated "Very High" for both political feasibility and ease of implementation.

Alternative 1: Dynamic Spectrum Sharing

Likely Outcomes

This is the most feasible alternative, but it is not perfect. While this policy alternative does not address the threats from satellite-based interference, it lays the technological groundwork for doing so. DSS can utilize existing similar technologies from the sharing paradigms of 4G and 5G cell networks, and demonstrate a policy that will (eventually) be needed across the industry. Such sharing could even potentially alleviate some of the travails of the meteorology industry, where observations are time-sensitive and must be taken in populated (radio noisy) areas – indeed, Barb et al. (2021) estimate a maximum data loss of 25% under DSS, far better than NOAA's 70% loss prediction (Jacobs, 2019). This alternative efficiently balances the needs of passive radio services against those of the commercial sector, and of all alternatives in this analysis it has by far the best long-term viability.

Cost Effectiveness

This policy would reduce the costs to society by over $95 billion over the next ten years by lowering interference for the meteorology and radio astronomy industries. Due to the non-sharing-conducive nature of radar altimeters (when the altimeter is on, it *must* have unimpeded spectrum access, or the plane could crash), this policy would not significantly help aviation.

Overall, the total cost to society for this decade would be roughly $93 billion. With a total number of lost hours of observation of around 140,000, would save radio astronomy 157,000 hours of observation time, and nearly 71,000 for meteorology. The cost effectiveness of this policy, then, is as follows:

$93,163,159,000 total cost to society / (368,201.89 - 140,073.22) hours = **$408,379.88** per hour of observation time saved.

Equity

This would be a highly equitable policy for its protection of the comparatively low-political-leverage radio astronomy industry. Major power players such as telecommunications companies would have to cede some of their dominance over the electromagnetic spectrum.

For the everyday telecommunications consumer, this policy is unlikely to change daily life from the status quo, since spectrum sharing techniques are designed to take advantage of natural lulls in spectrum activity (Baby & James, 2016). However, it will significantly improve equity because of the improvements to weather forecasting relative to the status quo; this alternative will reduce the inequities generated by poor forecasting of weather disasters already disproportionally harming marginalized communities. Therefore, this alternative receives a "High" equity rating.

Political Feasibility
This alternative would likely meet with support from the FCC Board of Commissioners, the key gatekeepers in the decision process. When the CBRS, the current main U.S. spectrum sharing scheme, was developed, all five commissioners (three Democrats, two Republicans) gave their support (FCC, 2016). Democrats generally were more enthusiastic advocates for the sharing scheme, so if a vote were forced upon the 5-person FCC committee, a spectrum sharing agreement would likely pass during the current Presidential administration. Thus, this alternative is given a rating of "Very High" for this criterion.

Ease of Implementation
This alternative would require multiple rounds of rulemaking, since different frequency bands to be designated for sharing would need to be regulated separately. This could raise issues if increasing numbers of sharing schemes become unpopular with powerful industry players like cell companies. Still, the rulemaking process is more straightforward than legislation. Overall, this alternative receives a "Low" ease of implementation rating.

Alternative 2: Protecting National Radio Quiet Zone & Subsidizing Radio Astronomy Facilities

Likely Outcomes
FCC is unlikely to establish another NRQZ in the U.S., nor will it dismantle the existing one. This policy would involve additional budget allocations to FCC, which is always politically challenging. Though the NRQZ was established and nominally is under the jurisdiction of FCC, they do not currently run or finance it. Funds infused into the NRQZ could rejuvenate and modernize what might otherwise become an obsolete burden on FCC's resources. Additionally, the funding to NRAO would be an interagency transfer (essentially, internalizing the externalities of radio interference). The rulemaking on broadcasts and personal devices within the NRQZ would simply strengthen existing rules, and should be a relatively straightforward process.

Satellites, including the problematic mega-constellations, need FCC approval before launch (CFR, 1991). Thus, FCC could make non-broadcasting over the NRQZ, VLA, and VLBA a condition of approval. Implementation of the satellite rulemaking could be technically challenging, but companies like SpaceX have shown willingness to modify their satellite constellations to protect science in the past, as with their telescope-saving DarkSat (Tregloan-Reed et al., 2020). Still, this rule would only apply to American satellites, so radio astronomy would not necessarily be wholly protected.

Overall, while this policy option would protect passive radio services in the NRQZ, it would not fix broader policy problems like the loss of meteorology data. Moreover, its reliance on additional budget allocations could be a flaw, though in relative terms the increase is small.

Cost-Effectiveness
Under this policy, costs to society would increase by roughly $6 million by 2030, a small increase. It would reduce the number of wasted hours for radio astronomy to effectively zero after 2022, saving almost 200,000 hours in the policy period. Aviation and meteorology would be unaffected by this policy. Overall, cost-effectiveness is as follows:

$188,459.309 total cost to society / (368,201.89 - 171,736.05) hours = **$959,247.22** per hour of observation time saved.

Equity
Relative to the status quo, this policy would do little to improve equity for the average American. However, it would protect the radio astronomy industry very effectively, ensuring a strong future for scientific discoveries. Given these considerations, this policy receives a "Moderate" equity rating.

Political Feasibility
Roughly $5 million per year is a very small amount relative to FCC's annual budget of over $500 million. However, in the current regulatory environment, spending increases—particularly to another government agency—are politically unpopular. This policy therefore receives a "Low" political feasibility rating.

Ease of Implementation
In logistical terms, this policy would be very easy to implement once enacted. The funding transfer is of negligible difficulty and the facilities receiving the funding would have little difficulty putting those funds to use, given how immediately urgent the RFI problem is for them. Thus, this policy has a "Very High" rating for implementation.

Alternative 3: Increase Spectrum Allocations to Passive Services

Likely Outcomes
As mentioned, spillover from neighboring frequency broadcasts would be an issue for this policy. On the other hand, this alternative would stand up both to terrestrial *and* space-based sources of RFI, since satellites passing overhead would simply be barred from transmitting in the frequencies of interest per 47 CFR § 26 (which gives FCC jurisdiction over American satellite broadcasts).

Politically, this option presents relatively few overt challenges since, like the other policy alternatives, it falls solely under the purview of FCC's rulemaking authority. However, it is unlikely to be popular with 5G and other technology advocates, and the radio astronomy community will likely object that this alternative is merely a stopgap for the larger RFI problem. Nevertheless, it is legally straightforward, and can be reversed if future technological developments render such allocations obsolete.

Cost-Effectiveness
By protecting meteorology and radio astronomy, this policy would save over 230,000 hours of electromagnetic observation time by 2030, and would decrease costs to society by $91 billion over the same time period. The cost effectiveness of this alternative is thus:
$97,443,031,000 total cost to society / (368,201.89 - 137,445.22) hours = **$422,276.12** per hour of observation time saved.

Equity
This policy, like Alternative 1, would decrease the disproportionate impacts of severe weather events on racially marginalized groups in America relative to the status quo. It would also protect passive radio services very effectively, by ensuring (for a while, at least) that accurate weather and

astronomical radio observations can be made free from major interference events. Therefore, this policy receives a "Very High" equity rating.

Political Feasibility

Because this policy would require action at the international level, given the need for ITU cooperation, it would be extremely difficult to pass. Industry players who benefited by receiving the spectrum range in question would be strongly averse not only to losing future spectrum allocations, but also to *return* the range they acquired so recently. Presumably FCC would also have to reimburse those actors who purchased licenses to broadcast in this spectrum – which would cost them $2 billion. Thus, this policy is rated "Very Low" for political feasibility.

Ease of Implementation

There would probably be some compliance difficulties for this policy, as existing technologies would have to be retrofitted according to new spectrum rules. Some companies certainly will be reluctant to comply, requiring enforcement action on FCC's (and its international equivalents') part. However, the rulemaking process itself would be simple. Still, getting Congressional approval for a $2 billion transfer to former licensees would probably require some legislative action, making implementation difficult. This policy therefore receives a "Low" implementation rating.

Outcomes Matrix

The evaluations given above are summarized in the following table. Apart from cost-effectiveness, points are assigned according to a scale where "Very High" is 5, "High" is 4, and so on. In order to weight cost-effectiveness in a manner comparable to the other criteria, the inverse of the number given in the cost-effectiveness cell is multiplied by 1 million. Weights are applied to each category score as designated in the top row.

Figure 4: Outcomes Matrix

Policy	Cost-Effectiveness (40%)	Equity (20%)	Political Feasibility (30%)	Ease of Implementation (10%)	Overall Ranking
Status Quo	**$511,820.25** per hour ruined	Very Low	Very High	Very High	2.98
Dynamic Spectrum Sharing	**$408,379.88** per hour saved	High	Very High	Low	3.48
Support RA Facilities	**$959,247.22** per hour saved	Moderate	Low	Very High	2.27
Protect Allocations	**$422,276.12** per hour saved	Very High	Very Low	Low	2.45

Recommendation

Based on this evaluation of the existing evidence, I recommend FCC implement Alternative 1: Dynamic Spectrum Sharing. It will generate significant savings to society, and provide industries affected by 5G a practical way to thrive in an ever-more-crowded spectrum. This alternative will combat unjust disparities in the impact of extreme weather events, and similar, smaller-scale policies have enjoyed the support of both parties. Even if implementation becomes a challenge over time, the rulemaking process by which this policy would be enacted will enable some benefits to be realized almost immediately.

The most crucial advantages of this alternative are two-fold: first, it allows for growth in the use of spectrum. Spectrum sharing is already expected to enable cooperation between overlapping 4G and 5G networks, necessitated by leaps forward in technology and increased demand for wireless communication (Barb et al., 2021). This alternative shifts the regulatory paradigm into a forward-looking direction. The existing framework of strict allocation fails both to account for existing demand for a limited spectrum and to protect established allocations as the spectrum gets more crowded in the future. Second, this alternative's benefits are wide-reaching; as wireless devices proliferate with developments like the Internet of Things, spectrum sharing *will* eventually be necessary. Implementing a sharing scheme now will keep American telecommunications at the forefront of wireless innovation while preparing this country for a more connected future.

Implementation

Step 1: Establishing Hierarchy of User Licenses

Spectrum sharing schemes designate users by a set order of preference given to their licenses for a given spectrum band: primary, secondary, etc. As the names suggest, primary users are generally "first in line" for use of the spectrum, depending on the sharing scheme. For example, with a spectrum underlay network (one time of sharing arrangement), secondary users are required to keep their interference with primary users' transmissions below a set level (Baby & James, 2016). CBRS uses a model like this one; Navy communications have "incumbent user" status (actually higher than a primary user, in this case), which entitles them to a maximum interference level.

In order to avoid inequitably burdening the less-well-funded radio astronomy industry, FCC should specifically designate primary licenses for NRAO and the Green Bank Observatory for the physical areas around their installations. There is precedent for this kind of step: the current system of protected frequency allocations specifically designates areas of radio astronomy, and incumbent-user licenses were automatically granted to Navy users of the CBRS (Celona, 2021). In the areas near radio astronomy installations, telecommunications facilities should be granted secondary-user access, similar to Ramadan et al.'s (2017) proposed network. In areas far from passive radio services, where interference currently poses a less urgent problem, FCC can run auctions as it normally does for broadcasting licenses. This will allow an economically efficient and cost-effective distribution of licenses.

Exceptions and Considerations

For certain circumstances, a hierarchy of user licenses is not necessary, and a "horizontal sharing" approach can be used. In this kind of arrangement, licensed and even unlicensed users can share a spectrum range (RSPG, 2021). Such schemes are best suited to "shared band[s] for unlicensed use by a multitude of equipment and services" or for bands dedicated solely to one service (RSPG, 2021). As such, it may be best to designate portions of spectrum more commonly used for "crowded" areas, like Wi-Fi hotspots or Bluetooth speakers. Such an arrangement would not be an issue for weather satellites, since their concern is primarily with 5G technology.

Step 2: Designating Frequency Ranges for Sharing and Initiating Rulemaking

It will next be necessary to determine which frequency bands should be designated for sharing first. Traditionally, passive radio services have opportunistically observed unused frequencies outside their protected bands, since their remoteness makes it less like that, for example, a cell tower is located nearby. This paradigm may not change immediately; only in the longer term will opportunistic observation become impossible as more facilities build up around areas like the desert where the VLA is located. FCC should therefore initiate spectrum sharing rulemaking in the frequency bands adjacent to currently protected bands. The reason for this is two-fold: first, it provides a convenient "test" area for a sharing scheme to see how active and passive spectrum users can collaborate and to work out "kinks" in the process; and second, it will act as an immediate-term relief to radio astronomers from spurious and out-of-band emissions from neighboring frequencies (NAS, 2010).

At the same time, FCC should carefully review the views of relevant stakeholders during the comment period of the rulemaking process. For instance, it may transpire that the first proposed sharing ranges are of lesser scientific interest to radio astronomy, or government groups may note that there are parts of their spectrum that they control but do not often use. By following this method, FCC can maximize the efficiency of the sharing process while gaining more buy-in from powerful groups. In particular, FCC should take heed of the views of deep-pocketed mobile communications companies while remaining firmly dedicated to the protection of passive services.

Toward this end, questions for comment should be framed with language such as "Is there a better frequency range than the proposed one," or "How can this sharing scheme best balance the needs of *all* stakeholders." In this way, FCC can frame the debate in a more productive light and gain the productive opinions of groups who might otherwise simply oppose the process.

Step 3: Evaluate Results and Expand Program

After rules are finalized and the initial spectrum scheme is operational, FCC should systematically collect feedback from all parties involved. This will add some steps to the process, since it will likely require Paperwork Reduction Act (PRA) disclosures, but it will provide valuable information for future rulemakings.

Based on this feedback, FCC should continue to implement sharing programs in key frequency ranges. Some sharing will most likely be necessary between 5G and 4G-LTE networks, for example. Over time, the need for such arrangements will grow, and the experience FCC has developed from these efforts to protect passive services will be highly useful.

Drawbacks and Challenges

One drawback of this policy is its failure to address the needs of aviation. Under all scenarios, some delays will probably take place under poor weather conditions (that demand an instrument landing), but in absolute terms, this is a small factor. These delays will probably be confined to regional flights with older planes, and those prone to adverse landing conditions.

Conclusion

RFI is a technically complex and perennially challenging policy issue. The old format of rigid spectrum allocation favored by FCC and ITU is no longer sustainable in a world with ever-growing demand for electromagnetic spectrum use. The current paradigm fails to protect passive users of the spectrum, and everyday commercial device users will soon feel the effects of interference too. As scientific discoveries have time and again proved incalculably useful to society, and as astronomers peer ever farther into the mysteries of the Universe, the need for rigorous protection of science has never been greater. By implementing dynamic spectrum sharing across the United States, FCC can ensure an efficient, sustainable, and more connected future for the global public.

Source: National Science Foundation

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Appendix: Cost-Effectiveness Methodology and Tables

Note: For all calculations, a standard discount rate of 3% is used.

Status Quo

Table 1.1: Total Costs, Status Quo

	Astronomy	Aviation	Meteorology	Total ($M)
Year 0: 2020	$5.250	0	0	$5.250
2021	$5.352	0	0	$5.352
2022	$5.456	$8,128.005	$17,815.063	$25,948.523
2023	$5.562	$7,891.27	$17,296.18	$25,193.006
2024	$5.670	$4,596.85	$16,792.41	$21,394.929
2025	$5.780	$4,462.97	$16,303.31	$20,772.051
2026	$5.892	$4,332.98	$15,828.45	$20,167.321
2027	$6.007	$4,206.77	$15,367.43	$19,580.209
2028	$6.123	$4,084.25	$14,919.83	$19,010.203
2029	$6.242	$3,965.29	$14,485.28	$18,456.805
Year 10: 2030	$6.363	$3,849.79	$14,063.37	$17,919.531
Total ($M)	$63.696	$45,518.17	$142,871.32	$188,453.181

Table 1.2: Total Outcomes, Status Quo

	Astronomy	Aviation	Meteorology	Total (hours)
Year 0: 2020	16,161.00	-	-	16,161.00
2021	16,969.05	-	-	16,969.05
2022	17,817.50	4,560.00	12,264.00	34,641.50
2023	18,708.38	4,560.00	12,264.00	35,532.38
2024	19,643.80	2,730.00	12,264.00	34,637.80
2025	20,625.99	2,730.00	12,264.00	35,619.99
2026	21,657.29	2,730.00	12,264.00	36,651.29
2027	22,740.15	2,730.00	12,264.00	37,734.15
2028	23,877.16	2,730.00	12,264.00	38,871.16
2029	25,071.02	2,730.00	12,264.00	40,065.02
Year 10: 2030	26,324.57	2,730.00	12,264.00	41,318.57
Total (hours)	229,595.89	28,230.00	110,376.00	368,201.89

Summary

Outcomes and Costs for Radio Astronomy

Radio astronomy loses roughly 5% of operating time based on ITU estimate, leading to over $5 million in annual losses. These losses grow, however: from 1957 to 2016, the number of satellites in orbit grew from 0 to 1466, adding roughly 21 satellites per year, on average (Salas, 2022). From 2016 to 2022, that number ballooned to 4,877 active satellites in orbit, with an average annual growth rate of roughly 28%, as satellite "megaconstellations" began launching in 2019 – in fact, the growth rate was over 40% between 2019 and 2021 (Salas, 2022). As other companies such as OneWeb, Telesat, and Amazon deploy their own constellations, this high growth rate will continue – as will the amount of interference placed on radio astronomy facilities (Petrova & Sheetz, 2019; Scharping, 2021). However, the increase in interference will correlate more strongly with the number of *constellations* overhead, rather than the number of *satellites*, because not all satellites will fly above radio astronomy installations. Therefore, I make the conservative assumption of a 5% increase in interference and associated costs each year.

The Green Bank Observatory operates roughly 6500 hours per year, so a loss of 5% of that time equates to 325 wasted hours of observation time (GBO, 2016). The Very Large Array (VLA) and Very Long Baseline Array (VLBA), the two other main American radio astronomy facilities, are mostly autonomous and are intended to be operated continuously (VLA, n.d.; VLBA, n.d.). Therefore, I will assume 24 * 365 = 8,760 hours for each installation. VLBA has 10 dishes spread across the United States, while VLA has 27 arranged in various patterns in one large area (VLA, n.d.; VLBA, n.d.). 5% of time lost for each of these dishes is 428 hours lost each.

Thus the total outcome for radio astronomy is (27 * 428) + (10 * 428) + 325 = 16,161 hours of lost observation time annually. Per the above discussion, this figure will grow at 5% each year under the status quo.

Outcomes and Costs for Aviation

As noted in this report, 10% of flights are currently barred from instrument landings, because the radar altimeters used to help planes land in such conditions can no longer be trusted to function properly in the presence of 5G cell towers (Dickson, 2022; Shepardson, 2022). Over time, however, some of these altimeters will be cleared for use, while others will simply be phased out as planes are decommissioned. Therefore, I assume 5% of flights will experience a delay for the first two years and 3% after that, with an average delay of roughly one hour. Based on the externalities generated from pollution caused by the extra flight time (Tiseo, 2021), the cost to airline companies (FAA, 2020), and the wasted time of passengers (U.S. Census Bureau, 2021), I calculate in the above report a status-quo loss to society of $8.623 billion per year for the first two years once 5G rolls out in 2022, and $5.1738 billion annually for the remaining 6 years in the analysis period. (FAA, n.d.). There are roughly 16.4 million flights in America each year, so 5% of that total is 820,000 flights, and 3% is 492,000. Projections of radio interference during flight landings predict an interference spike around 275 feet, creating about 20 seconds of faulty observations before landing (RTIA, 2020).

20 seconds of ruined observation time multiplied by 820,000 flights leads to roughly 4,560 hours of lost observation time per year for two years, and 2,730 hours annually after that.

Outcomes and Costs for Meteorology

5G will affect portions of the radio spectrum specifically needed by the National Weather Service to measure water vapor and precipitation totals (Calma, 2019). Acting National Oceanic and Atmospheric Administration (NOAA) Commissioner Neil Jacobs testified in 2019 that 70% of data observations will effectively be lost, creating a 30% reduction in forecast accuracy (Jacobs, 2019). Across the American economy, roughly $13 billion is generated in revenue as a direct result of accurate weather predictions, meaning that $3.9 billion will be lost annually due to 5G radio interference, assuming losses proportional to prediction accuracy (NWS, 2017). There is another direct cost created by this poorer accuracy: damage caused by severe weather. For example, Jacobs testified that NOAA will miss the average hurricane landfall by 2-3 days. An increase by 30% in these costs (again, assuming losses proportional to prediction accuracy) means that the $50 billion the U.S. currently loses per year due to severe weather will increase by $15 billion (NOAA, 2021). Ultimately, this means an annual loss of over $17.8 billion once 5G technology is initiated.

NOAA's current satellites use a tool called the Advanced Baseline Imager (ABI) that scans an entire hemisphere of Earth over the course of a 10-minute cycle, in addition to taking other scans (NOAA & NASA, n.d.). This means that each of NOAA's main satellites (GOES-16 and GOES-18, as of March 2022) scans 144 times each day. If 70% of the data gathered during these scans is lost, that is 7 minutes of wasted observation time *per scan*.

Thus, the total loss is as follows:
2 satellites * 7 minutes wasted * 144 scans/day * 365 days / 60 minutes/hour = 12,264 hours wasted

As with aviation, this loss will start in 2022 as 5G technology in America launches, so there are no wasted observations during the first two years of the policy period. The 12,264 figure will remain constant after that because this phenomenon is caused by the mere presence of active 5G operations, rather than the intensity of use.

Alternative 1

Table 2.1: Total Costs, Alternative 1

	Program Costs	Astronomy	Aviation	Meteorology	Total ($M)
Year 0: 2020	0	$5.250	0	0	$5.250
2021	0	$5.352	0	0	$5.352
2022	0	$1.091	$8,128.005	$5,938.354	$14,067.450
2023	0	$1.112	$7,891.27	$5,765.39	$13,657.771
2024	0	$1.134	$4,596.85	$5,597.47	$10,195.457
2025	0	$1.156	$4,462.97	$5,434.44	$9,898.557
2026	0	$1.178	$4,332.98	$5,276.15	$9,610.305
2027	0	$1.201	$4,206.77	$5,122.48	$9,330.451
2028	0	$1.225	$4,084.25	$4,973.28	$9,058.748
2029	0	$1.248	$3,965.29	$4,828.43	$8,794.961
Year 10: 2030	0	$1.273	$3,849.79	$4,687.79	$8,538.857
Total ($M)	0	$21.221	$45,518.17	$47,623.77	$93,163.159

Table 2.2: Total Outcomes, Alternative 1

	Astronomy	Aviation	Meteorology	Total (hours)
Year 0: 2020	16,161.00	-	-	16,161.00
2021	16,969.05	-	-	16,969.05
2022	3,563.50	4,560.00	4,380.00	12,503.50
2023	3,741.68	4,560.00	4,380.00	12,681.68
2024	3,928.76	2,730.00	4,380.00	11,038.76
2025	4,125.20	2,730.00	4,380.00	11,235.20
2026	4,331.46	2,730.00	4,380.00	11,441.46
2027	4,548.03	2,730.00	4,380.00	11,658.03
2028	4,775.43	2,730.00	4,380.00	11,885.43
2029	5,014.20	2,730.00	4,380.00	12,124.20
Year 10: 2030	5,264.91	2,730.00	4,380.00	12,374.91
Total (hours)	72,423.22	28,230.00	39,420.00	140,073.22

Summary

Costs for Alternative 1

Costs for this policy are determined by how they affect the three main stakeholder industries. The administrative costs borne by FCC are negligible because FCC recoups its investments by selling broadcasting licenses and auctioning spectrum access – for example, FCC recently netted $4.5 billion by auctioning licenses for the Citizens' Broadband Radio Service, the first operational spectrum sharing scheme in the U.S. (Gold, 2020).[3]

Barb et al. (2021) estimate the maximum data loss under a DSS scheme would be roughly 25%. I assert that this figure does not apply to the aviation industry, because the nature of altimeters does not lend itself to sharing at all. However, a decrease of data loss from 70% to 25% would be highly beneficial for the meteorology industry, so I predict that forecast accuracy will increase proportionally. Thus, the new figure is a loss of only around 10% in accuracy. For astronomy, access to the whole spectrum is not always needed, so a DSS scheme could eliminate almost all problematic interference, reducing costs for that industry to 1% of budget (down from 5%). FCC would not implement this policy until 2022 (analysis year 2), so costs from Years 0 and 1 would remain for astronomy.

Outcomes for Alternative 1

For radio astronomy, this alternative would significantly curtail wasted observation time with immediate effect, though some interference due out-of-band emissions would almost certainly remain. Thus, the 5% of total time wasted under the status quo would be reduced to 1%, as stated above. Still, I assume this figure will continue to grow as radio-emitting devices and satellites continue to proliferate over the next decade, as it is unrealistic to assume these new devices would not interfere at all, even under a spectrum sharing scheme. Thus the 16,161 hours wasted annually becomes 3,563 hours in Year 2 (16,161 grows by 5% each year, but is reduced five-fold in year 2).

As stated above, this policy would not affect the aviation industry. However, for meteorology, a reduction of data loss from 70% to 25% means that only 2.5 minutes of each 10-minute scan is lost. Therefore, there are only 4,380 hours of lost observation time annually under this alternative.

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[3] FCC does not seem to account for these costs in any systematic manner in its own economic analyses. See, for example: Federal Communications Commission. (2020). *Report and Order and Further Notice of Proposed Rulemaking, In the Matter of Unlicensed Use of the 6 GHz Band: Expanding Flexible Use in Mid-Band Spectrum Between 3.7 and 24 GHz*. https://ecfsapi.fcc.gov/file/0424167164769/FCC-20-51A1.pdf

Alternative 2

Table 3.1: Total Costs, Alternative 2

	Program Costs	Astronomy	Aviation	Meteorology	Other	Total ($M)
Year 0: 2020	0	$5.250	0	0	0	$5.250
2021	0	$5.352	0	0	0	$5.352
2022	$5.74	0	$8,128.01	$17,815.063	$0.943	$25,949.750
2023	$5.74	0	$7,891.27	$17,296.18	$0.92	$25,194.099
2024	$5.74	0	$4,596.85	$16,792.41	$0.89	$21,395.888
2025	$5.74	0	$4,462.97	$16,303.31	$0.86	$20,772.874
2026	$5.74	0	$4,332.98	$15,828.45	$0.84	$20,168.006
2027	$5.74	0	$4,206.77	$15,367.43	$0.81	$19,580.756
2028	$5.74	0	$4,084.25	$14,919.83	$0.79	$19,010.610
2029	$5.74	0	$3,965.29	$14,485.28	$0.77	$18,457.070
Year 10: 2030	$5.74	0	$3,849.79	$14,063.37	$0.74	$17,919.653
Total ($M)	$51.66	$10.602	$45,518.17	$142,871.32	$7.56	$188,459.309

Table 3.2: Total Outcomes, Alternative 2

	Astronomy	Aviation	Meteorology	Total (hours)
Year 0: 2020	16,161.00	-	-	16,161.00
2021	16,969.05	-	-	16,969.05
2022	-	4,560.00	4,380.00	8,940.00
2023	-	4,560.00	4,380.00	8,940.00
2024	-	2,730.00	4,380.00	7,110.00
2025	-	2,730.00	4,380.00	7,110.00
2026	-	2,730.00	4,380.00	7,110.00
2027	-	2,730.00	4,380.00	7,110.00
2028	-	2,730.00	4,380.00	7,110.00
2029	-	2,730.00	4,380.00	7,110.00
Year 10: 2030	-	2,730.00	4,380.00	7,110.00
Total (hours)	33,130.05	28,230.00	39,420.00	100,780.05

Summary

Costs for Alternative 2

This alternative is directed mainly at the radio astronomy industry, and would not significantly change outcomes or costs for aviation or meteorology. For astronomy, there are direct spending costs due to the infusion of funds from FCC to the Green Bank Observatory (the telescope located in the NRQZ) and to the National Radio Astronomy Observatory (which manages VLBA and VLA). There are also costs created by the restrictions placed on satellites.

This analysis proposes increasing NRQZ funding by $2.59 million – the difference between Green Bank's FY2020 spending and the funding it previously got in FY2019 from the National Radio Astronomy Observatory (NSF, 2020; NSF, 2021). NRAO funding would also be increased by $3.5 million annually; this amount reflects how much was spent in FY2020 on a special spectrum innovation project designed to protect radio astronomy services from RFI (NSF, 2022).

The costs to satellite producers are as follows: SpaceX, by far the largest satellite owner in low-earth orbit, plans to launch 30,000 Starlink internet satellites by 2030, at a cost of roughly $250,000 to $500,000 per satellite (Barrett, 2022; Rainbow, 2022). The proposed FCC regulations would require such satellites to stop broadcasting over the NRQZ. The simplest way to estimate costs, then, is to use the proportion of Earth's surface area over which the satellites could not operate. The NRQZ has a surface area of roughly 13,250 square miles, which is about 0.00673 percent of the Earth's surface area. If 30,000 satellites valued at $500,000 each cannot operate over that 0.00673% of the Earth, there is an opportunity cost of about $1 million each year. The VLA and VLBA sites are excluded from this calculation because the VLA is located on a comparatively tiny parcel of land, while VLBA is primarily composed of single telescopes spread across the U.S.

Outcomes for Alternative 2

The additional funding to radio astronomy in the U.S., particularly in the NRQZ and the remote area where VLA is located, is presumed to practically eliminate significant RFI issues for that industry. However, it would not protect aviation or meteorology at all, somewhat diminishing the change in outcomes.

Alternative 3

Table 4.1: Total Costs, Alternative 3

	Program Costs	Astronomy	Aviation	Meteorology	Total ($M)
Year 0: 2020	0	$5.250	0	0	$5.250
2021	0	$5.352	0	0	$5.352
2022	0	$1.091	$8,128.005	$17,815.063	$25,943.067
2023	0	$1.112	$7,891.27	$17,296.18	$25,187.444
2024	$2,022.676752	$1.134	$4,596.85	$16,792.41	$21,389.259
2025	0	$1.156	$4,462.97	0	$4,462.965
2026	0	$1.178	$4,332.98	0	$4,332.976
2027	0	$1.201	$4,206.77	0	$4,206.773
2028	0	$1.225	$4,084.25	0	$4,084.245
2029	0	$1.248	$3,965.29	0	$3,965.287
Year 10: 2030	0	$1.273	$3,849.79	0	$3,849.793
Total ($M)	$2,022.676752	$21.211	$45,518.17	$51,903.65	$97,443.031

Table 4.2: Total Outcomes, Alternative 3

	Astronomy	Aviation	Meteorology	Total (hours)
Year 0: 2020	16,161.00	-	-	16,161.00
2021	16,969.05	-	-	16,969.05
2022	3,563.50	4,560.00	12,264.00	20,387.50
2023	3,741.68	4,560.00	12,264.00	20,565.68
2024	3,928.76	2,730.00	12,264.00	18,922.76
2025	4,125.20	2,730.00	-	6,855.20
2026	4,331.46	2,730.00	-	7,061.46
2027	4,548.03	2,730.00	-	7,278.03
2028	4,775.43	2,730.00	-	7,505.43
2029	5,014.20	2,730.00	-	7,744.20
Year 10: 2030	5,264.91	2,730.00	-	7,994.91
Total (hours)	72,423.22	28,230.00	36,792.00	137,445.22

Summary

Costs for Alternative 3

This policy is costly, because it would involve FCC reclaiming the band of radio frequency that was auctioned off in 2019 which caused so much harm to the meteorology industry. Current licensees of that spectrum would miss out on much of their investment, which in 2019 totaled over $2.022 billion (FCC Public Reporting System, n.d.). That cost is factored into Year 4 of this analysis since licensees would not have to give up their spectrum until 2024 at the earliest. However, at Year 5, the meteorology would no longer have any costs from RFI, generating significant cost savings adding to those from radio astronomy throughout. The aviation industry would again not realize any change in costs.

Outcomes for Alternative 3

By protecting radio astronomy, this policy would, like Alternative 1, reduce the 5% lost observation time to roughly 1%, as a total protection in this case would be unrealistic. The meteorology industry would benefit later, going from losing 70% of observations likely to 0% by Year 5, meaning that each 10-minute scan loses 0 minutes due to interference. This alternative would not help aviation, because it does not impact the presence of potentially harmful 5G installations near airports.

Table 5: Overall Cost-Effectiveness

Scenario	Cost to Society (M)	Hours Wasted	Hours Saved	Cost-Effectiveness
Status Quo	$188,453.18	368,201.89	N/A	511,820.25
Alt. 1: Spectrum Sharing	$93,163.16	140,073.22	228,128.67	408,379.88
Alt. 2: Protect Radio Astronomy	$188,459.31	100,780.05	267,421.84	704,726.70
Alt. 3: Strict Allocation	$97,443.03	137,445.22	230,756.67	422,276.12