Satellite Constellations and Their Effect on Radio Astronomy

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

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Spring 2024

On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Radio frequencies are a finite resource that have become an integral part of everyday life. Radio astronomy, which requires these frequencies, gave astronomers a new way of learning about the universe, including distant stars and galaxies. It was born in 1933 when Karl Jansky created the first radio telescope while working for Bell Labs, trying to remove background noise (Madrigal, n.d.). Over the years, astronomers have found new uses for the technology and have continually tried to preserve more of the finite radio frequencies.

Radio astronomy was about two decades old before the first spacecraft, Sputnik, was launched on October 4, 1957 (Divine, 1993). Since then humanity has dreamed about what could be done with spacecraft orbiting Earth. From communications to research to reconnaissance, the use cases have continued to increase. Figure 1 shows the increase in the satellites over time which has only accelerated in recent years. Much of this increase in the number of satellites can be attributed to new satellite constellations. Unfortunately, this drastic increase in the number of satellites also means the amount of interference has also increased over the years. While some aspects of the rapid growth in satellite constellations have drawn large scrutiny, others such as radio interference haven't gained as much attention. "Environmental concerns regarding satellites during their operational lifetimes have focused foremost on their impacts on human views of the nighttime sky" (Gaston et al.,

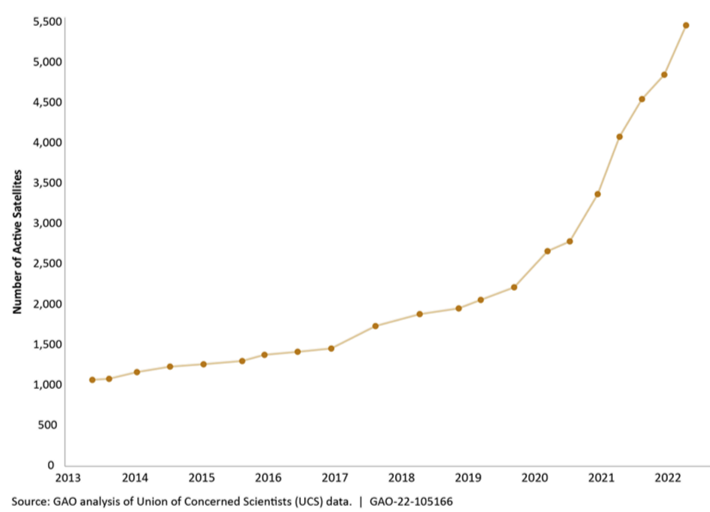

Figure 1: Satellites in Orbit (*Large Constellations of Satellites*, 2022)

2023). As Gaston states, most of our attention has focused on what we can see, not necessarily what might impact the devices or science around us.

Much of the growth in the number of satellites has come from satellite constellations with many having the goal of making a reliable internet connection more widespread. Companies like SpaceX with Starlink, Amazon with Kuiper, and Telesat with Telesat Lightspeed are all trying to get in on the new space economy to connect those without access to reliable internet. Satellite constellations aren't a new concept, but the location of these satellite constellations compared to most from the past is. While most constellations of the past positioned satellites in Geostationary Orbit (GEO) which is very far away from the Earth, but has the benefit of needing just a few satellites, these new constellations are positioning themselves much closer to the Earth in Low Earth Orbit (LEO). These constellations benefit from much lower latency and the ability to transmit at much higher speeds but require many more satellites.

Both radio astronomers and satellite operators rely on regulators to allocate frequencies to them so they can use them to complete science and transmit data respectively. As the number of satellites has continued to increase, the amount of frequency requested for use by satellite companies has increased, and the amount of frequency has remained constant. Regulators have to play a difficult balancing act to ensure both radio astronomers and satellite operators are getting the frequencies they need to operate, but also that neither party is interfering with the other or other external actors.

In this paper, I argue that regulation organizations need to be more involved in the regulation and prevention of interference between radio astronomers and satellite operators. National and international organizations regulate these frequencies to prevent interference from occurring, but yet, with frequency bands as crowded as they are, interference still occurs. Due to the number of organizations involved with the regulation and prevention of interference, many don't know who is responsible for what which leads to confusion and missing pieces of regulation.

This paper first explores the methods being used in analyzing the connections between the parties involved. I will then explore examples of interference in the past, how those situations have been solved, and what regulators are doing to mitigate these issues. Then a further analysis of each of the main actors involved is undertaken, including radio astronomers, satellite operators, and regulators. A chart showing the relation between the actors is seen in Figure 2. Regulatory agencies bridge the gap between satellite operators and radio astronomers, acting as gatekeepers to the important frequency that each needs to successfully operate. The paper then concludes by giving an analysis of the connections between the stakeholders, using Actor-Network Theory (ANT) and giving some potential ideas of how to mend the connections between the stakeholders.

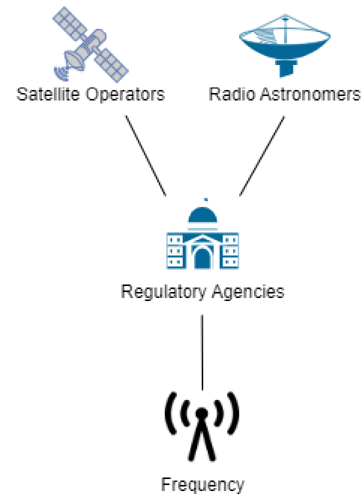

Figure 2: Actor Relationships

Method

In analyzing usage and interference of frequencies used by both radio astronomers and satellite constellations, as a result of the explosion in growth within the industry, this paper uses Actor-Network Theory (ANT). It is useful in this scenario as the limited radio frequency has resulted in a complex network of relationships to increase frequency allocations for each of the respective parties. There are many stakeholders involved in supporting radio astronomers and satellite operators in vying for the limited allocation available. ANT postulates that every system is just a combination of human and non-human actors at work that make up a network (Nickerson, 2023). The ANT framework describes these human and non-human players, making it appropriate for use in this paper. Actor-Network Theory, which is a science, technology, and society framework, analyzes the current conflict between different radio frequency users. To identify the issues and how to potentially solve them the paper then analyzes the relationships between each of the actors. The first step is to identify the main actors of the networks as the regulators, radio astronomers, and satellite operators with other actors being NASA, the frequency, universities, science foundations, and satellite manufacturers. I argue that this complex scenario is two separate networks with one centered around radio astronomers and one centered around satellite operators with the networks connecting with the regulators.

This paper will use a mix of historical references, public policy, and communications and media. The broad range of different methods allows for a clearer picture of the situation and helps to remove the bias from a specific source, even though this bias could be a useful tool during analysis. The use of historical references allows the paper to describe examples from the past of radio inference and solutions to resolve the issue. Whether society could employ these methods from the past in the challenges relating to the current radio interference is analyzed from the information collected from these historical sources. Public policy looks into the different organizations that have an input in the regulation of the radio spectrum and whether what they are currently doing is working for the industry as a whole. Communications and media will also play an important role in analyzing the complex relationship between the actors involved. Media then gives a picture as to where most of the support for radio allocations and interference is, either with the radio astronomers or the satellite operators. The paper also leverages more recent documents that analyze the current satellite networks and radio astronomers. Altogether, along with the use of ANT, these methods give a picture of the relationship between radio astronomers and satellite operators.

This paper dives into the different actors at play relating to radio frequency. Why radio interference is such a large problem will be the first section of the paper. Next, I will discuss each of the main actors relating to the radio frequencies. The paper then discusses the radio astronomers and satellite operators, who are the two main parties going after the radio frequency. After that, I will discuss the role of regulators and their relationship between the radio frequency and other actors. The paper finally addresses that it is important to note that some of these actors have more power than others with the end goal actor, the regulators.

Background

Fortunately or unfortunately these mega-constellations aren't the first satellites to have problems producing interference for radio telescopes. On one hand, there is the benefit of being able to learn from past mistakes, but at the same time, the fact that it has happened before so much shows just how easy it is for it to occur. GLONASS, which is the Russian equivalent to GPS, the Global Positioning System, submitted its proposal for radio frequency usage to the International Telecommunication Union (ITU) in 1983 with no objections within the approved time. GLONASS was launched and began transmitting close to the 1612 MHz band in 1984 (Robinson, 1999). While to many this might not seem of any consequence, the 1612 MHz band is extremely important to radio astronomers as this is a satellite line for Hydroxyl (OH). Despite this fact, it would not be until November 1993 that an agreement was reached to phase out the use of that band with GLONASS by 2007 (Robinson, 1999). GLONASS highlights one of the issues with the industry in that if satellites are launched that produce interference, it could be years or even decades to solve the problem when a new set of replacement satellites is launched.

Iridium, one of the first satellite constellation operators has also had a fair share of difficulties with radio interference. The Iridium constellation comprises 66 satellites that provide voice and low data rate services with the 1616-1626.5 MHz band. Again radio astronomers were worried about the possible interference at the 1612 MHz band. In 1994, the National Radio Astronomy Observatory (NRAO) signed an agreement with Iridium, but international radio astronomers were not happy with the few restrictions placed on Iridium (Robinson, 1999; Cohen, 2004). Further agreements were created between Australia and Europe and talks between India and Canada continued (Robinson, 1999; Cohen, 2004). While countries came together to protest GLONASS and Iridium interference, it was up to individual countries and observatories to create agreements to mitigate interference. Not only is this a time-consuming and expensive process, but it also results in fractured agreements that might not be the best for radio astronomers as a whole. Interference coordination between astronomers and satellite operators has been taking place for decades and only has continued to accelerate.

Radio Astronomers

Not only does astronomy advance scientific understanding and give technological advancements, but "Astronomy is one of the few scientific fields that interacts directly with society. Not only transcending borders, but actively promoting collaborations around the world" (Rosenberg et al., 2013). Building these connections between countries is good for the world as a whole and opens up the doors to possible cooperation in other industries. Looking at radio astronomers they are concerned with specific ranges of the spectrum, which allows astronomers to see things in space that we would otherwise not be able to detect (Driel, 2009). These are all important aspects of radio astronomy, and more generally astronomy, that must be protected. Radio astronomers rely on regulators to keep certain parts of the frequency protected which allows them to identify different kinds of compounds and elements such as hydroxyl. At frequencies less than 4 GHz, radio astronomers have about 5% of the spectrum with some kind of protection against interference (Vruno et al., 2023). It has become increasingly hard for radio astronomers to do their work with the increasing connectivity of the world, but astronomers have gotten around it by locating equipment in locations with low radio emissions. Figure 3 shows the differences between radio emissions in Sydney compared to Murchison, New Zealand, where a radio telescope is located. Figure 3 shows the high usage of the radio frequency, which would make it difficult to get usable data in a place like Sydney or Narrabri. Location has been an important factor for radio telescopes over the past few decades, but with satellite constellations beaming down from space, these quiet zones are much harder to find. Figure 4 shows what a star looks like for ground-based observatories if no satellites were transmitting in orbit vs the thousands that currently are.

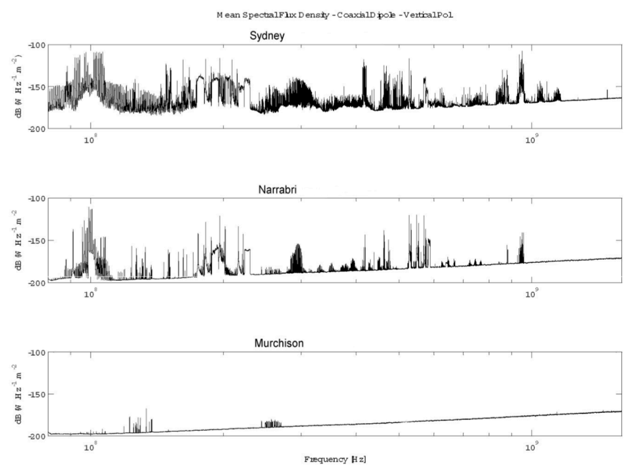

Figure 3: Radio Interference by Location (Kesteven, 2010)

Unfortunately for astronomers, it is harder for them to get their case across to members of government and regulators as radio astronomers do not have any easily identifiable impacts on the economy. Unlike the spacecraft manufacturers and operators, most public scientific organizations are not driven primarily by profit. Members of the government would rather support a project, like a satellite network, that has a large economic value but might impact other current uses of the frequency. This is where the importance of the public reaching out to

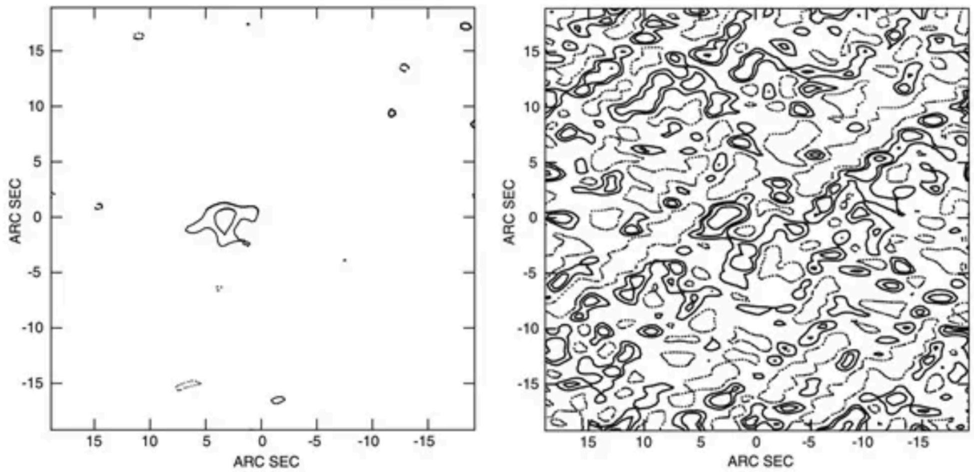

Figure 4: Star with and without Radio Interference (DePree, 2023)

members of the government comes in. Astronomers also rely on their connections and scientific organizations to participate in lobbying on their behalf.

Figure 5 gives a good summary of some of the actors described above that radio astronomers have for assisting in coordinating with regulatory agencies and how they are connected. Radio astronomers work on strengthening these relationships with each of the members

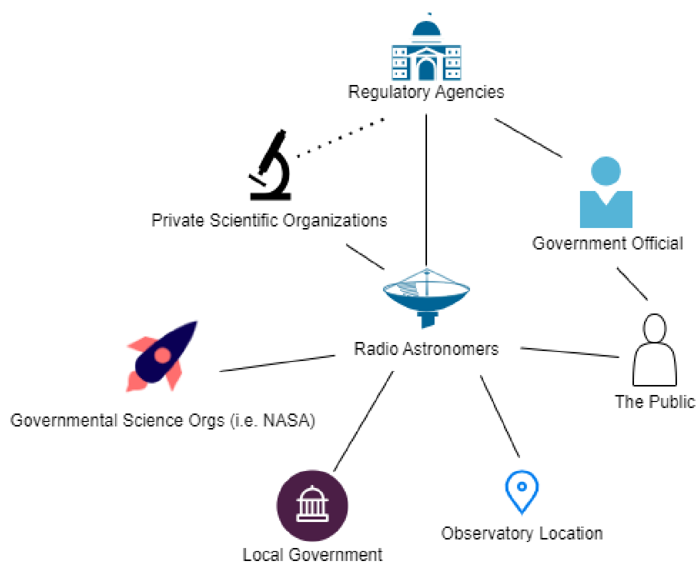

Figure 5: Radio Astronomers Network

within their network since they help them lobby regulatory agencies to continue protecting the frequency needed to do their work. Comparing this network to the limited network shown in

Figure 2 displays a completely different story, and Figure 5 just highlights a few of the larger actors involved with radio astronomers.

Satellite Operators

Internet providers have struggled to provide cost-effective and competitive internet services to those in rural locations as the opportunity cost is not good for these areas, but satellite internet constellations are aiming to change that. Satellite internet constellations have been around for decades, but have provided service with low bandwidth and high costs. New startups are jumping rapidly into this market to provide internet services that rival terrestrial-based equivalents thanks to the advent of cheap and reliable rocket launches. These startups require massive constellations and allocation of frequency bands to operate. Governments and regulators have generally been very accommodating as they realize the economic potential, and for many, the re-election potential, of connecting those without internet access in an age when reliable internet access is a need.

Many of the companies focus their claims on being able to connect the masses, Matthew Graydon and Lisa Parks explain that "It is not surprising that US satellite companies face challenges adhering to a vision of supporting unconnected communities given that they are ultimately driven by profit" (Graydon & Parks, 2020). They raise an interesting point that many of these companies are hoping for a massive profit by operating these systems in space and the truth is those who don't currently have internet access comprise of many people who would not be able to pay for it either. Gray and Parks go on to explain that it will be important to ensure satellite internet operators are held to the promises they make. Not only would they not be delivering on the promises they make, but they would be taking away from frequency that could otherwise be used by radio astronomers.

For these companies to begin offering service, they must be allocated the frequency in which the satellite may operate. This is the important step where licensing agencies and regulators must ensure new allocations won't overlap with existing allocations. Different from radio astronomers, these companies need a piece of the spectrum to be used for transmitting and receiving signals. Radio astronomers need small pieces of frequency protected across the spectrum, as each of these pieces aligns with some kind of emission from distant sources. While satellites are generally allocated frequency in bands where little to no interference will occur, there is often unintended electromagnetic radiation, which is produced just from the operation of the satellite. This is exactly what happened with the Iridium constellation discussed above. SpaceX with Starlink is also subject to these same problems. A recent study showed that Starlink, while allocated for the frequency band of 10.7–12.7 GHz, has radiation being output in the 110 and 188 MHz range (Vruno et al., 2023). While most of these signals are not nearly as strong as the main signals being transmitted, they have huge impacts on radio astronomers since most of the signals they are trying to detect are very distant and very weak.

Just like the radio astronomers above, satellite operators have allied themselves with many stakeholders within the industry to promote their case for frequency allocation. Some of these actors include satellite manufacturers, launch providers, public officials, and the public. The defense industry is also very interested in satellite constellations as they provide another means of communication in the event of a global conflict or some other event that knocks out primary forms of communication. Figure 6 highlights some of these actors and their relationships with each other. These are just a few of the actors that satellite operators have on their side to assist in convincing regulators of the importance of allocating frequency to them.

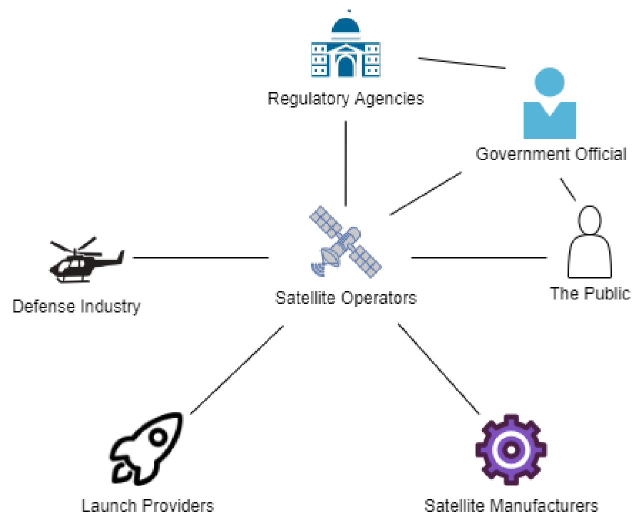

Figure 6: Satellite Operators Network

Regulatory Agencies

Regulators play an important role and their influence can be seen in the complex networks, as shown in Figures 5 and 6, that have been formed by both radio astronomers and satellite operators. While allocations of frequency take place at the national level by organizations part of national governments, the International Telecommunication Union (ITU), specifically the radiocommunications branch (ITU-R), is responsible for coordinating frequencies between nations to ensure that allocations will not overlap with one another (Vruno et al., 2023). Although the ITU has the final say in the coordination of allocations between countries, other organizations specifically have the concerns of radio astronomers in mind. The Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science (IUCAF) is an international organization that represents radio astronomers and radio observatories and was instrumental in solving interference from GLONASS (Ibrahim, 2021). There are also three regional organizations, the Committee on Radio Frequencies of the National Academy of Science (CORF), the Expert Committee on Radio Astronomy Frequencies of the European Science Foundation (CRAF), and the Radio Astronomy Frequency Committee in the Asia-Pacific region (RAFCAP) (Driel, 2009). While the radio astronomy community has done a good job of setting up these organizations, a lack of international coordination has created challenges as evidenced in the agreements with Iridium. In a recent interview with Harvey Liszt, the chair of the IUCAF, he stated, “Outside of ITU-R we are attempting to get additional protections implemented through the UN Office of Outer Space Affairs (UNOOSA) Subcommittee on the Peaceful Uses of Outer Space (COPUOS)” (Ibrahim, 2021). This quote from Husam Ibrahim’s interview of Liszt highlights the issue that there is not just one centralized organization of radio astronomers can go to regarding frequency. Another recent agreement, in early 2023, between SpaceX and the National Science Foundation (NSF) was announced to protect radio observatories within the United States (*NSF Statement on NSF and SpaceX Astronomy Coordination Agreement | NSF - National Science Foundation,* 2023). This incomplete description of organizations and agreements highlights the sheer number involved with radio astronomy and frequency allocation. Each time there is a new agreement regarding the protection of frequencies, it seems to be between a different organization. As more constellations and satellites are launched into space, coordination between and consolidation of the organizations should be encouraged. Astronomers can not afford to deal with already launched satellites creating interference as evidenced by GLONASS.

Analysis

Regulators of radio frequencies have been trying to catch up with the industry for the past few decades. Satellite operators, radio astronomers, and frankly, the general public all rely on regulators to ensure widespread interference of one of the most important finite resources does not occur. Figure 7 shows the complete network with the two subnetworks combined, highlighting the importance that regulatory agencies play in safeguarding the frequency. Satellite

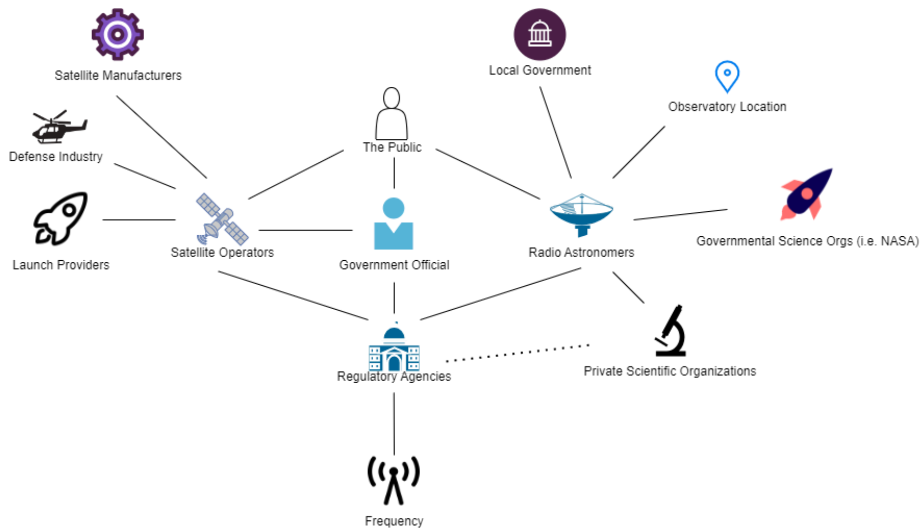

Figure 7: Full Network surrounding Regulatory Agencies

operators have been continuously expanding with every increasing constellation size being proposed. This massive expansion has caught regulators off guard, understaffed, and overworked, which has resulted in fractured and insufficient agreements. A side effect has been that there are now too many different organizations trying to play a part in the allocation and regulation of frequencies which has made it difficult for uniform results internationally. The ITU, which internationally has the most power concerning frequencies, needs to have the final say on who gets allocated frequencies due to their international nature. There can be an organization that has the authority to create agreements relating to radio observatories, but there should not be one for each observatory or every nation. The truth is that no matter where you are on Earth, the satellite hydroxyl line is at the same frequency. This is true of all phenomena from space. Radio observatories need to work together and consolidate their agreement-making to ensure their scientific capability is not lost.

Regulators also need to put more emphasis on testing for unintended electromagnetic radiation. This is where much of the interference experienced today is coming from and not enough effort had gone into ground testing and mitigation before the launching of satellite constellations. While there wasn't much consequence when a few dozen satellites were orbiting the Earth, the effects are much higher with thousands of satellites in orbit.

Potential Changes

Many of the new mega satellite operators realize they need to make changes to coincide with radio observatories with limited frequency resources. In SpaceX's 2023 agreement with NSF, they stated "its [SpaceX's] second-generation satellites include dielectric mirror film, solar array mitigations, new black paint that minimizes brightness and glints, and best practices during flight operations" (*NSF Statement on NSF and SpaceX Astronomy Coordination Agreement | NSF - National Science Foundation*, 2023). Radio astronomers and satellite operators should not be the ones taking the front seat concerning what needs to be done to keep interference reduction to a minimum. Regulators including the ITU need to analyze what needs to be done to keep interference reduced and be the ones to outline industry standards required by all satellite operators. More funding and a reorganization of the ITU to set it up for the rapidly advancing industry would be an important step in ensuring further interference doesn't occur.

Another potential change besides restructuring regulators is to introduce what are called Radio Dynamic Zones. These are not to be confused with Radio Quiet Zones, which while providing protection from terrestrial interference, provide little to no protection from space-based transmissions (Vruno et al., 2023). Radio Dynamic Zones are a new type of zone that allows for streamlined coordination between active and passive users (Zheleva et al., 2023). In this case, the active user is the satellite operator and the passive user is the radio observatory. Innovations such as the Radio Dynamic Zones will continue to be needed to ensure both satellite operators and radio astronomers are able to work effectively. Figure 4 shows the importance of being able to coordinate between the various stakeholders as ranges of the spectrum have been allocated to multiple stakeholders. The dark shades display where frequency has been allocated, while lighter shades show the capability of each stakeholder (Zheleva et al., 2023). Figure 5 also highlights how rapidly the spectrum has been becoming more crowded. While light blue, for radio astronomers spread across the spectrum, there are only a few small ranges, in dark blue, that are allocated for radio astronomers to use. It can be seen that allocations for radio astronomers have been extremely limited over the past few decades, while allocations for satellite operators, in yellow, have been fairly extensive.

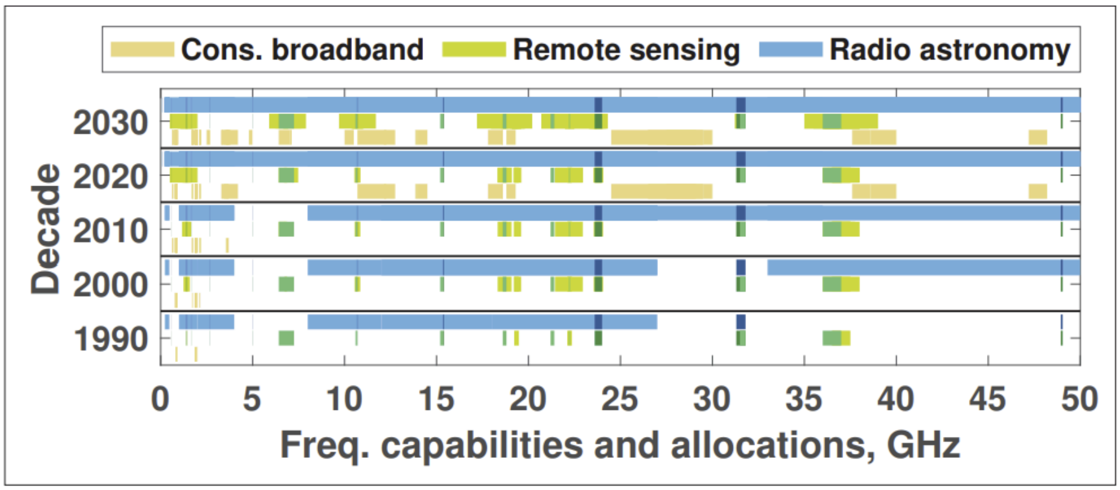

Figure 8: Radio Frequency Capabilities and Allocation (Zheleva et al., 2023)

One longer-range solution could be to use the benefits of increased and cheaper access to space to the advantage of astronomers. This could be done by locating radio telescopes in places in space that wouldn't have nearly as much interference. One example of this would be to place one on the far side of the moon. Almost all of the man-made radio signals would be blocked by the moon, creating a great environment for telescopes. A few decades this suggestion would have been crazy, but with NASA's plans to put humans back on the moon and create a pipeline of cargo missions landing on the surface, this doesn't seem nearly as far off as it once did.

Conclusion

Regulators play a key role in the relationship between satellite operators, radio astronomers, and the frequency they use. Using the actor-network theory it was shown how important it is for regulators to be involved with and throughout the allocation of frequencies. More work and analysis needs to be done on the work regulators are doing and what else can be done to consolidate the process. Much of the regulation of frequencies between radio astronomers and satellite operators seems fractured with individual operators and astronomers creating agreements for specific use cases, such as the agreement discussed above between the NSF and SpaceX's Starlink.

While the main point of this thesis was to discuss the difficulties faced by frequency coordination between satellite operators and radio astronomers, some potential changes were briefly highlighted and should be researched further in the future. Some examples of these potential solutions include restructuring the regulation groups for who has authority on what or introducing Radio Dynamic Zones. An even longer-range solution would be to move radio telescopes to the far side of the moon which would have less interference than anywhere on Earth could offer. Unfortunately, there is no easy answer as to how much frequency should be allocated between the groups. Radio frequency has become an integral part of our everyday lives with each group claiming they need it more than the other. The advent of satellite communication has exasperated the issue as a national issue has turned into an international issue as radio waves can be easily propagated across the world by a few satellites. While satellite communication is an important technology to continue advancing, I believe more work and modeling should be done to understand the effects that mega-constellations will have before it's too late.

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