RadioSTAR (Radio Spacecraft for Telecommunications Assessment and Risk-reduction): A 3U CubeSat for validation of ground stations and link budgets

by

Thomas J Murphy

Submitted to the Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degree of

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Abstract

As the number of small satellites in orbit increases, an increasing number of ground stations must be constructed, recommissioned, or updated in order to provide uplink and downlink access. However, prior to deployment of a spacecraft, it is difficult to evaluate a ground station's performance capabilities. Over-the-air testing with the spacecraft, prior to launch, may not be possible for remotely located ground stations, or stations in environmentally challenging locations due to humidity or season. In the event that a spacecraft is deployed, and the ground station has a flaw, the critical first days on-orbit may be spent debugging ground station hardware, leaving the spacecraft uncontacted and in an unknown state. In the event that a spacecraft has an unusually short lifetime, such as a low-orbiting CubeSat or a mission with limited fuel or power, a non-functional ground station could make the difference between getting little data and getting no data at all. This paper proposes a spacecraft with a versatile software-defined radio onboard, which can simulate nearly any upcoming spacecraft's radio system, thus qualifying a ground station's readiness for on-orbit operations. Furthermore, this spacecraft can be used for refining the link budget design, eliminating uncertainties like proper values to use for system noise temperature. Additional applications for such a spacecraft will be explored, including acting as a known signal source for calibration of radio astronomy installations. This paper acts as a first look at the feasibility of a RF calibration and validation spacecraft.

Thesis Supervisor: Kerri Cahoy
Title: Associate Professor

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Acknowledgments

Although the name at the top of this thesis is mine, I share the credit with all the people who have supported me through my life. So many others have contributed toward my growth as a person and positioned me to be capable of writing this thesis. It's generally bad form for the acknowledgements section to be longer than the thesis, so I'll keep this brief.

First, I'd of course like to thank my parents and siblings for everything they've given me as I grew up. Their encouragement always made me feel like the things I aimed for were achievable. I get to build satellites at MIT and pursue all my curiosities, and I wouldn't have gotten here without them pushing me forward and building my strengths. I can never thank them enough.

Next, I'd like to thank the people who have helped me in my official time as a student. Of course this starts with my advisor Kerri who has believed in me and propped me up as a Person Who Knows What They're Doing. She took me into her lab in the Summer of 2017 and tasked me with setting up the ground station on top of Building 37, which was the foundation for my entire career since then. It enabled me to make a good showing and become a grad student, and ultimately was the platform for this thesis. Kerri's support has been absolutely instrumental in the progress I've made so far in my professional career, and I look forward to continuing working with her and seeing what I can accomplish under her supervision.

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I was an undergraduate student at MIT before transitioning into grad school. My time here was incredible, and there are so many reasons I knew I wanted to keep

getting to spend my time here. Most of all, the people. I'd like to thank my friends Madeleine Jansson, Charlie Garcia, and Andrew Adams for the time we've spent together and their unwavering kindness toward me. They're the greatest gift MIT has given me.

Continuing on the theme of friendship, I'd like to thank the new friends I've made through the Converging Section. We're drawing toward the end of the COVID-19 pandemic, and the friends I've made in the Converging Section have been a huge contributor toward making it bearable. They're a fantastic group of folks who love all the same things I do, and it's amazing to be able to share our passions. They're the only group where I really feel like I can open up and know they're going to share the enthusiasm I feel over all sorts of topics - especially when things turn to Bismuth. I'm particularly grateful to have gained the close friendships I now have with Joe Barnard, Jenna Foertsch, and Casey Doran. Especially, thank you Joe for believing in my engineering skills and trusting me to build things you rely on.

The next group I'd like to thank is the MIT professors who have had endless patience with my incessant questions I'm known for asking during class. I can't say I've ever had a bad professor here, but a few stand out as particular favorites. They include, but are not limited to, David Darmofal, Steve Leeb, Paulo Lozano, Anna Frebel, Zoltan Spakovszky and Raul Radovitzky. Thank you all for feeding my curiosity.

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Ultimately I'm a huge sum of all the people who have spent time around me and influenced who I've become as the person I am today. Basically, if you know me well enough that you call me Joey, it probably means you belong in this section, and I thank you for everything you've done with me.

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Chapter 1

Introduction

The MIT STAR (Space Telecommunications, Astronomy, and Radiation) Laboratory has been developing CubeSats since 2011, and flying them since 2014. In recent years, the laboratory has installed an on-site satellite communications ground station for communicating with its satellites. Satellites that have used this ground station include MiRaTA, DeMi, and the upcoming BeaverCube. Each of these satellites use different UHF radios, with slightly different ground hardware. This has resulted in a set of challenges involving commissioning of the ground station, and ensuring that the ground station will be ready to communicate with each spacecraft immediately after deployment.

Prior to deployment, the absence of a space asset to communicate with leads to difficulties in establishing confidence in the ground station's functionality. Additionally, some of these missions have used secondary ground stations in remote locations which introduces its own difficulties. The best testing of the radio that can be done is to set up the spacecraft a few miles away from the ground station and try to communicate across the ground, but this approach does not work in situations where the environment is inhospitable (to either spacecraft or engineers). In the past, users of the MIT UHF ground station have attempted to validate transmit capabilities by transmitting to radios on other on-campus buildings, and to validate receive capabilities by searching for beacon signals originating from Russian COSMOS satellites, but these methods are not reliable as representatives for communicating with a new

CubeSat due to differences between radios, the inability to properly represent a link to space without hardware in space, and other limitations in standing in for the real system.

This thesis proposes a software-defined radio serving as a payload on a satellite (separate from the spacecraft standard operational command and telemetry radio) that can be remotely programmed to emulate the radio on any upcoming spacecraft, thereby informing ground station operators of any issues that may be present in their stations. Furthermore, this spacecraft can help to validate link budgets, and remove a large degree of uncertainty that has been involved in calculating them in the past. By having a standardized satellite to validate uplink and downlink fidelity, satellite operators can have increased confidence in the ability of their link budgets to close.

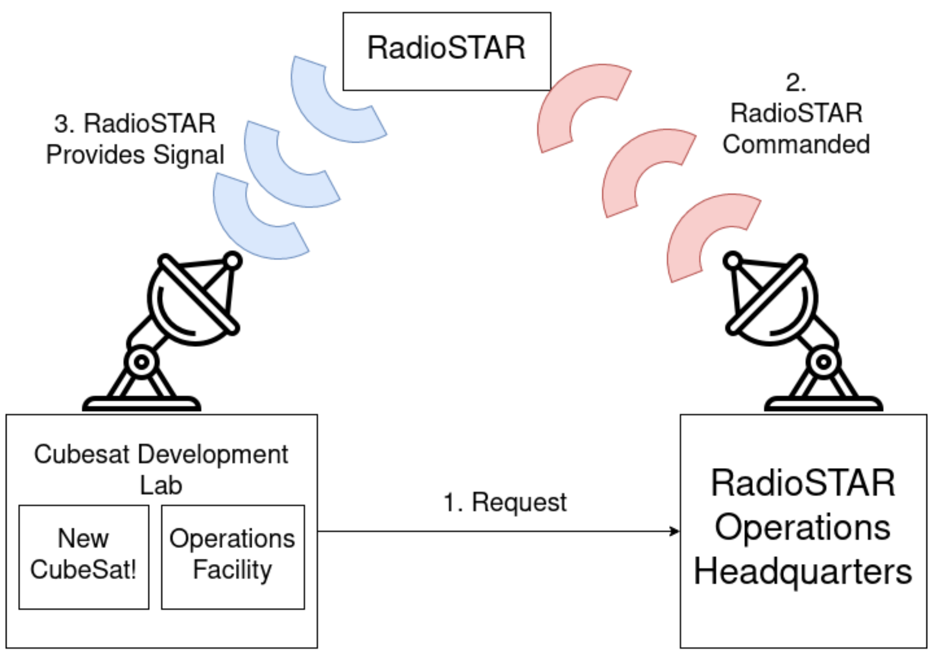

Figure 1-1: Basic concept - A team interested in using RadioSTAR's services to validate their ground station (while their new CubeSat is still on the ground) contacts RadioSTAR operations, which then commands RadioSTAR to initiate a downlink over the customer team's ground station.

It is notable that, at the present time, the number of CubeSats in orbit is sufficient such that an arbitrary location (such as the MIT campus) will almost always have at least one CubeSat visible in the sky above it. This illustrates the proliferation of small spacecraft and highlights the usefulness of a spacecraft for communications diagnostics. To validate the quantity of spacecraft visible in the sky, Figure 1-2 was generated, which iterates through every CubeSat (according to Jonathan McDowell's GCAT [5], combined with TLE files from Celestrak [6]) and, for each minute of a day, counts how many are above the horizon, as observed by MIT. This script uses the Python package Skyfield [43] to perform the orbit propagation and find satellite positions.

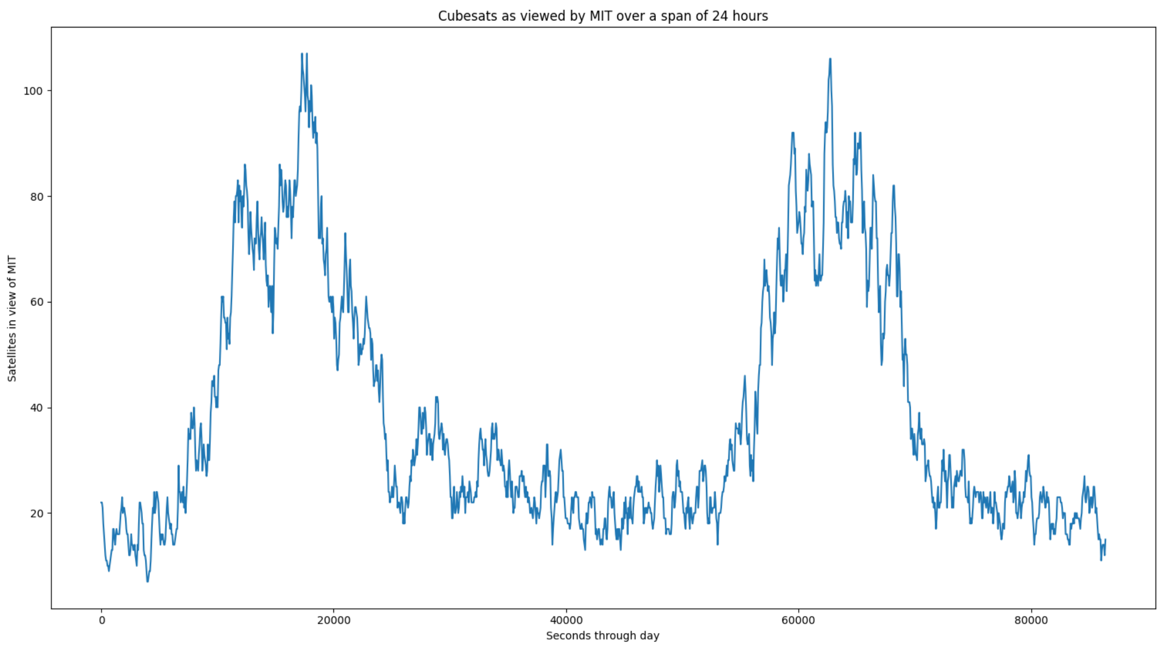

Figure 1-2: Plot of number of CubeSats visible over MIT campus over span of one day

Several takeaways are made clear by this plot. The first is that there is always at least one CubeSat visible from MIT (the minimum ever seen through the course of the orbit propagation was 7). Another is that the CubeSats are not distributed uniformly. The two very large groups of satellites we observed are the Planet Flock spacecraft, which almost all operate in the same orbital plane – we observe them all racing by, 12 hours apart, as they each traverse their polar orbits with one ascending and one descending pass during the day. If we ignore the Planet Flock, we see that the line generally hovers around 20 satellites visible at any one time. Clearly, the CubeSat market is large, and it stands to reason that validating ground stations would be an important goal to undertake, especially since, to the author's knowledge, no existing spacecraft has been purpose-built to increase confidence in a ground station setup prior to flight of upcoming spacecraft missions.

1.0.1 On-the-fly Troubleshooting

Along with using RadioSTAR to validate a ground station prior to establishing a spacecraft on orbit, RadioSTAR also has the potential to serve as a useful diagnostic tool for other missions. In the event that a spacecraft operator is unable to contact their spacecraft, there is always a question regarding whether the contact issue lies in the ground station or the spacecraft. Generally, there are 4 steps that have to happen for a successful contact to be made.

1. The ground station transmits a command to the spacecraft.
2. The spacecraft receives and interprets the command.
3. The spacecraft responds with whatever the result of the command is.
4. The ground station receives that response.

Any step in the chain could fail, but all the ground station knows is "I sent a command, but I didn't get a response back". By using RadioSTAR, the variable of the satellite can be removed. If the ground station can successfully transmit to RadioSTAR, and receive a downlinked signal from RadioSTAR, it becomes more clear that the issue lies in the spacecraft. On the other hand, if the ground station attempts to listen for RadioSTAR and does not receive a signal, the team can increase their confidence that their spacecraft is fine and that their ground station needs some work on its receive path. This use case would also apply in the event that a ground station operator reports receiving weak signals from their spacecraft. If a reception from RadioSTAR is also weaker than expected, the operator will gain confidence that the weakened signal is due to a ground-side issue (such as a loose cable, or a receiver having issues), and not anything to do with their primary spacecraft. Other potential issues a ground station could experience which would prevent it from communicating with a spacecraft are listed in Table 1.1.

Table 1.1: Common issues ground stations may face preventing communication with a spacecraft

Corrosion of metallic parts (especially in coastal areas with salt air)
Wind-induced misalignment of antennas
Building maintenance crews disconnecting station components
Rain intrusion into outdoor equipment boxes
Failure to return station to operational configuration after tests
Bends in cables increasing signal attenuation
System time diverges from real time and prevents synchronization of spacecraft tracking

1.1 Additional Applications

Naturally, ground station communications validation is not the only application for a flexible radio transceiver in space. Some applications would benefit from having a signal source transmitting in space; others would benefit by being able to receive signals in space. In this section, we will discuss those possiblities.

1.1.1 Radio Astronomy

A major application of radio signals in the sky is that of radio astronomy. The largest telescopes on Earth are radio telescopes, which detect both direct radio emissions, and red-shifted emissions from stars at the time of the formation of the Universe. These telescopes are constantly evolving, increasing their ability to detect weaker signals, and adding new techniques like interferometry to improve our ability to image celestial objects. These new techniques allow new astronomy capabilities - the Event Horizon Telescope [11] utilizes interferometry and was able to produce the famous 2019 Black Hole Photo. One of the most important signals for radio astronomers is the “21-centimeter hydrogen line”, which corresponds to a very particular frequency emitted by hydrogen atoms when the electron changes energy state. This frequency is 1420.406 megahertz. Therefore, it would be useful for RadioSTAR to be able to transmit on this frequency in order to allow ground telescope operators to prove out their equipment. An example of this utility would involve a telescope failing to receive astronomical emissions, leading operators to question the instrument’s sensitivity to very weak celestial signals. RadioSTAR could transmit at a higher power level than real astrophysical sources (when adjusting for the difference in distance for a ground station observing RadioSTAR versus a celestial object light-years away), thus allowing the ground telescope to know whether it’s entirely unable to receive signals, or if its sensitivity is just too low. In addition to direct operation at this frequency, it is also useful to transmit at the red-shifted equivalent of this frequency. As the universe expands, the light that was emitted billions of years ago is stretched, and ultimately red-shifted. This red-shift is proportional to the elapsed time since the emission was produced. Large new radio astronomy projects such as the Square Kilometer Array are interested in examining the "epoch of reionization" [12], describing the time the first galaxies began to form. By the time the light from this era reaches the Square Kilometer Array, it will have been shifted by a factor of approximately 7 to 8. That is, the light’s frequency is now 1/8 to 1/7 of what it was at the time of emission, placing it now roughly in the range of 150-200 MHz. Therefore, ground telescopes must monitor these lower frequencies to receive light that was initially 1420 MHz prior to being red-shifted. Because an orbiting spacecraft will not experience this type of red-shift (and will only experience Doppler shift associated with flying past a ground station), we can directly transmit at the lower frequencies to perform the same tasks to validate a ground telescope. Of especially great interest to astronomical radio telescope operators is the ability to experimentally validate the beam-shape of the radio telescope.

Radio telescopes can, broadly, be put into two categories. The simpler category is dishes, which consist of a large parabolic antenna capturing radio waves. A dish is usually attached to a mount which allows it to be aimed at different portions of the sky, which requires large motors with a combination of high strength and high precision to point the dish at a particular location in the sky. The more complex category of radio telescopes is that of arrays, which consist of a large field of small individual antennas which work in tandem to receive signals together. There are several advantages with these arrays, but they are more challenging to operate. There are multiple individual units receiving signals, and they must operate together in order to properly process an incoming signal. Additionally, directing them toward a position in the sky is done through interferometry of signals and complicated phase measurements, which requires advanced signal processing. A particular region of the sky is able to be measured by changing the signal processing performed, rather than by physically steering the antenna. While these two systems have their benefits and drawbacks, one commonality between them is that it is currently difficult to know exactly which portions of the sky are being sampled by a telescope's receiving infrastructure. While a dish or array can be pointed at a portion of the sky, knowing exactly the size and shape of the region being viewed becomes difficult. RadioSTAR may be able to help.

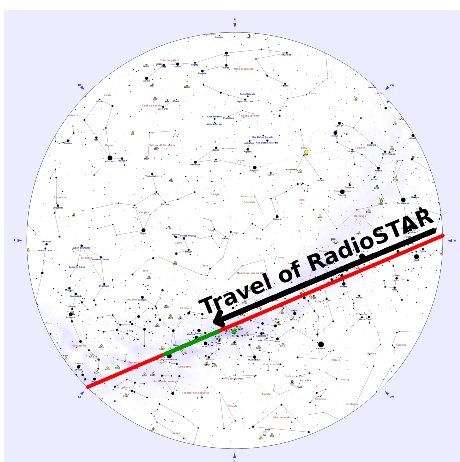

Figure 1-3: Evaluating the shape of a telescope's receive beam area on one axis. RadioSTAR travels through the sky from West (on the right, because the star chart is drawn from the ground looking into the sky) to Southeast (on the lower left). In red are the periods of the overhead pass where the telescope does not receive a signal, and in green is the period where the signal is received at a sufficient strength.

Because a spacecraft's position is relatively well-known due to the predictability of orbits, by having the spacecraft transmit while flying through the telescope's receiving beam, the exact nature of the beam can be established – whenever the radio telescope starts seeing the spacecraft's transmission, we know the spacecraft has entered the beam and when it stops receiving, the spacecraft has left the beam. Such a calibration exercise could easily be planned by predicting when the spacecraft will pass over the radio telescope, and the spacecraft operators could schedule a constant beaconing period for that time. By combining several such passes over the telescope at different controlled alignments, the overall shape of the receive area could be effectively characterized. This is especially crucial for phased array systems, where their receive pattern is meant to be changed from one configuration to another. By having a new set of RadioSTAR passes, the radio telescope operators can gain improved knowledge of the new beam shape that has been achieved.

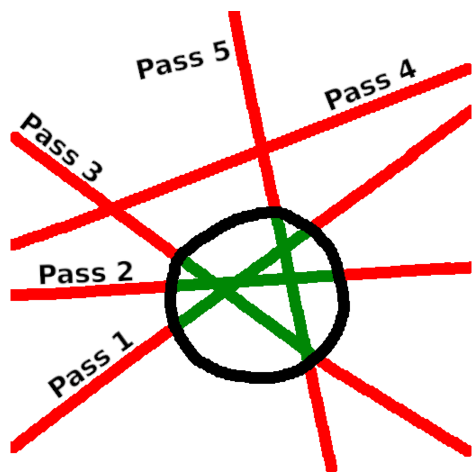

Figure 1-4: Identifying the shape of a telescope's receiving beam through successive spacecraft passes, with repeats of the same type of passes as in the previous figure (stars removed for clarity). Sufficiently many passes will enable an approximation to be drawn as to the beam shape, with more passes increasing the fidelity.

1.1.2 GPS Signal Reception

In radio astronomy applications, we discussed RadioSTAR's ability to act as a known signal source. On the opposite side, RadioSTAR could be useful for receiving signals. There are multiple useful example cases. One application of radio reception on science CubeSats has been that of GPS radio occultation. In this technique, a satellite precisely and rapidly monitors signals from GPS satellites. Particularly, it captures the signals received when the path the signal takes from the GPS satellite to the receiver passes through the atmosphere, and uses the amount of bending (frequency shift) the signal experiences in order to infer the properties of the atmosphere along that path. RadioSTAR, being capable of receiving signals across many bands with customizable channel sampling and abilit to use high-gain GPS receiving antennas, would be able to serve this capability. Rather than GPS radio occultation requiring entire dedicated spacecraft, this could instead be a task performed by RadioSTAR as a more flexible science instrument. Or, looking at this situation from the opposite angle, rather than building spacecraft to perform only GPS radio occultation, it would instead be possible to create RadioSTAR satellites, which would be capable of doing that job and more. These satellites would alternatively be able to also act as transmitters for active radio occultation measurements (rather than passive reception of signals that already exist). GPS signals operate at 5 different bands, given designations from L1 to L5. Their frequencies are, in order: 1575.42 MHz, 1227.60 MHz, 1381.05 MHz, 1379.9133 MHz, and 1176.45 MHz. Notably, these are all in the general vicinity of the 1420 MHz of the hydrogen line discussed earlier, indicating that they may be able to share front-end hardware including antennas, filters, and amplifiers, though this capability would require additional testing with hardware.

Realistically, achieving GPS radio occultation measurements that are useful is a tall order. As described in the Active Temperature, Ozone and Moisture Microwave Spectrometer experiment conducted by Kursinski et al. [1], the frequency shift experienced by a microwave signal traveling through the refractive index gradient of the atmosphere is very small, and would necessitate an ultra-stable oscillator, which may require a more dedicated mission, as well as an extremely sensitive radio receiver. While chip-scale atomic clocks are beginning to become commonly available, the evaluation of the utility of a chip-scale atomic clock as a suitable oscillator for radio occultation is beyond the scope of this RadioSTAR thesis. Other intriguing, though difficult, uses of passive GPS reception may include GPS reflectometry, which measures the signals received from GPS signals as they bounce off the earth, which reveals information such as ground topography and soil moisture.

1.1.3 Primary UHF Communications

Returning to the primary goal of the spacecraft, RadioSTAR may serve as a reliable contact station for UHF CubeSat operations. The UHF band from 400 MHz to 450 MHz (and particularly around 437 MHz) is very common for uplink and downlink with small satellite missions. We take a closer look at some existing UHF communication modules, including five selected market offerings, outlined in Table 1.2.

Table 1.2: A selection of UHF radios available on the market. Sources: [13][14][15][16][17]

Name	Manufacturer	Uplink Frequencies (MHz)	Downlink Frequencies (MHz)	Modulation Schemes	Data Rate (bps)	Maximum Transmit Power (W)
SatCOM UHF	NanoAvionics	395-440	395-440	GFSK	2400-38400	3
Cassiopeia	Aphelion	143-146	430-438	OOK, FSK, GFSK	9600	2
UHF Transceiver II	Endurosat	400-403 or 430-440	400-403 or 430-440	OOK, GMSK, FSK, GFSK	Up to 19200	2
Pulsar-TMTC	ClydeSpace	140-150 or 400-420 or 430-440	400-420 or 430-440	GMSK, AFSK	9600 (GMSK) 1200 (AFSK)	2
Lithium	Astrodev	130-450	130-450	FSK, GMSK	9600	4

The first four of these options are also depicted in Figure 1-5. A few things can be gleaned from this lineup. One is that transmit power is usually only a couple watts at best. If RadioSTAR can operate at 5W, that would far and away cover the required transmit power to match other missions. Another is that GMSK and GFSK modulation appear to be the most common types, and that overall the modulations are not usually particularly varied (there are no radios using unusual modulations like QAM-16 commonly showing up, for example). Finally, this analysis validates that the frequencies listed in this work are indeed usually in the range of 400 to 450 MHz. Notably, this assessment has also revealed that cross-band capabilities are somewhat common in CubeSat radios, using VHF for low-rate uplinks. This makes it clear that it would be useful for RadioSTAR to be able to receive VHF signals to validate uplink capabilities from ground stations.

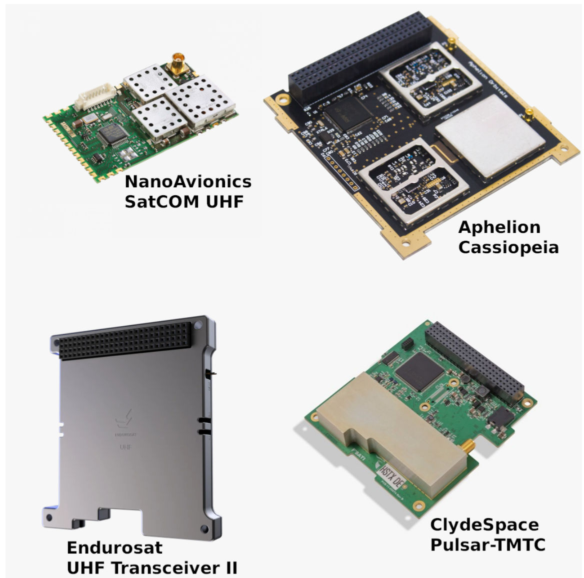

Figure 1-5: A sampling of 4 UHF radios on the market. Image sources: [13][14][15][16]

1.2 Prior Art

Like any project, RadioSTAR is not an entirely new concept. However, the details of its purpose and capabilities set it apart from any mission that has previously been completed. It is useful to examine similar missions which hold conceptual similarities and define how RadioSTAR outperforms their abilities. Particularly, we will look at prior missions which consisted of radio diagnostic instruments in orbit, either monitoring missions or signal source missions. Notably, no prior mission that the author has been able to find has done both.

1.2.1 CubeRRT

The first comparable mission of interest is CubeRRT, the Cubesat Radiometer Radio Frequency Interference Technology Validation Mission. [2] CubeRRT was developed primarily by an Ohio State University team, and orbited from May 2018 to November 2020. CubeRRT was intended to monitor terrestrial radio frequency interference which pollutes the signals used in microwave radiometry. Importantly, CubeRRT was meant to improve radio-based science instruments, without an intended application toward satellite communications. CubeRRT operated from 6 GHz to 40 GHz. In addition to monitoring RF noise, CubeRRT was intended to demonstrate how this interference could be mitigated on the spacecraft end, and result in science data that is less impacted by the interference.

1.2.2 RAX

Another mission in this signal-monitoring field is the Radio Aurora Explorer (RAX), from the University of Michigan. [3] RAX was developed to evaluate the properties of the upper atmosphere. Its concept revolved around a ground-based radar system which would send signals intended to be affected by the upper atmosphere, at which point RAX would receive those signals and characterize how they had been modified through their interactions with the ionosphere. RAX operated in the UHF band, from 426 to 510 MHz. This is interesting because this range directly aligns to common CubeSat command and telemetry frequencies. Notably, however, RAX was meant to receive highly particular signals from a known signal source, and characterize how they had been affected. RAX was not intended for analysis of overall RF conditions. Unfortunately, the original RAX-1 spacecraft suffered severe solar panel degradation and its mission was cut short, ending only 2 months after its launch in November of 2010. A follow-up mission, RAX-2, was developed to perform the same goals as the original RAX-1, and was much more successful, with stronger long-term performance and ultimately conducting numerous science operations sessions. [4]

1.2.3 HawkEye 360

Perhaps the most similar mission to RadioSTAR is that of HawkEye 360, which is distinct from the other two mission examples in that it is a for-profit company operating spacecraft to observe Earth radio conditions. HawkEye 360 operates a small constellation of small satellites which perform signal monitoring from space. Effectively, they're performing Signals Intelligence as a commercial operation. One of their primary signals of interest is the AIS (Automatic Identification System), a system used by ships where they report their identity and location, allowing ships to avoid collisions and companies to maintain knowledge of the locations of their ships. When ships turn off these beacons, they can effectively "vanish off the radar", so to speak, which may enable illicit maritime activities. By directly receiving any other signals the ships may emit, HawkEye 360 can maintain knowledge of the ships' locations even when AIS information is not volunteered. HawkEye 360's primary purpose is to listen in on signals that are not necessarily intended to be received from orbit. This presents interesting ideas for capabilities that could be added to RadioSTAR, in terms of monitoring unusual signals that may exist on the ground.

Figure 1-6: CubeRRT[18], RAX[19], and a group of HawkEye 360 satellites[20].

1.3 High-Level Requirements

We start by examining the requirements for the RadioSTAR system. Because the purpose of the system is to act as a reliable radio beacon in space, with an ability to simulate other spacecraft, we must consider the parameters of the other customer spacecraft on orbit and aim to replicate (or be compatible with) the characteristics that exist among spacecraft. These variables include the different potential orbital altitudes a spacecraft could be in, the different frequencies it could operate at, the different modulation schemes available, the different signal polarizations that could be used, the different levels of Doppler shift that could be produced, and many others. Additionally, RadioSTAR aims to serve ground station operators all over the globe, and as such, it would be desirable to provide as many of these ground station locations with access to RadioSTAR as possible. The most high-level requirements fall into two categories: Radio Design and Mission Design. Table 1.3 defines particular requirements, in the R (Radio) and M (Mission) categories. Broadly, the R requirements represent the ability of RadioSTAR's radio payload to adequately represent the radio aboard a customer spacecraft. The M requirements represent RadioSTAR's orbital situation and its ability to serve the ground stations of interest, as well as some baseline requirements for RadioSTAR's bus to support the payload.

These requirements were arrived at by considering the parameters that would importantly represent a customer spacecraft, ultimately reflecting the purpose of RadioSTAR. The first two requirements naturally flow from the fact that a customer CubeSat could have any number of different frequencies and modulations, and we seek to be compatible with those. The third flows from the fact that many different modulations exist, in which case we want to be prepared to represent any modulation that may not have been pre-programmed into the spacecraft before flight. Finally, R-4 represents the fact that Doppler shift is a reality of spacecraft communications, and RadioSTAR should represent it to whatever degree possible to ensure that a ground station under test is capable of coping with those shifts. Moving into the Mission side, we hope to represent the orbits of existing CubeSats, so that the relevant path loss of the distances signals traverse is accurately represented. M-2 reflects the fact that a ground station can only be reached by orbits with equal or greater inclination, and RadioSTAR hopes to serve as many ground stations as possible (and not only those in equatorial regions). M-3 and M-4 represent the need for RadioSTAR to accurately initiate a downlink toward a particular location. RadioSTAR needs to be able to cause a signal to reach the ground station, in which case it must know the relevant locations of itself and the ground station, and be capable of using that

Table 1.3: Baseline High-Level Requirements for RadioSTAR

R-1: RadioSTAR shall be capable at operating at the most common CubeSat frequencies.
R-2: RadioSTAR shall be capable of modulating and demodulating in the most common CubeSat modulation schemes.
R-3: RadioSTAR shall be capable of receiving, storing, and transmitting raw I/Q data, such that it can serve even environments for which it does not have pre-made modulation and demodulation.
R-4: RadioSTAR shall be capable of performing Doppler compensation on its signals, as may be required of the spacecraft it seeks to emulate.
M-1: RadioSTAR shall be placed into an orbit which covers the 5th to 95th percentile of CubeSat orbital altitudes.
M-2: RadioSTAR shall be placed in a high-inclination orbit to access diverse latitudes.
M-3: RadioSTAR shall possess pointing capabilities equal or better than its antenna beam-width, so as to maximize antenna gain toward a given ground station.
M-4: RadioSTAR shall possess onboard orbital knowledge, such that it may know its position relative to a chosen ground station and determine uplink/downlink opportunities.

information to target the ground station. This set of motivations naturally flows into the requirements we have established.

With a baseline set of requirements established in Table 1.3, we can now move into developing the concept for RadioSTAR. We will begin by describing the overall Approach in Chapter 2, evaluating the relevant trades for the spacecraft. This will lead into Chapter 3, evaluating trade studies on the design of the mission's orbit and hardware, followed by preliminary selection of hardware in Chapter 4. We'll then finish by discussing the anticipated impacts of the mission on the future of spaceflight operations.

Chapter 2

Approach

As with any engineering system, RadioSTAR will need to prioritize its goals and make trades between them. It would be impossible (or at least, unreasonable) to cover all parts of the radio spectrum, from the kilohertz to tens of gigahertz. It would also be infeasible to have a spacecraft that can adequately operate at all altitudes, from an ISS orbit (the orbit of the International Space Station, at an altitude of approximately 400 kilometers, and an inclination of 51.6 degrees) up to geosynchronous (at an altitude of 35,786 kilometers). We will begin this chapter by discussing the relevant trades for the main radio payload, and then move into the orbit and mission design. Initially we'll discuss the "design for utopia", as if we could choose every bit of maximal performance possible, and then transition into the practicalities of what we expect to actually be achievable, before ultimately arriving at a chosen balance that meets our high-level performance requirements as listed in Table 1.3.

2.1 Radio Trades

In evaluating the trades associated with the design of the radio hardware on RadioSTAR, we will augment Table 1.3 with a "wish list" of what an idealized payload would be capable of, and then discuss what real-world limitations will necessitate trimming down from there. The crucial parameters of interest for a radio signal generally fall into the following 4 categories:

1. Frequency
2. Modulation
3. Power Level
4. Polarization

Note that these parameters independently apply both to the transmit and receive side of a link – if RadioSTAR is serving as a signal source, its goal is to generate a signal which meets these properties. If RadioSTAR is serving as a receiver, monitor, or interloper, then its goal is to be able to detect a signal mathing some subset of these properties. Although we could consider these parameters for both transmit and receive capabilities, this section will assume RadioSTAR is acting as a transmitter.

An ideal spacecraft would have what ultimately amounts to an arbitrary function generator, and be able to emit any wave with any frequency, modulated data, amplitude (power), and polarization. However, of course this is unobtainable. An antenna is only able to properly emit electromagnetic waves within a particular band (where it is resonant) [21]. And the waves it emits must ultimately resemble a sinusoid which is modified to encode the data – one cannot transmit a square wave out of an antenna and expect to receive a square wave on the other end. [22] Of course the power level of a signal will need to be high enough to be received with sufficient margin by the ground station (or other receiver), and it is capped at whatever the board electronics are capable of supplying (along with the power level the radio is licensed for).

With the key parameters for the radio now defined, we will revisit the RadioSTAR requirements, and ultimately these will feed into the trade studies discussed in Chapter 3.

2.1.1 Frequency

In terms of the frequency, RadioSTAR has several desired goals. The primary mission objective is to act as a proving ground for ground-based CubeSat communication systems. Therefore, we need to replicate the most popular CubeSat frequencies.

These are usually in the UHF band or S-band, which are around 430 MHz and 2.02 GHz, respectively. Therefore, it would be ideal for RadioSTAR to replicate these; the exact frequencies will be considered in Chapter 3. These frequency selections apply to both the uplink and the downlink portions of the mission capabilities. Moving to the next objective, serving as a radio astronomy signal source, RadioSTAR should produce signals that correspond to the 21-cm Hydrogen Line, which can be received directly or red-shifted. The direct reception will be at 1.42 GHz, while the red-shifted frequency of most interest is in the VHF range from approximately 115 MHZ to 200 MHz [23]. Finally, GPS signals, which exist in the range of 1176.45 MHz to 1575.42 MHz, may also be of interest. This rounds out the frequencies we hope to target. However, there is also a reasonable possibility that other individuals and organizations may have interest in other signals which may be produced or received by RadioSTAR, so as much as possible, the capability of expanding to other frequencies should be preserved. The selected set of frequencies of interest are listed in Table 2.1:

Table 2.1: Frequencies at which we desire for RadioSTAR to be capable of operations

Band	Frequency Range of Interest	Rationale
UHF	400-450 MHz	CubeSat Communications
VHF	115-200 MHz	Radio Astronomy
GPS	1175-1580 MHz	Passive signal monitoring
21cm	1420 MHz	Radio Astronomy

2.1.2 Modulation

Next, we move to modulation schemes. This becomes more challenging because modulation schemes do not work as simply as parts of the electromagnetic spectrum. There are all kinds of different ways to encode data into analog signals. However, we can look at the most common modulation types and aim to target them. Table 1.2, showing several radios on the market, makes it clear that CubeSat missions often use GFSK, GMSK, FSK, OOK, and AFSK modulation schemes (with priorities in that order – in accordance with which options in Table 1.2 appear to be most common).

This subset of modulation types will be a good start toward being able to encode data in many different formats. Additionally, RadioSTAR may possess the ability to handle arbitrary radio waveforms. These are usually in the form of "I/Q Data", which takes an arbitrary wave and defines it using two waves 90 degrees out of phase, deemed "In-Phase" and "Quadrature" components, which is useful for processing of some forms of modulation [24]. In this case, the waveform could be uplinked and downlinked and result in any transmission, even if the modulation is not known to RadioSTAR. That is, RadioSTAR does not have to be able to understand the bits encoded in a waveform to be able to record (or generate) and store the raw waveform itself. However, this type of waveform processing takes a massive amount of data. The waveform must be sampled at 2x the frequency of interest, with a sufficiently high-resolution analog to digital converter, meaning that this data can quickly result in files approaching a gigabyte in size, which is difficult to transfer to and from RadioSTAR's primary computer. This would take an infeasible amount of time to uplink and downlink at the limited data rates usually associated with CubeSats. However, for the sake of this initial discussion, it should be considered as an option which would be nice to have the capability of, despite being unlikely to be easily implemented.

2.1.3 Power

Moving into the power level trades, things again become relatively simple. According to Bryan Klofas' list of CubeSats [10], none have a power level reaching 5W. Even the Iris radio flown on the MarCO CubeSats only transmitted at 4W [25]. 5W is still a relatively low power level, meaning that it should be achievable for RadioSTAR. If RadioSTAR can transmit a signal at 5W, it should have no problem serving as a replicant of any CubeSat of interest. Ideally, it would also be able to transmit as low as 100 mW, to truly evaluate a ground station's signal sensitivity. By dialing back the power, a ground station can properly evaluate how much margin exists in the link budget. If the ground station can observe RadioSTAR at 100mW, and the station's primary mission is to receive signals from a spacecraft transmitting at 1W, then the station's operators will know that they can tolerate 10 dB of unforeseen signal losses (due to degradation in pointing performance, increase in the noise floor, cables breaking down under UV exposure, etc) without losing communications with their spacecraft. However, if the power levels are going to be used for precision measurement of communications capabilities, it will be essential for RadioSTAR to be able to ascertain the level of power being transmitted at any given time. A final point regarding power: 5W is approximately a factor of 2 higher than any other CubeSats we are aware of, which may introduce licensing challenges. This, and further limitations involving licensing, will be discussed in Chapter 5. This will be especially important for CubeSats launched from the International Space Station, and will require careful consideration of astronaut RF safety limits (even though the CubeSats would never intentionally transmit before deployment).

2.1.4 Polarization

Finally we consider polarization. An emitted radio signal can have 4 types of polarizations: Horizontal, Vertical, Right-Hand Circular, or Left-Hand Circular [22]. A few notes are important to mention on this topic. The first is that "horizontal" and "vertical" are not well-defined, especially when signals are being transferred through the sky rather than across the surface of the Earth. Horizontal and vertical simply define two fundamental orthogonal axes, which may be at any angle about the direction of travel of the wave. Another critical note about these waves is that circular polarization is equivalent to two waves traveling orthogonally, 90 degrees out of phase. The horizontal component is at a maximum when the vertical component is at zero, and vice-versa. This has several advantages. One is that the receiver does not need to know a definition of "horizontal" and "vertical", since the circular wave is agnostic to any particular angle about its axis of travel. Another is that, because the circularly-polarized wave is comprised of two separate waves, a linearly polarized wave can be received by a circularly polarized antenna, or vice versa, with 50% efficiency. That is, if a signal is transmitted from a linearly polarized antenna, the linearly polarized wave that is generated is able to be received by a circularly polarized antenna, because the circular nature of the antenna can receive a wave of any polarization. However, because it is only receiving one wave (rather than the two superimposed that it is primed for), it only operates at half capability. On the other side, if a circularly-polarized wave is received by a linearly-polarized antenna, the antenna will only be able to capture the component of the wave (half) that does match its polarization, and not the other, orthogonal wave. This infrastructure is used on some CubeSats, where the spacecraft has a single linear antenna, and the ground station has a more complex circularly polarized antenna. This allows for communications that can entirely ignore polarization, since the link will deliver half the power on both uplink and downlink.

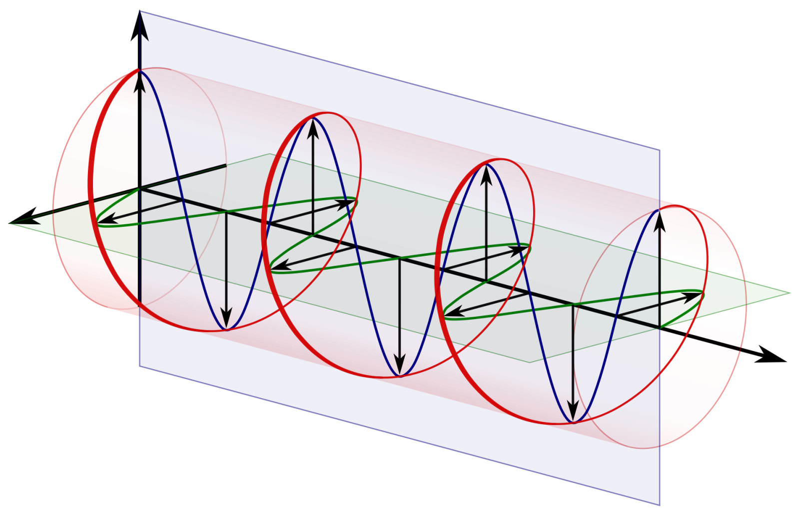

Figure 2-1: Polarization options for a traveling wave. The wave is traveling along the long axis, left to right. Three polarization options are visible. Green shows horizontal polarization, blue shows vertical polarization, and red shows circular polarization. Note that the circular polarization is a simultaneous combination of the other two. Image source: [26]

Polarization is a relatively simple trade. The options are to have only a single polarization, or all polarizations. For a single polarization, only one antenna is needed, at the relevant polarization. For arbitrary polarizations (circular, or any linear polarization), two antennas at orthogonal angles are needed. Additionally, feed electronics will be needed in order to ensure that the two orthogonal antennas are driven properly – for circular polarization they must be 90 degrees offset in phase, and for linear polarization, one of the two orthogonal antennas must be entirely undriven. This will add a considerable degree of complexity to the radio management electronics. Additionally, the approach must be replicated for each set of antennas on the spacecraft, and antennas should be tuned for each frequency. There is also the option to only allow for some frequencies to be circularly polarized while others would be limited to a single linear polarization. An additional interesting consideration related to polarization is that of multipath measurement – when a signal bounces off a surface, its polarization gets reversed, meaning that it is possible to detect when a signal and its reflection are received through measurement of the polarization. This has many potential uses, including the ability to triangulate the location of a source of a signal by measuring the time-delay between receiving the original signal and the reflected signal (assuming the reflection's origin is known). [27] Polarization measurement offers additional value in the received data.

We will now transition to the trades associated with the mission as a whole, and especially the selected orbit for the CubeSat. Once the mission trades are defined we will be ready for Chapter 3, where the design that leverages all of the Chapter 2 trades will be presented.

2.2 Orbit Considerations

A Keplerian orbit possesses 6 critical parameters to define precisely where a spacecraft is and where it is going. [8] These can broadly be broken into the shape of the orbit, the position of the orbit, and the position of the spacecraft in the orbit (at any given time). The shape of the orbit is defined by the semi-major axis, defining the average distance of the spacecraft from the Earth, and the eccentricity of the orbit, defining the specific shape of the ellipse it travels in, and what degree of variation there is between the lowest portions of the orbit and the highest. The position of the orbit is defined by the inclination, the argument of periapsis, and the right ascension of the ascending node. Finally, the position of the spacecraft as it repeatedly traverses the orbit is defined by the Mean Anomaly (or other derived terms).

In controlling these six parameters, we will have several goals that will need to be balanced. RadioSTAR hopes to serve many locations on Earth, but this creates a tension between the goal of "Make sure no location goes unvisited within a particular timespan" and the goal of "Make sure a given location can get as many visits as possible within a particular timespan". For example, only a polar orbit will be able to serve every location on Earth, but a polar orbit will also mean every location gets only two visits per day (once as the satellite travels north to south, and once from south to north). On the other hand, an equatorial orbit will visit every location on the equator, every 90 minutes, which may be desirable, but at the expense of being unable to support any other latitudes. It means all the equatorial locations will have many visits per day, at the expense of losing visits to all non-equatorial sites. In Chapter 3 we will need to choose the orbit for RadioSTAR to operate in, balancing the various orbit-related goals of the mission.

2.2.1 Orbital shape: The Semi-Major Axis and Eccentricity

Spacecraft operate at many different altitudes, and therefore, for RadioSTAR to accurately model a spacecraft's radio performance, particularly the free-space loss in the link budget analysis, RadioSTAR must be established in an orbit that can support the same ranges. In order to evaluate the current small satellites on-orbit to choose what orbital altitudes would be best served, a Python script was developed. This script goes to Jonathan McDowell's GCAT [5] and loads in a list of space objects. It then finds all objects with "cubesat" listed in their entries. For each object identified as a CubeSat, it obtains the SATCAT number, then goes to Celestrak [6] to obtain a two-line element set (TLE) for the satellite. From there, each satellite's TLE data was evaluated to find which spacecraft had the highest apoapsides, and which had the lowest periapsides. This Python script is included in Appendix A. This script shows that, at the time of writing, the 95th percentile in CubeSats with a high apoapsis is at 743 kilometers, while the 95th percentile in CubeSats with a low periapsis is at 382 kilometers. Alternatively, we can take the data for apoapsis and periapsis for all spacecraft and instead interpret it graphically and continuously, as shown in Figure 2-2 below.

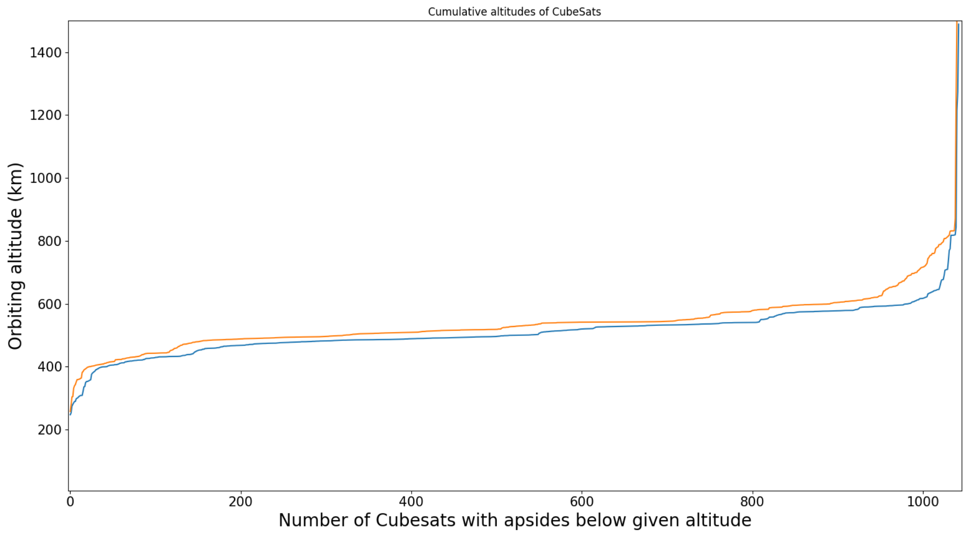

Figure 2-2: Plot of the orbiting altitudes of currently-orbiting CubeSats. The vast majority are between 400 and 600 kilometers.

The ideal orbit for RadioSTAR would be able to traverse both of these extremes, representing 90% of all CubeSats, and hopefully even go beyond them to allow for margin in the event that future spacecraft begin to inhabit farther-away orbits, though this is unlikely due to deorbit requirements and the generally low number of CubeSats possessing the requisite propulsion capabilities to undergo an active deorbit.

2.2.2 Inclination

In order for RadioSTAR to be accessible to all potential satellite operators, it must be available to every location where a user may be placing a ground station. An orbiting spacecraft can only reach a latitude approximately equal to its own inclination. For example, the International Space Station's orbit has an inclination of 51.6 degrees, meaning that its latitude never exceeds 51.6 degrees north or south (This means that the ISS will never fly over Anchorage, Alaska, at 61.2 degrees north, for example). Therefore, for RadioSTAR to supply its services as broadly as possible, it will be highly desirable to maximize its inclination. This directly connects to requirement M-2 in Table 1.3. In order to access all latitudes (especially, to support operators of polar ground stations, such as the one at Svalbard, Norway), RadioSTAR must be placed into a polar or sun-synchronous orbit.

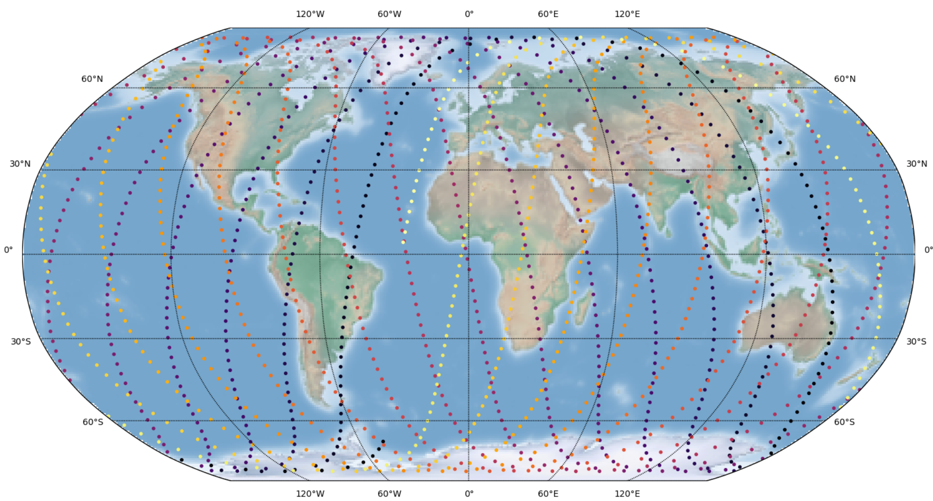

Figure 2-3: Ground track of the sun-synchronous MiRaTA CubeSat [28] over the course of 24 hours. Plotted with one dot per minute. Color indicates progress of time, starting from black and progressing through red up to bright yellow. Track starts near 60 degrees West, near Antarctica and finishes bright yellow near 30 degrees West, just north of Equator. This demonstrates wide global coverage from polar orbit.

While a true polar orbit requires a spacecraft to have an inclination of exactly 90 degrees, a more common choice of orbit is Sun-Synchronous, which has an orbital inclination slightly over 90 degrees (for example, MiRaTA operates at an inclination of 97.7 degrees). The advantage of a Sun-Synchronous orbit is that it passes over all locations on Earth twice per day, at the same local time every day. This is useful for many types of missions, especially earth-observation missions. Visiting the same location at the same time of day allows operators to image the same locations with the same solar illumination conditions from one day to the next.

For all possible locations on Earth to have a chance to communicate with RadioSTAR, RadioSTAR must be placed into a polar or near-polar orbit. The inclination becomes a primary driver of the visitation rate of the spacecraft. In order to visit all locations a polar orbit is required, but to maximize re-visit rate we want the inclination to be as low as possible. The ISS orbit ultimately becomes a balance, where the majority of land area (areas likely to have ground stations) will be covered, while also allowing higher revisitation rates than a strict polar (or sun-synchronous) orbit would allow.

2.2.3 Argument of Perigee, Right Ascension of the Ascending Node, and Mean Anomaly

The Argument of Perigee and the Right Ascension of the Ascending node define the orbital plane in relation to the Earth, the Sun, and the celestial sphere. However, these parameters precess throughout each orbit of a spacecraft. See Figure 2-4, which indicates this behavior. No matter where the spacecraft orbit initially sets these

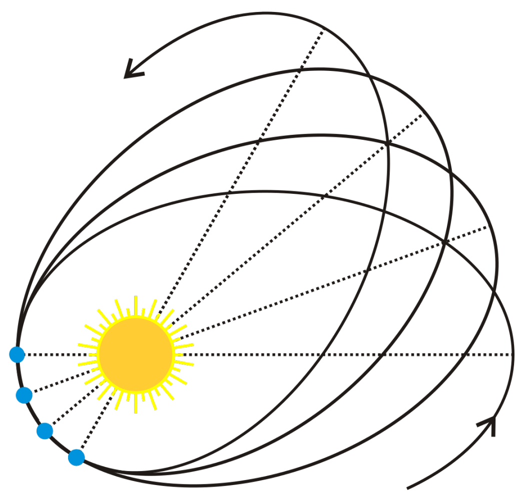

Figure 2-4: Behavior of apsidal precession. As the orbit evolves, the orbit precesses counter-clockwise. Blue dots in lower left indicate position of perihelion from one orbit to the next; without precession, these dots would all be in the same location.

parameters, they will quickly move. Therefore, aside from special orbits like the Sun-Synchronous Orbit, asserting initial values for these parameters will not be useful. RadioSTAR does not particularly care about its alignment with anywhere else, and therefore will not benefit from asserting values for these parameters. However, in Chapter 3, we will discuss the precession and how it can be used to our advantage.

Finally, Mean Anomaly just describes where the spacecraft is along its orbit. This is certainly useful for situations like orbital rendezvous, and knowing what particular time the spacecraft will be flying over a given ground station, but because we do not care about RadioSTAR's positioning relative to anything else, or the particular time that it reaches any particular location, we have no need at all to assert it.

Having now processed all six orbital elements, we have completed the description of what is desirable for RadioSTAR. We have now discussed the desires for both the instruments and the mission, meaning we are ready to move into Chapter 3, which will begin to outline what the system as a whole will look like.

Chapter 3

Trade Studies and Preliminary Design

We have now discussed the key aspects behind the mission objectives, and the next step will be to choose which we need to compromise on, given spacecraft resource constraints. As with Chapter 2, we'll start with the realities of the radio, and then move to the orbit and mission design as a whole.

3.1 Radio Trades

For the sake of analyzing the radio, we'll return to the 4 parameters outlined throughout Section 2.1. As a reminder, these are the frequency, the modulation, the power levels, and the polarization.

3.1.1 Frequency

First, the frequency. RadioSTAR has a wide range of desired frequencies, spanning an entire order of magnitude from VHF up into the gigahertz. This will mean that a diverse RF front-end will be required, one that can properly deliver signals of many different frequency ranges. There are several ways to accomplish this. First, it is treated as a given that the system will use a software-defined radio (SDR), due to the large flexibility they offer. For a flexible system with multiple modulation schemes, an SDR the clear choice. The physical implementation of an SDR can come in many forms, but ultimately it will be a chip on a board which has a digital data interface to some microcontroller, and an RF in/out port. Beyond that, we need to take the desired frequencies and somehow make them all conditioned for that RF port. We'll need antennas, filters, amplifiers, and whatever switching circuitry is necessary to route each signal to where it belongs. Alternatively, there are some chips on the market with multiple RF in and out ports, in which case we may be able to eliminate switching requirements and simply have each port connect directly to its RF hardware, thus allowing dedicated ports for each frequency band. We have 4 general frequency ranges of interest, the being VHF, UHF, 1.4 GHz, and 2 GHz. These will each need to be served by separate RF front-ends, which will either feed into separate ports on a multi-port radio, or have a proper switching network to connect each to the port of a single-port radio. It would additionally be desirable to have space in the design for additional front-end systems, to allow other frequencies to be added, should there be a new frequency of interest introduced at any point in the design process.

3.1.2 Modulation

Next we move to modulation. All the modulation schemes of interest that we named (FSK, GFSK, GMSK, OOK, and AFSK) should be managed, if possible. This will be a driver behind our choice of SDR chip at the heart of our radio. The option for raw I/Q data recording, while nice, may not be easily achievable. A recording that reaches 1 gigabyte in size would take over 9 days to transfer between the ground and spacecraft, assuming a 9600 bit-per-second low rate uplink. Even if we increased to 115200 bits per second, that would still take over 19 hours. Any higher data rates would quickly run into difficulties with maintaining a link budget with a low downlink power and low-gain antennas on the spacecraft side (note that the data transfer with RadioSTAR would be performed with a separate radio for managing the spacecraft itself – there would be one radio that acts as the instrument and one that connects to the main onboard computer for uplink and downlink with the operators of RadioSTAR itself. Refer to Figure 1-1 - the main payload radio is communicating over the link drawn in blue while the spacecraft commanding is done via a separate radio, with its signal drawn in red). It may be possible to do experimental downlinks with the payload radio, since it is flexible and can try pushing a link to its limits, rather than being guaranteed to operate even under worst-case conditions. But in any case, the limitations of sheer file size make it unreasonable to assume RadioSTAR will be capable of supporting arbitrary modulation via large I/Q files. Therefore, any modulation it can perform must be established prior to launch, meaning it will be essential to track any desired alternative modulation schemes and integrate them into the spacecraft as early as possible. Alternatively, it may be possible to use a form of file compression to represent each possible data symbol as an I/Q waveform, and instruct RadioSTAR to send each of these symbols in sequence, in a manner which somewhat resembles the MIDI format for storage of music in the form of notes played in sequence.

3.1.3 Power

Next, have power to consider. The desired power limits of 100 mW to 5W are likely quite achievable – cheap handheld radios meant for use on the VHF and UHF amateur bands are capable of these power levels. The ability to measure power level should be reasonably simple, since plenty of chips exist on the market which will pass a 50-ohm RF signal through, and report out the power of that signal, with minimal losses. These include the MAX4002, the HMC1020LP4E, and the ADL5902, among others. For now, we will baseline Analog Devices' ADL5902, which measures 50 MHz to 9 GHZ, fully encompassing our range and more. It has a dynamic range of 65 dB, which is far more than we expect our generated signals to reach. The power of our transmitted signals should not be something that needs to be compromised – we can fully fulfill the original "wish list" values of 100 mW to 5W.

3.1.4 Polarization

Finally, we move to polarization. As discussed in Chapter 2, we have two primary options. We can either use linear polarization or arbitrary polarization. For this, we can look to the current world of CubeSats and see that linear polarization wins out – the vast majority of spacecraft have simple monopole or dipole antennas. We have no particular application for which we can identify that the ability to control polarization would be useful. On the flipside, controlling polarization massively increases our complexity, since it doubles all the RF filters and amplifiers and introduces complications associated with phase-matching of signals. With a high cost and limited budgets, polarization control will be removed from the scope of RadioSTAR.

We've now gone through our four parameters of interest and mostly settled them. The frequencies will be segmented into the VHF, UHF, 1.4 GHz, and 2 GHz bands. We will need to be capable of FSK, GFSK, GMSK, OOK, and AFSK modulations, but without the full flexibility of arbitrary I/Q waveforms. We will keep our power window of 0.1W to 5W (and measure it, with ground-calibration to ensure accuracy), and use linear polarization. We will now move into the trades associated with the design of the orbit.

3.2 Orbit Trades

In the previous section, we outlined the 6 Keplerian elements and how the particulars of RadioSTAR's goals drive our desired values for these elements. We determined that the elements we particularly care about for our particular mission are the orbital altitude, and the inclination (along with the inherent coupling between those parameters and the orbit's precession). Now we will look at the values we desire for the orbital altitude and inclination to hold. We will begin with the orbital altitude.

3.2.1 Orbital Altitude

In Chapter 2, we determined that the ideal orbit to encompass 90% of current CubeSats would stretch between 382 and 743 kilometers. However, encompassing this entire range has consequences that are highly undesirable. 382 kilometers is nearly 10% lower than the ISS in its orbit, and the ISS is well-known to need frequent reboosting to maintain its orbit to forestall the impact of orbital decay induced by drag from the atmosphere. If RadioSTAR were to reach down to 382 kilometers, its apoapsis would quickly decrease due to drag, and its mission would be shortened as a result (potentially under 1 year [30]). To preserve RadioSTAR, we will avoid going quite down to 382 kilometers and increase our chosen periapsis to 400 kilometers. This should be a reasonable target altitude that adequately represents a spacecraft operating relatively low, while balancing the hope to not have RadioSTAR deorbit too soon. Ideally RadioSTAR would be able to operate for 1-2 years and prove out its capabilities prior to its ultimate decay. Note that, because 382 kilometers is necessary to represent 90% of the spacecraft, and RadioSTAR's newly-chosen periapsis only reaches as low as 400 km, this technically does not fulfill the M-1 requirement. However, it is reasonable to assume that most of the spacecraft operating below 400 kilometers were not initially operating in that orbit, and are instead later in their missions. That is to say, most of the sub-400-kilometer spacecraft were not designed to operate that low, and instead started in higher orbits and decayed down to below 400 km. Therefore, it is less essential to replicate these spacecraft, because the measurement below 400km is not properly representative of how the spacecraft were intended to operate. By keeping RadioSTAR up at 400 kilometers, RadioSTAR can replicate the lowest CubeSats while avoiding compromising its own orbital lifetime.

Next we can move to the apoapsis. Our analysis of existing spacecraft indicated a desire for an apoapsis reaching up to 743 kilometers. In order to add a bit of margin, the apoapsis will be placed at 750 kilometers. This is high enough to encompass most CubeSats, while also avoiding entering too heavily into the inner Van Allen Belt. [7] If we went much further than 750 km, RadioSTAR would likely encounter increased radiation damage which could result in, potentially, total mission loss. Given that very few CubeSats exist beyond 750 km, there would not be much benefit in going beyond 750 km anyway. Our span from 400 to 750 km will cover the majority of the spacecraft of interest. Encompassing this large portion of CubeSat missions ought to be sufficient for RadioSTAR to serve its purpose. Note that, depending on the deorbit timing requirements imposed by regulators at the time of the start of RadioSTAR's mission, we may be required to decrease the apoapsis to prevent RadioSTAR from remaining in orbit for an excessively long time. For now, we will assume we are allowed to occupy the chosen 400 kilometer by 750 kilometer orbit.

Now that the semi-major axis and eccentricity have been determined (thus fixing the shape of the orbit), we will move to the inclination.

3.2.2 Inclination

Recall that in Chapter 2 we noted that a polar orbit would be desirable for RadioSTAR, in order to serve every potential latitude. If this were the only consideration, we would like to simply set the inclination to 90 degrees, such that RadioSTAR would fly over every point on the planet. We will see in Section 3.2.3 that going fully polar may be undesirable, but it is important to remember that for RadioSTAR to have any hope of serving a large number of ground stations, its inclination must be high. A driving force in choosing the exact inclination will be maximizing RadioSTAR's ability to benefit from apsidal precession. We will explore this precession as we move into the discussion of the argument of periapsis and the right ascension of the ascending node.

3.2.3 Precession

Spacecraft operators are commonly familiar with the phenomenon of nodal precession, where the ascending and descending node of an orbit precess. This is the behavior which sun-synchronous orbits exploit to enable them to rotate in harmony with the Earth's orbit around the sun. Apsidal precession is a related, though different phenomenon. Apsidal precession refers to the behavior of an eccentric orbit to evolve in such a way that the locations of the apoapsis and periapsis change over time. In the case of a 90-degree polar orbit, apsidal precession would drive the orbit to move so that if the periapsis is initially over the North Pole, it will gradually drift around the orbit, moving around the planet until it is over the South Pole, then continue around back to the North Pole, revolving forever. Figure 2-4 illustrates this behavior.

For RadioSTAR, apsidal precession will be a necessary phenomenon to utilize in order to maximize mission utility. Specifically, given the spacecraft's 400 km x 750 km orbit, a satellite operator planning to place their spacecraft in a 400 km orbit will want to test communication with RadioSTAR while RadioSTAR is near periapsis. A different operator who wants to test a satellite which will operate at a higher altitude will, similarly, want to communicate with RadioSTAR near apoapsis. Therefore, for any location on the Earth which is within RadioSTAR's service area, it is desirable for that location to have particular passes that see RadioSTAR near apoapsis, and near periapsis. In the event that a station desires to make contact when RadioSTAR is at the "wrong" altitude, RadioSTAR could also change its output power to simulate the difference in range.

In order to ensure that RadioSTAR is available to a particular ground station at the desired altitude within a reasonable timeframe, this precession must be modeled. The equation describing the rate of apsidal precession closely resembles the equation for nodal precession, owing to their both being caused chiefly by the oblateness of the Earth [8].

The equation describing apsidal precession is found in on page 651 of [8] and is duplicated here:

$$\dot{\omega} = \frac{3nR_E^2 J_2}{4p^2}(4 - 5sin^2 i) \tag{3.1}$$

Where variables are:

$\dot{\omega}$: The time rate of change of the argument of perigee

n : The mean motion of the spacecraft traversing its orbit. This is usually revolutions per day, degrees per second, etc. Note that because all other values in the formula are either dimensionless or cancel, the units of these first two variables will match.

R_E : The radius of the Earth. This may be in meters or kilometers, but must match p

J_2 : A term describing the oblateness of the Earth; constant

p : The orbit's semi-latus rectum. This is equal to $a(1-e^2)$ where a is the semi-major axis and e is the eccentricity.

The radius of the Earth is taken to be 6371 kilometers (the average value). The value of J_2 is well known to be 1.083×10^{-3} [31].

We have already chosen to place RadioSTAR into a 400 km x 750 km orbit. Therefore, the semi-major axis (keeping in mind to add the radius of the Earth, since 400 km and 750 km are altitudes above sea level) is 6946 kilometers. The eccentricity is 0.018, meaning we arrive at a semi-latus rectum of 6943.75 kilometers.

To place this equation into its final form, we need the mean motion. Given that this value will dictate our final answer's units, it should be chosen carefully. Our goal is to enable the customers of RadioSTAR to have RadioSTAR reach them at a desirable altitude in as few days as possible. Hence, it is reasonable to calculate this in terms of degrees per day. To find mean motion in degrees per day, we will find the orbital period, which is naturally in terms of seconds per orbit, then invert the value to get orbits per second, and multiply by 360 degrees per orbit, and finally multiply by 86400 seconds per day to get from orbits per second to degrees per day. The conversion factor comes out to 31,104,000, to go from orbits per second to degrees per day. The orbital period of RadioSTAR's orbit, with a semimajor axis of 6946 kilometers, is 5761 seconds (per one orbit). We take the conversion factor 31,104,000 and divide by 5761 seconds to find a mean motion of 5399 degrees per day.

Combining these values, we get:

$$\frac{3nR_E^2 J_2}{4p^2} = \frac{3(5399)(6371^2)(1.083x10^{-3})}{4(6943.75)^2} = 3.692 \quad \text{deg/day} \tag{3.2}$$

However, remember that this is not our final apsidal precession value, this is just the combined result of the orbital parameters we chose previously, and does not include the significant influence of inclination, which now becomes our final knob to adjust and determine our precession. We return to the initial equation for apsidal precession, which now for our particular orbit simplifies to:

$$\dot{\omega} = 3.692(4 - 5\sin^2 i) \tag{3.3}$$

We'd like to maximize our precession value. Figure 3-1 indicates how much precession occurs for any chosen orbital inclination. This plot was generated with a simple Python script with heavy use of the Matplotlib plotting library. [9] The code to generate this plot is given in Appendix A.

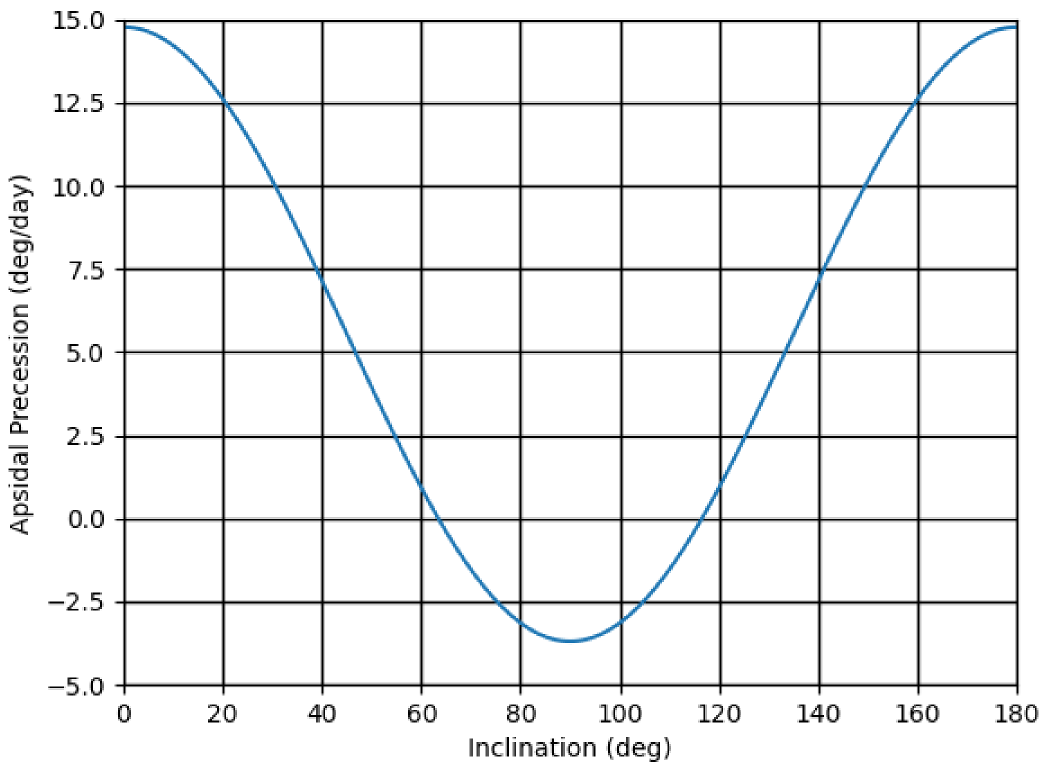

Figure 3-1: Influence on apsidal precession of RadioSTAR's orbit, as a function of orbital inclination

From this plot, several important points can be observed. First, it is notable that the apsidal precession is zero when the inclination is 63.4 degrees (as well as when it is 116.6 degrees). This corresponds to Molniya orbits, where avoidance of apsidal precession was critical for keeping the apogee positioned over Russia.

The other, more critical point of interest is that orbits which are closer to polar will have smaller degrees of precession. That is, the higher our inclination, the slower we will precess, and the longer a potential customer will have to wait for the orbit to arrive at their location. If our goal was only to maximize precession, we would place the inclination to zero – but of course this would then mean our only customers would be those positioned on the equator. This means there will be a trade-off between maximizing the number of customers that see RadioSTAR at a desired altitude, and maximizing the customers that will ever see RadioSTAR at all.

In navigating this trade, one important data point to keep in mind is that of the International Space Station. A large number of CubeSats are deployed from the ISS, meaning that many potential customers for RadioSTAR will necessarily be accessible from an ISS orbit. The ISS has an inclination of 51.64 degrees. Using this value in our precession equation returns a value of 3.43 degrees per day. This means that, in the worst case, a potential customer may have to wait up to 105 days before RadioSTAR's orbit cycles around to place the desired portion of the orbit over their location, which is undesirable. By reducing the inclination to only 45 degrees, we will only slightly reduce our number of customers (removing only those between 45 and 51.6 degrees latitude), while also increasing our precession rate to 5.54 degrees per day, making for a maximum wait of 65 days for any accessible location, reducing the wait nearly in half. This means RadioSTAR will have opportunities to pass overhead for nearly all of the United States, and will be accessible in lower sky elevations for locations even further north.

Due to considerations of maximizing precession rate while also keeping the inclination high enough to allow RadioSTAR to serve as many customers as possible, an inclination of 45 degrees is selected. Our inclination has been chosen such that it optimizes for fast precession, while also keeping the range of servable latitudes high.

3.2.4 Orbit choice Summary

An orbit has 6 critical elements: semi-major axis, eccentricity, inclination, argument of perigee, longitude of the ascending node, and mean anomaly. In choosing RadioSTAR's orbital elements of 400 kilometers by 750 kilometers at an inclination of 45 degrees, we have addressed each of these elements. By choosing an orbit with a perigee of 400 kilometers and an apogee of 750 kilometers, RadioSTAR's semi-major axis and inclination have been selected. Next, by using considerations of apsidal precession and geographical accessibility, we chose an inclination of 45 degrees. We are intentionally allowing the orbit's argument of perigee to precess, and hence we do not need to select it. Finally, longitude of the ascending node does not matter to RadioSTAR, as its orbit will perform the same regardless of its celestial orientation. The longitude of the ascending node will be allowed to precess throughout the mission and will be considered irrelevant for operations. Finally, the true anomaly will not be important, because RadioSTAR does not need to operate in any position with respect to other spacecraft.

While we have gone over the ideal orbital parameters, from a practical perspective, RadioSTAR is unlikely to actually operate in this orbit. CubeSats are currently almost always launched as ride-share missions, and it is unlikely that a ride that will already be going to the highly specific orbit RadioSTAR requests. The orbital eccentricity is especially uncommon. This means we will need to make one of two choices: Compromise on our orbit, or add propulsion to reach the desired orbit, after initial injection into a more standard orbit. The next section will consider the possibility of adding propulsion to RadioSTAR.

3.3 Propulsion

Ideally, RadioSTAR would receive its own launch vehicle, or otherwise would be able to be delivered by a launch vehicle precisely to the desired orbit. With the rise of dedicated SmallSat launchers [32], including Rocket Lab's current operations and upcoming providers like Virgin Orbit, Astra, and Firefly, a dedicated ride to the exact chosen orbit may be possible in the future. Currently, however, the status quo is that SmallSats are generally launched on a Ride-Share basis, alongside a larger primary payload (or many dozens of other SmallSats). Therefore, in order for RadioSTAR to reach its desired operational orbit of 400 km by 700 km at 45 degrees inclination, it may need a propulsion system to transfer from the initial deployment orbit. Additionally, adding propulsion would be useful for orbit maintenance, station-keeping, or enabling visitation of a particular ground station sooner than the orbit would passively allow RadioSTAR to perform a flyover.

3.3.1 Propulsion required for orbital boosting

In order to determine the requirements for the propulsion system, calculations must be performed to outline RadioSTAR's required delta-V. For this purpose, we will assume an initial deployment orbit from the ISS. We will assume the ISS is in a 400 x 400 km orbit, with an inclination of 51.6 degrees. Therefore, RadioSTAR must boost from 400 x 400 km to 400 x 750 km orbit, as well as reduce its inclination to the 45 degree desired operational orbit.

For a first-pass approximation calculation, we will assume that the thrust may be applied impulsively. More realistically, the proper thruster choice for RadioSTAR will likely be electrospray, which has an extremely low thrust, but this will afford it a large delta-V due to the high specific impulse achievable with electrospray thrusters (for example, Accion Systems sells an electrospray thruster which reaches a specific impulse of 1650 seconds [33]). This impulsive thrust will be calculated to be applied directly on the equator, since applying thrust at the ascending or descending node (as the spacecraft crosses the equator) is the most effective way to adjust inclination. Of course, actually implementing this may be impossible, but for now we will calculate the best-case delta-V required.

To find the required velocities before and after the burn, we use the vis-viva equation:

$$v = \sqrt{\mu \times (\frac{2}{r} - \frac{1}{a})} \tag{3.4}$$

Where: μ : Standard Gravitational Parameter of the Earth, 3.986×10^{14}

r : Current radius (distance) from spacecraft to center of the Earth; both before and after the burn we are at 400 km, which, taking into account the size of the Earth itself, gives a value of 6,771,000 meters.

a : Semi-major axis of the orbit. In the initial orbit, the orbit is circular and thus this value will be equal to the r value. In the final orbit, the semi-major axis is the average of the perigee and apogee values, placing us at 6,946,000 meters.

Therefore, prior to the burn, our velocity is:

$$v = \sqrt{3.986x10^{14}(\frac{2}{6771000} - \frac{1}{6771000})} = 7673 \quad \text{m/s} \tag{3.5}$$

And after the burn, in our operational orbit, our velocity is:

$$v = \sqrt{3.986x10^{14}(\frac{2}{6771000} - \frac{1}{6946000})} = 7769 \quad \text{m/s} \tag{3.6}$$

This is a difference of 94 meters per second. The required delta-V to boost a spacecraft from an initial 400 x 400 kilometer orbit to a 400 x 750 kilometer orbit is 94 m/s.

3.3.2 Propulsion required for Plane-Change

While the magnitude of the spacecraft's velocity needs to change by 94 meters per second, in order to change the orbital plane from the ISS inclination at 51.6 degrees to 45 degrees, the burn must also have a normal (that is, perpendicular to the plane of the orbit) component. The addition of the plane change becomes the majority of the required delta-V, by a wide margin. To determine the total delta-V, we will imagine the spacecraft frozen in time at exactly the moment it reaches the ascending node of its orbit. We can then examine the velocity vector of the spacecraft, immediately before and immediately after the thrust is applied. The magnitude of the two velocity vectors was found in the previous section. The direction of each velocity vector is simply the inclination of the orbit. The two vectors align as shown in Figure 3-2.

We are increasing the magnitude of our velocity, but also redirecting it. The black arrow represents our delta-V, taking us from one velocity vector state to the other. We can use simple vector math to find the magnitude of that black vector. We take the final velocity vector and subtract the initial vector, in a component-wise fashion. The final velocity vector is at 45 degrees and therefore has two identical components, at 5494 m/s. The initial velocity vector is at 51.6 degrees and therefore it has a "vertical" (in the frame of this drawing) component of 6013 m/s, and a "horizontal"

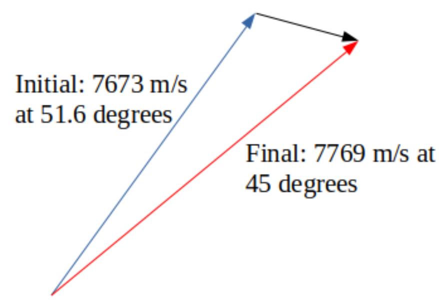

Figure 3-2: Comparison of velocity vectors before and after applying propulsion to move from ISS orbit to ideal operational orbit. Black vector indicates ultimate delta-V vector required.

component of 4766 m/s. We then subtract these values and find that our delta-V must have a horizontal component of $5494 - 4766 = 728$ m/s and a vertical component of -519 m/s. Combining these via the Pythagorean Theorem yields a final required delta-V of 894 m/s.

Again, note that this value is prior to any management of non-impulsive considerations. 894 m/s is totally out of reach with CubeSat technology. This makes it clear that the desired orbit can not be reached from an ISS orbit.

It is clear that RadioSTAR can not reach its desired orbit from an ISS orbit using propulsion. However, remember that the orbit was a “wish list” item. RadioSTAR can serve its mission from any orbit, but with compromises to its ability to maximize customer availability. It is not a mission-breaking change to operate simply from the standard ISS orbit. Additionally, without the plane change maneuver, the delta-V was only 94 meters per second, which is more manageable. It will likely be best for an early version of RadioSTAR to take on an orbit which does not fulfill all the access desires, but if a pilot spacecraft is well-received, one of the new SmallSat launchers which delivers to dedicated orbits may be able to deliver a more ideal orbital situation. Alternatively, a version with a small propulsion module to deliver 94 m/s would be sufficient to bring RadioSTAR to a higher orbit, thus partially completing the goal of wide access. A final option would be for a “kick stage”, as provided by some of the upcoming SmallSat rocket launch companies, to serve as propulsion for RadioSTAR to get into an ideal orbit.

3.3.3 Alternative Approach: Sun-Synchronous

While we were unable to attain the most ideal orbit, we found that we may be able to operate from an ISS orbit. An alternative to consider is that of sun-synchronous orbit (SSO). At the time of this writing, SpaceX has just performed its Transporter-1 rideshare mission, which delivered more payloads into orbit than any prior mission [34]. It took its CubeSats to a sun-synchronous orbit. Leveraging the high frequency at which CubeSats prefer operating in this orbit will be beneficial to RadioSTAR's ability to secure a launch. With more SpaceX rideshares coming in the future, and other providers such as Rocket Lab often conducting flights to SSO, this will be RadioSTAR's best opportunity to operate. Taking Transporter-1 as a standard example flight, we can imagine RadioSTAR as one of its payloads and analyze RadioSTAR's situation as a result. One of the spacecraft carried on Transporter-1 has the following TLE:

```
    LEMUR-2-NOOBNOOB
1 47538U 21006DY 21046.43157050 .00000948 00000-0 58004-4 0 9996
2 47538 97.5116 109.7721 0012339 157.8098 202.3669 15.12554019 3601
```

Unfortunately, this places us in a region of low nodal precession. Specifically, referencing back to Equation 3.3 we find that the spacecraft inclination of 97.5116 degrees yields a precession of only 3.377 degrees per day (in the negative direction). This would mean the orbit will precess every 107 days. This may be longer than ideal, but a second RadioSTAR placed in an orbit 180 degrees out of phase would take care of this, halving the amount of time taken between passes of either RadioSTAR. This operational concept with two sun-synchronous spacecraft orbiting 180 degrees apart has design history in NOAA's Suomi-NPP and NOAA-20 spacecraft, which operate 180 degrees apart to minimize time between ground imaging passes; a similar benefit exists in RadioSTAR minimizing time between radio sampling passes. Adding a second spacecraft would certainly improve the mission prospects, while also offering some redundancy in the event that one of the spacecraft experiences an orbital failure. Two spacecraft in a sun-synchronous orbit would be a beneficial option, or alternatively, one could operate in an ISS orbit and one operate Sun-Synchronous.

3.3.4 Final Orbit Thoughts

Clearly, RadioSTAR has several orbit options available. Although none are able to fully perform everything we hoped for due to the realities of access to orbit, it is clear that there are several highly viable options available. RadioSTAR should be agnostic to what type of launch it requires – it can enter an ISS orbit, a polar orbit, or almost any other orbit and still serve a useful purpose. Likely, the orbit will ultimately be determined simply by what launch provider is available to launch the spacecraft. However, being capable of a wide range of operating orbits should increase the ability to find a suitable launcher. Depending on what orbit is reached, several different particular mission plans are available to RadioSTAR. A polar orbit would be necessary for any mission plan which requires visitation of all locations (for example, if there was known to be a particular ground site at a polar location which desires to be served by RadioSTAR). Alternatively, if an equatorial site existed which would benefit from a high visitation rate (which may be connected with launch sites, should they have a need for services of the type RadioSTAR provides), naturally RadioSTAR could be placed in an equatorial orbit which would visit the site nearly 15 times per day. No particular orbit is necessary for RadioSTAR, but it is clear that many orbits provide different balances of factors which may be beneficial for highly particular applications of RadioSTAR's capabilities. Keeping in mind the radio astronomy application of RadioSTAR, we should be sure that our inclination captures their latitudes. These include the Square Kilometer Array at 31 degrees South, the Murchison Widefield Array at 27 degrees South, or the Very Large Array at 34 degrees North. To avoid losing the service of these telescopes, RadioSTAR would desire to keep its inclination at least above 34 degrees.

Chapter 4

Design

We have now examined the trades going into the spacecraft, and reduced the design space from what we would ideally like to have in a perfect spacecraft into a list of more achievable goals. With a reasonable set of goals outlined, we can now consider hardware components that are available on the market, and arrange them into a preliminary design of what the software-defined radio's architecture will look like. We will focus only on the radio system itself. To reiterate what we determined for the desired capabilities of the radio: The frequencies will be segmented into the VHF, UHF, 1.4 GHz, and 2 GHz bands. We will need to be capable of FSK, GFSK, GMSK, OOK, and AFSK modulations, but can live without without the full flexibility of arbitrary I/Q waveforms. We will plan to keep our transmitting power window of 0.1W to 5W (and measure it), and use linear polarization.

We begin by selecting a particular market offering of Software-Defined Radio chip, which will act as the central component of the payload, and which will be the primary component to drive the required parameters for all other components.

4.1 Primary Radio Hardware

After a survey of the options on the market, one of the strongest options for an RF integrated circuit to reside at the heart of RadioSTAR is the Analog Devices AD9363 [36]. In the event that an alternative is needed (for example, if the AD9363 ends production), backup options exist, such as the Texas Instruments CC1110 or a custom solution with dedicated mixing based around a microcontroller with a fast Analog-Digital converter such as the LPC4320 used in the HackRF One. For now, we will baseline using the AD9363. Several parameters of this device make it highly attractive for this application. First, its operational frequency range is 325 MHz to 3.8 GHz, which easily accommodates the common bands from UHF, to the 915 MHz ISM band, all the way up through S-band. Its frequency characteristics will allow it to operate at any likely desired frequency. Second, it has 4 differential transmit outputs, and 6 differential receive inputs. This means that individual RF front-ends can be connected to individual ports, eliminating the need for complex RF routing to connect a single receive or transmit port to the multiple amplifiers, filters, and antennas which correspond to the multiple operational bands. The alternative (using a single-port software-defined radio chip such as the CC1110) would require RF switching between multiple systems, and careful software control to ensure that the entire system is synchronized, and that transmission at a particular frequency occurs only when all the components connected are configured for that frequency. To transmit at 450 MHz, the filters and antennas must all be controlled into 450 MHz mode. Additionally, having only a single RF port presents issues related to Standing Wave Ratio, and if misconfigured, the one and only transmit port could be destroyed, ending all operations, as was unfortunately experienced on the MicroMAS-1 mission [37]. By using a chip with dedicated inputs and outputs for each frequency range, a large number of parameters of the system can be simplified. Another strong point acting in the AD9363's favor is that it is at the heart of the Analog Devices ADALM-PLUTO [38], a platform designed for software-defined radio experimentation. This device has a USB port to plug into a computer and allows for easy interfacing to the AD9363, which can then receive or transmit across its frequency range. This means that a large amount of preliminary experimentation can be done with the chip that will be used on the spacecraft, and also means that we will have a reference design which incorporates this device, thus allowing for increased confidence of the validity of the RF design.

4.2 Frequency Selection

With a center chip chosen, we now need to choose frequencies to address. These will drive our choices of antennas, amplifiers, filters, and other crucial RF components. Ideally, we will not use any switching for any of these. There are 6 receive channels and 4 transmit channels, and we will need to select frequency ranges to assign to each of these channels.

4.2.1 VHF operation

The first thing to address is that there are several applications where we desire to use VHF, around 140 MHz. Clearly, our chosen integrated circuit can not serve those frequencies, as it bottoms out at 325 MHz. However, it is possible for us to indirectly operate in the VHF band. Pasternack sells the PE88D1001, which is a "Divide by 10 Frequency Divider". This takes an incoming frequency and divides it by 10. Therefore, if we desire to generate a signal at 180 MHz, the AD9363 can generate a signal at 1800 MHz, which then gets divided by 10 by this component, and ultimately transmitted at 180 MHz. The opposite component, a Frequency Multiplier (which would receive a VHF signal and produce an output within the range of the AD9363's sensitivity) is also a component that exists, but a survey of the market turned up no results within the VHF range – these devices only exist on the Gigahertz spectrum. Ongoing study will evaluate whether these multipliers could be employed for the purposes of receiving VHF, but for the moment VHF reception will not be planned. We allocate one of our 4 transmit ports to VHF, with the frequency divider in-line. This will serve for the purposes of providing a radio astronomy signal source at VHF.

4.2.2 UHF operation

Next, we move up the spectrum to UHF. This comes into RadioSTAR's original primary purpose of transmitting and receiving nominal CubeSat communications. We will use one transmit port and one receive port dedicated for UHF. In terms of an antenna, many options exist on the market. Ideally we would be able to have a dipole centered near 405 MHz, and another centered near 440 MHz, as these appear to be the two common frequency ranges [10]. Additionally, it is likely possible to reuse one or both of these as our VHF antennas. Fortunately enough, the VHF band is almost exactly at frequencies 1/3 that of UHF, so a dipole is capable of resonance on both bands, though this performance will need real-life testing. This architecture (using a single antenna which is capable of being resonant in both the UHF and VHF bands) is commonly used in monopole form on handheld radios. By reusing an antenna for VHF and UHF, we reduce the mechanical complexity of the spacecraft. Proper lab testing will be critical to evaluate whether the same antennas can indeed be used on the spacecraft side.

4.2.3 GHz operation

We have now allocated a transmit port to VHF, and a transmit and receive port to UHF. That covers our plans for the sub-GHz range. Above the GHz, our desires are relatively simple. Around 1.4 GHz, we want to receive GPS, and be able to generate 21-cm Hydrogen Line signals for astronomy calibration. This will consume another transmit and receive port. Finally, we want to use 2 GHz for S-band communications which will consume another port of each type. That means we've used all 4 of our transmitting ports (VHF, UHF, 1.4 GHZ, and 2 GHZ), and only 3 of our receive ports (UHF, 1.4 GHz, and 2 GHz).

4.3 Remaining ports

We have now left 3 receive ports vacant, which will be able to be allocated to other signal reception purposes. This will depend on what niches in the field need to be filled, possibly connecting with the earlier-mentioned goals of Hawkeye 360 to receive signals that may be coming from ships. Another option would be to receive signals associated with search-and-rescue beacons used by stranded individuals. There is additionally a potential application of receiving the ADS-B transponder signals which aircraft use to report their locations. Receiving these signals from space may be useful, especially for the case of tracking aircraft as they fly over open ocean with no ground stations in the area to directly receive their signals. A final use of these extra ports would be for polarization management. As mentioned earlier, we have the ability to double up on antennas to generate (or receive) two signals of orthogonal polarizations, which would enable us to specify a transmitted polarization, or to detect a received polarization. This may be an attractive option, as it would increase RadioSTAR's knowledge of the signals in its area, or allow for ground stations to test the polarization dependence of their signal reception. Additionally, because a signal's polarization changes when it reflects off a surface, it may be possible to do interesting types of measurements of reflected multi-path signals (such as GNSS-R, or using signals actively transmitted by RadioSTAR itself) by knowing what signals are directly received and which have had their polarizations influenced by reflecting. Table 4.1 outlines our selections for how to use each of the AD9363's ports.

Table 4.1: Ports available on AD9363 and RadioSTAR's uses for each

Port	Selected Use
TX1	VHF transmit
TX2	UHF transmit
TX3	1.4 GHZ transmit
TX4	2 GHZ transmit
RX1	UHF Receive
RX2	1.4 GHZ receive
RX3	2 GHZ receive
RX4-RX6	Available for Future Use

4.4 Overall Configuration

After all the discussions thus far, we have an overall representation of what the signal should look like. The AD9363 chip will be used to generate and process signals. We have chosen how to allocate its ports, aside from the three vacant receive ports which are available for future configuration. Two final components will also be discussed here: Alongside the AD9363 manufactured by Analog Devices, we will also use Analog Devices' ADL5902 RF Power Detector integrated circuit [39]. See Figure 4-1 for a computer rendering of this part.

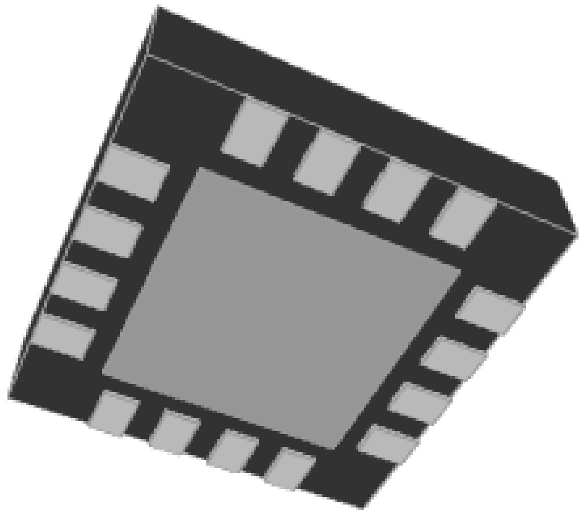

Figure 4-1: 3D model of QFN (Quad Flat No-Leads) device package of ADL5902 [40]

This device, with its single port, is able to measure the power level of a signal which is passed through it. This signal may be anywhere in the range of 50 MHz to 9 GHz, which is far beyond any of the signals we've discussed interest in for RadioSTAR. By attaching one of these to each of our transmit lines, we can ensure complete onboard knowledge of our true signal output levels. Therefore, we can be sure that the signals being transmitted to the ground are at a known power level, and know that any differences in received power are related either to the receiver, or to the path the signal took to get there. Finally, on each of the frequencies in which we intend bi-directional operation, we will use an RF circulator, which is a device with three ports, which routes signals going into any port to be directed out of the next port - a signal into Port 1 will be sent out of Port 2, a signal into Port 2 will be sent out of Port 3, and a signal into Port 3 will come out of Port 1. This allows us to use an antenna for both capabilities without allowing the chip to fry itself by transmitting directly into its receiver - by connecting the transmitting channel to Port 1, the antenna to Port 2, and the receive channel to Port 3, we ensure that transmitted signals come out of the antenna and received signals go from the antenna to the receive channel where they belong. Figure 4-2 shows a block diagram for the system.

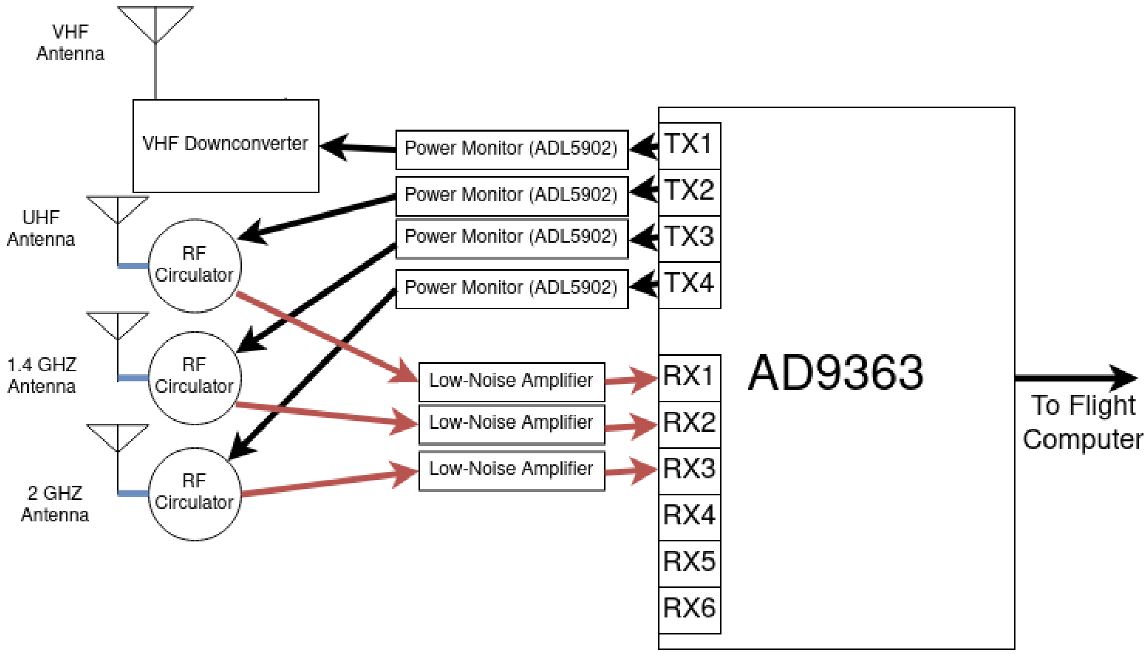

Figure 4-2: Notional Block Diagram of RadioSTAR's core Radio Frequency hardware, depicting the AD9363 Software-Defined Radio, the ADL5902 power monitor, RF circulators, antennas, and the downconverter utilized for VHF operation. Black arrows indicate signals flowing from RadioSTAR out toward antennas; Red arrows indicate signals coming in; Blue arrows indicate locations where signals may travel either direction.

We have now notionally selected a set of hardware to allow RadioSTAR to serve its mission. With the overall spacecraft design established, we can move into a final chapter, discussing future work to still be done on RadioSTAR, as well as the expected impacts of RadioSTAR upon the stakeholders who serve to benefit from it.

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Chapter 5

Future Work and Anticipated Impacts

With the baseline concepts for the spacecraft and mission outlined, we will next discuss the most important choices that have yet to be made, and the critical tasks which still remain to allow RadioSTAR to move forward in the development process. We will then discuss the impacts that would be expected, should a mission like RadioSTAR become available as an orbiting asset.

5.1 Future Work

Several obstacles could stand in the way of RadioSTAR's concept coming to fruition. We will focus on a few broad categories. One of these is the licensing. Another is the level of confidence in RadioSTAR's ability to act as a pure frequency source for uses like calibration of frequencies. We will also consider other applications, including as a signal repeater. We will briefly discuss these topics and outline next steps and considerations.

5.1.1 Licensing

Traditionally, a CubeSat mission has a simple set of two frequencies – one for uplink, and one for downlink. A prospective operator requests a frequency allocation from the FCC, which then will ensure that the mission as proposed will not cause any problems. The FCC ensures that the frequencies requested are available for use, that they will not interfere with any other radio operation, and that their power levels are not going to be harmful to any outsiders. This licensing is conducted for both the spacecraft and the ground-side hardware. Once this license is granted, the operators are able to use the uplink frequency to command the spacecraft, and the downlink frequency to receive data back. The frequency allocation is generally granted for a period of several months, at which point it will either lapse (and the frequencies revert back to being held by the FCC, available for any other mission to request authorization for use), or the frequency-user will re-apply for a renewed frequency license.

RadioSTAR presents an unusual licensing challenge. Its goal is, explicitly, to not have a single dedicated uplink or downlink frequency, and instead to serve as a flexible piece of radio hardware. Therefore, the standard FCC licensing paths will likely not be adequate, and this will pose a significant challenge. It is likely that the design will need to be validated such that confidence is made that the spacecraft will not accidentally transmit on an unintended frequency – with a radio locked into a particular (explicitly licensed) frequency, as on a normal spacecraft, unintended transmissions are less of a problem because the spacecraft is only transmitting on the frequency it is supposed to (albeit not at the time, or potentially not with the data, that was intended). With RadioSTAR having a radio which is physically capable of transmissions at any frequency, there is a risk that this radio could begin transmitting at a frequency some other system relies on. This could be another spacecraft, or an object on the ground. For RadioSTAR to be licensed, the design must have fail-safes to prevent accidental transmission.

Beyond the dangers of accidental transmission, it is unclear what the licensing implications are for RadioSTAR's nominal operations. In the most standard of cases, RadioSTAR is validating a ground station by acting as another spacecraft, which will not yet be launched. However, whatever frequency it is transmitting on will not be a frequency which has normally been assigned to RadioSTAR – it will be a frequency assigned to that other spacecraft. Therefore, RadioSTAR would technically be stepping on that spacecraft's authorization, even though the transmission is being solicited from the very people who would stand to have their desired communications interfered with. The fact that the frequency RadioSTAR is using will be naturally clear at the time requested serves to somewhat reduce the risks associated with using that particular frequency. It is not possible to "step on" someone else's frequency if that particular someone else is the one who requested the transmission in the first place. Additionally, it is unclear whether it is possible for a spacecraft to operate under another spacecraft's frequency authorization. As far as the author can tell, nowhere on the FCC paperwork is there any type of identification of which space hardware is allowed to use a particular frequency. The authorization just says that the operators are licensed to transmit at a particular frequency, with a particular bandwidth, at a particular power level. Therefore it may be possible for the licensee to say "We hereby grant RadioSTAR permission to operate under our frequency authorization and transmit at our frequency for the purposes of validating our ground station". A similar issue exists in terms of being a signal source for radio astronomy, as sections of the band are generally reserved for those purposes, and are therefore forbidden to operate on due to the risk of interfering with radio telescopes. But if the transmission is explicitly requested by the telescope operators to perform diagnostics on the telescope, it is reasonable to imagine that an exception could be made.

Clearly, many questions remain to be resolved as far as licensing for a wide-band space-based signal source goes. Consultation with legal experts, or the FCC themselves if possible, will likely be necessary to resolve this and determine what bounds RadioSTAR would be allowed to operate in.

5.1.2 Frequency Management

No radio is perfect. A radio tuned to 1 MHz will theoretically undergo one million wave cycles per second. However, natural imperfections in manufacturing, tuning, and timing will result in it running slightly above or below this value. Normally this is not a problem. A radio only needs to be close enough to lock onto the signal and can then demodulate it. But with RadioSTAR, we hope to serve as a reliable, stable signal that can be used for calibration of ground systems. Specifically, the ability of a ground station to continue to track a signal in the presence of Doppler shifting will be important. In order to get reliable results, RadioSTAR will need to be able to be confident in its ability to generate a signal precisely at the requested frequency, which is a challenge. Many pieces of RF hardware experience temperature-dependent behaviors, where the frequency drifts when the system gets hotter or colder. This is especially a problem during initial startup, since RF hardware tends to produce a large amount of heat, which causes its temperature to drift upward, meaning that even if a system is perfectly tuned initially, its own generated heat causes it to lose its alignment. RadioSTAR will need some sort of feedback system to ensure its generated frequency is the desired one. This fine control is desirable, though not absolutely crucial for every use-case. Further work will investigate whether this type of frequency tracking (over the multiple operational channels and frequencies) is workable within the limitations of operating on a CubeSat.

5.1.3 Operation as a Crosslink / Repeater

RadioSTAR possesses a unique capability in that it is able to both intake signals across many frequencies, and produce signals across many frequencies. By using both of these capabilities, RadioSTAR would be able to act as a go-between, taking a signal which can be received in one location, and re-transmitting it to be received in another location. There are several situations where this may be useful.

One use case for this capability would be for exchanging data between two ground-based locations, in a Ground-to-Ground configuration. Two sites which are below each other's horizons may both be within reach of RadioSTAR, in which case RadioSTAR could relay messages between the two. This would resemble the existing Amateur Radio repeaters that have been built into spacecraft such as Fox-1Cliff [41]. An orbital data relay could also be useful as material for spaceflight outreach, in that demonstrations could be done with the public to use a satellite to carry messages between countries.

Another potential additional use case for RadioSTAR as a signal repeater would be to provide cross-link capabilities with other spacecraft to relay their signals with the ground, in a Space-to-Ground configuration. This may become useful if a particular spacecraft operator wants to increase their contact capabilities (they can contact their spacecraft directly, or contact it through RadioSTAR, if RadioSTAR has line-of-sight with it, somewhat similar to how some spacecraft, particularly crewed, are able to communicate either directly with the ground, or through TDRSS). In the event that a spacecraft is in a particularly dynamic environment (whether it has recently experienced an anomaly, or is undergoing a propulsive maneuver), maximizing the ability to continuously receive data would be a goal RadioSTAR could help with.

Another case where RadioSTAR could help ground operators by acting as a relay to another spacecraft would be in the event that a spacecraft has an anomaly in its downlink radio's power amplifier – it may be possible for RadioSTAR to receive a faint signal when it is nearby that satellite, and relay its status down to the ground, with its higher-power fully-operational radio. However, this use case would be very situation-specific and would not necessarily be helpful in all circumstances. Still, it is worth noting the hardware capability exists. With the large time and financial resources invested in a spacecraft, RadioSTAR possessing the capability to restore radio contact with a spacecraft, even if it only happens once, would be a great service to whoever has contact restored.

On the topic of RadioSTAR as a relay, we've discussed Ground-to-Ground communication, Space-to-Ground communication, and that leaves only Space-to-Space communication. There are several opportunities for this. One would be spacecraft constellations, where exchanging data between different spacecraft may be useful for planning purposes, or for coordinating operations. Two spacecraft that are separated by a large fraction of an orbit, or operating in different orbital planes, may be able to mutually contact RadioSTAR, in which case RadioSTAR could allow the two to exchange data in a way they would otherwise be unable.

In addition to wide-spread crosslinks, another interesting application for (likely a derivative of) RadioSTAR would be that of acting as a hub or a mothership node for one of the concepts that has been proposed for a swarm of spacecraft. A group of extremely small spacecraft, each of which may have a radio at a power level in the region of a milliwatt or less, would have no chance of closing a link with a ground station directly. However, if RadioSTAR were to fly alongside them, then RadioSTAR could be the spacecraft which holds the sole link to ground, and then redistributes that connection to all the smaller spacecraft. This could also apply in the case where this derivative of RadioSTAR would possess a deployment mechanism, where it would be launched with the sub-satellites onboard and they would then deploy out of the body.

Clearly through these examples, the notion of a cross-link through a spacecraft like RadioSTAR is generally appealing. Further study, including discussion with future potential stakeholders, seems valuable in this domain.

5.2 Anticipated Impacts

Assuming RadioSTAR becomes operational, it would provide an increased level of situational awareness for spacecraft operators. It would be able to validate ground stations, and aid in troubleshooting in the event of anomalies. It would also aid radio astronomy telescopes, enabling characterization and diagnostics, especially of their beam profiles. RadioSTAR could also act as a listening station for any signals of interest, including to evaluate the RF noise environment in low-earth orbit, and determine how that noise changes over time. The flexibility of RadioSTAR enables it to interact with many types of systems using radio, and ultimately it is likely that additional uses will be found for other, previously-unknown industries and systems. The author is aware of ocean exploration vehicles which may be able to use RadioSTAR to act as a signal repeater for their collected data, for example. It would also not be out of the question for RadioSTAR to unintentionally discover new applications for radio sensing in space, in the event that a serendipitous signal is received – there could be potential for RadioSTAR to report some types of space weather events, for example. Because RadioSTAR is designed from the ground up to be a flexible piece of hardware, it could have additional uses beyond the already valuable planned contributions of the applications described in this thesis.

Given the number of benefits associated with launching a RadioSTAR spacecraft, it is also meaningful to imagine applications associated with having multiple copies of RadioSTAR. With more RadioSTAR spacecraft, the constellation of satellites would, in aggregate, be able to visit any ground site more often. This could have applications associated with keeping track of a ground target, for example. If a ship is in distress on the open ocean, multiple RadioSTAR satellites flying over could collect the ship's location transponder in succession, enabling constant knowledge of its position. Additionally, the set of spacecraft may be able to relay messages from one to the next, allowing a ground station to have constant contact with a spacecraft as it circles the Earth, which would be useful in the event of a highly dynamic environment where data is wanted through the whole course of flight. This could also be useful for modeling of the final phases of spacecraft deorbit, since RadioSTAR could receive telemetry from a satellite as it plunges into the atmosphere. This could improve knowledge of the behavior of reentry and improve predictions of impact locations. Another use of multiple RadioSTARs would be to have multiple satellites receive a signal at the same time, which could be used for interferometry applications. The flexibility of RadioSTAR could also be useful for education - if students were able to program a swarm of satellites to communicate in different fashions, it could aid their knowledge of spacecraft and how they work, in a manner similar to that done by Zero Robotics in the operation of the SPHERES satellites aboard the International Space Station [42].

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Appendix A

Python Scripts

Listing A.1: Script to count spacecraft visible from MIT Ground Station

```
from skyfield.api import load, EarthSatellite,wgs84
import math,requests
import matplotlib.pyplot as plt
ts = load.timescale(builtin=True)
#Can specify a different time with Skyfield's ts.utc()
start_time = ts.now()
minutes_to_run = 1440
groundstation = wgs84.latlon(42.360757, -71.093062, elevation_m=20)


#This is https://planet4589.org/space/gcat/tsv/cat/satcat.tsv
satcat = open('satcat.tsv','r')
#This list will hold all the satcat identifiers of the cubesats we find.
satcat_nums = []
for row in satcat.readlines()[1:]:
    #Status code of "O" indicates in orbit, still in free flight.
    status_code = row.split("\t")[11]
    if "cubesat" in row.lower() and status_code == "O":
        satcat_nums += [row.split("\t")[1]]

satellites = []
#We don't want to overload Celestrak, so we're going to get the data and then save to a
```

```
#Change this to true if you want to grab the TLE files anew.
fetch_data = False
if(fetch_data):
    big_tle_list = ""
    for ident in satcat_nums:
        raw_reply = requests.get('https://celestrak.com/satcat/tle.php?CATNR=' + ident).
        TLE = raw_reply.splitlines()
        print(ident)
        if len(TLE) == 3:
            satellites += [EarthSatellite(TLE[1],TLE[2],TLE[0],ts)]
            big_tle_list += "\n".join(TLE) + "\n"
        else:
            print(TLE)
    with open('cubesat_tle_list.txt','w') as outfile:
        outfile.write(big_tle_list)
else:
    #If you're getting a file not found error, you are probably running this script for
    #Change fetch_data to True above, and that should sort you :)
    with open('cubesat_tle_list.txt','r') as sat_file:
        lines = sat_file.readlines()
        for i in range(0,len(lines),3):
            satellites += [EarthSatellite(lines[i+1],lines[i+2],lines[i],ts)]

#Now go through all the satellites and determine if they're visible in our sky.
times = []
skycounts = []
end_time = ts.tt_jd(start_time.tt + minutes_to_run/1440)
current_time = start_time
while current_time.tt < end_time.tt:
    sky_count = 0
    for sat in satellites:
        alt,az,dist = (sat - groundstation).at(current_time).altaz()
        alt=alt.degrees
        if alt >0:
            sky_count += 1
    skycounts += [sky_count]
```

```
    times += [current_time.tt - start_time.tt]
    current_time = ts.tt_jd(current_time.tt + 1/1440) #advance by 1 minute
    if len(times) % 10 == 0:
        print(len(times))
plt.plot(times,skycounts)
plt.show()
```

Listing A.2: Script to Analyze Existing Spacecraft Altitudes

```
day_length = 86400 #in seconds
earth_mu = 3.986e14#Standard gravitational parameter
earth_radius = 6371000

class Satellite():
    #Takes a TLE as a list of 3 strings.
    def __init__(self, TLE):
        self.tle = "\n".join(TLE) + "\n"
        self.name = TLE[0][:-1]
        self.line1 = TLE[1]
        self.line2 = TLE[2]
        self.mean_motion = float(self.line2[52:63])
        self.orbital_period = day_length / self.mean_motion
        self.semimajor_axis = (earth_mu * self.orbital_period**2 / (4 * math.pi**2))**(1
        self.sma_altitude = self.semimajor_axis - earth_radius
        self.eccentricity = float("0." + self.line2[26:33])
        self.periapsis = (1-self.eccentricity) * self.semimajor_axis
        self.apoapsis  = (1+self.eccentricity) * self.semimajor_axis
        self.periapsis_altitude = self.periapsis - earth_radius
        self.apoapsis_altitude = self.apoapsis - earth_radius
    def __str__(self):
        return self.name + "\n" + self.line1 + "\n" + self.line2

import math
import requests

#This is https://planet4589.org/space/gcat/tsv/cat/satcat.tsv
satcat = open('satcat.tsv','r')
```

```python
#This list will hold all the satcat identifiers of the cubesats we find.
satcat_nums = []
for row in satcat.readlines()[1:]:
    #Status code of "O" indicates in orbit, still in free flight.
    status_code = row.split("\t")[11]
    if "cubesat" in row.lower() and status_code == "O":
        satcat_nums += [row.split("\t")[1]]
satellites = []
#We don't want to overload Celestrak, so we're going to get the data and then save to a
#Change this to true if you want to grab the TLE files anew.
fetch_data = False
if(fetch_data):
    for ident in satcat_nums:
        raw_reply = requests.get('https://celestrak.com/satcat/tle.php?CATNR=' + ident).
        TLE_lines = raw_reply.splitlines()
        print(ident)
        if len(TLE_lines) == 3:
            satellites += [Satellite(TLE_lines)]
        else:
            print(TLE_lines)
    with open('cubesat_tle_list.txt','w') as outfile:
        out_text = ""
        for satellite in satellites:
            out_text += satellite.tle
        outfile.write(out_text)
else:
    #If you're getting a file not found error, you are probably running this script for
    #Change fetch_data to True above, and that should sort you :)
    with open('cubesat_tle_list.txt','r') as sat_file:
        lines = sat_file.readlines()
        for i in range(0,len(lines),3):
            satellites += [Satellite(lines[i:i+3])]
highest_apos = sorted(satellites, key= lambda x:x.apoapsis_altitude,reverse=True)
lowest_peris = sorted(satellites, key= lambda x:x.periapsis_altitude)
if len(highest_apos) == len(lowest_peris):
    sat_count = len(highest_apos)
```

```
else:
    print("Something has gone horribly wrong...")
print(str(sat_count) + " satellites loaded")
margin_size = int(sat_count * .05)

print()
print("Top 5% of cubesats is the top " + str(margin_size))
marginal_high_satellite = highest_apos[margin_size]
print("The " + str(margin_size) + "th highest cubesat is " + marginal_high_satellite.nam
print("which has an apoapsis of " + str(marginal_high_satellite.apoapsis) + "m")
print("which has altitude " + str((marginal_high_satellite.apoapsis - earth_radius) / 1(

print()
print("Bottom 5% of cubesats is the bottom " + str(margin_size))
marginal_low_satellite = lowest_peris[margin_size]
print("The " + str(margin_size) + "th lowest cubesat is " + marginal_low_satellite.name)
print("which has a periapsis of " + str(marginal_low_satellite.periapsis) + "m")
print("which has altitude " + str((marginal_low_satellite.periapsis - earth_radius) / 1(
```

Listing A.3: Generating Plot of Apsidal Precession vs Inclination

```
import matplotlib.pyplot as plt
import math

inclination_range = range(0,181)

precession_values = [3.692 * (4 - 5 * math.sin(math.radians(i))**2) for i in inclination

fig,ax=plt.subplots()
plt.plot(inclination_range,precession_values)
plt.xlabel("Inclination (deg)")
plt.ylabel("Apsidal Precession (deg/day)")
plt.xlim(0,180)
plt.ylim(-5,15)
ax.grid(which='major',axis='both', color='k', linestyle='-', linewidth=1)
```

```
plt.show()
```

Listing A.4: Plot of MiRaTA spacecraft ground track

```
import matplotlib.pyplot as plt
from mpl_toolkits.basemap import Basemap
import numpy as np
import requests
from skyfield.api import EarthSatellite,load
session = requests.session()
page = session.get("https://celestrak.com/satcat/tle.php?CATNR=43015")
tle = page.text[:-1]#knock out the final newline
tle = tle.replace('\r','').split('\n')
ts = load.timescale(builtin=True)

satellite = EarthSatellite(tle[1],tle[2],tle[0],ts)

locations = satellite.at(ts.utc(2021,5,9,1,range(0,1440)))
alts = [np.linalg.norm(l.position.km) - 6371 for l in locations]
maxalt = max(alts)
print(maxalt)
minalt = min(alts)
altrange = max(alts) - min(alts)



fig = plt.figure(figsize=(10, 6), edgecolor='w')
m = Basemap(projection='robin', lon_0=0,resolution='c')
m.shadedrelief(scale=0.05)
m.drawparallels(np.arange(-90.,120.,30.),labels=[True]*4)
m.drawmeridians(np.arange(0.,360.,60.),labels=[True]*4)

x_vals = []
y_vals = []
colorvals = []
for l in locations:
    altitude = np.linalg.norm(l.position.km) - 6371
```

```
    lat = l.subpoint().latitude.degrees
    lon = l.subpoint().longitude.degrees
    x,y = m(lon,lat)
    colorfloat = (altitude-minalt) / altrange
    x_vals += [x]
    y_vals += [y]
    colorvals += [tuple([colorfloat]*3)]
colors = [i / len(x_vals) for i in range(len(x_vals))]
m.scatter(x_vals,y_vals,10,c=colors,cmap='inferno')
plt.inferno()

plt.show()
```

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