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CRITICAL VULNERABILITIES IN THE SPACE DOMAIN: USING NANOSATELLITES AS AN ALTERNATIVE TO TRADITIONAL SATELLITE ARCHITECTURES

by

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13. ABSTRACT (maximum 200 words)

Today, the U.S. military relies upon space-based technology for a myriad of functions from precision navigation to satellite communication. Satellites greatly enable the modern American military and particularly empower special operations forces across the globe, supporting decentralized and geographically disparate operations. However, the U.S. is highly reliant upon this technology and thus increasingly vulnerable with potential adversaries undoubtedly possessing, or at least cultivating, the ability to attack America's space-based infrastructure. As a safeguard against such vulnerabilities, nanosatellites, cube satellites (CubeSats), and other small satellites are a low-cost and expedient solution to build redundancy and resiliency, offering unique options as an alternative to traditional satellite systems. To support this hypothesis, this thesis provides such an alternative: A Software Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube). SAVIOR-Cube is a software-defined radio (SDR) payload operating as a very high frequency (VHF) relay via a nanosatellite in low Earth orbit. This thesis demonstrates the depth of the problem a payload such as SAVIOR-Cube could solve, the applicability of nanosatellite solutions to U.S. forces today, and the results of extensive testing, culminating with a proof of concept high-altitude balloon flight. Nanosatellites are a viable alternative to traditional space-based infrastructure—a solution to a critical vulnerability.

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CRITICAL VULNERABILITIES IN THE SPACE DOMAIN: USING NANOSATELLITES AS AN ALTERNATIVE TO TRADITIONAL SATELLITE ARCHITECTURES

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ABSTRACT

Today, the U.S. military relies upon space-based technology for a myriad of functions from precision navigation to satellite communication. Satellites greatly enable the modern American military and particularly empower special operations forces across the globe, supporting decentralized and geographically disparate operations. However, the U.S. is highly reliant upon this technology and thus increasingly vulnerable with potential adversaries undoubtedly possessing, or at least cultivating, the ability to attack America's space-based infrastructure. As a safeguard against such vulnerabilities, nanosatellites, cube satellites (CubeSats), and other small satellites are a low-cost and expedient solution to build redundancy and resiliency, offering unique options as an alternative to traditional satellite systems. To support this hypothesis, this thesis provides such an alternative: A Software Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube). SAVIOR-Cube is a software-defined radio (SDR) payload operating as a very high frequency (VHF) relay via a nanosatellite in low Earth orbit. This thesis demonstrates the depth of the problem a payload such as SAVIOR-Cube could solve, the applicability of nanosatellite solutions to U.S. forces today, and the results of extensive testing, culminating with a proof of concept high-altitude balloon flight. Nanosatellites are a viable alternative to traditional space-based infrastructure—a solution to a critical vulnerability.

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LIST OF ACRONYMS AND ABBREVIATIONS

A	ampere
AQIM	Al Qaeda in the Islamic Maghreb
ARGOS	Army Resilient Global On-the-move SATCOM
˚C	degrees Celsius
cm	centimeter
COCOM	combatant command
CONOP	concept of operations
CubeSat	cube satellite
dB	decibel
dBi	decibel isotropic
dBm	decibel milliwatt
LEO	low Earth orbit
LF	low frequency
LOS	line of sight
EDU	engineering design unit
EHF	extremely high frequency
g	gram
GEO	geosynchronous orbit
GEVS	General Environmental Verification specification
GHz	gigahertz
GPS	global positioning system
G_{rms}	G-force root-mean-square
GUI	graphical user interface
HAB	high altitude balloon
HF	high frequency

Hz	hertz
kg	kilogram
kHz	kilohertz
km	kilometer
m	meter
MAC	media access control
Mbps	megabits per second
mm	millimeter
MF	medium frequency
MHz	megahertz
MUOS	Mobile User Objective System
NPS	Naval Postgraduate School
OV-1	operational view-1
PNT	positioning, navigation, and timing
PST	Pacific Standard Time
RAM	random access memory
Rx	receive
SATCOM	satellite communication
SAVIOR-Cube	Software Assisted VHF Information Overhead Relay-CubeSat
SDR	software-defined radio
SFOD-A	Special Forces Operational Detachment-Alpha
SHF	super high frequency
SINCGARS	Single Channel Ground and Airborne Radio System
SOCAF	U.S. Special Operations Command Africa
SOF	Special Operations Forces
SPAWAR	Space and Naval Warfare Systems Command
STK	Analytical Graphics Inc. Systems Tool Kit

TLE	two-line element
TVAC	thermal-vacuum chamber
Tx	transmit
UART	universal asynchronous receiver transmitter
UHF	ultra high frequency
USB	universal serial bus
V	volt
VHF	very high frequency
VLF	very low frequency
W	watt
WGS	Wideband Global SATCOM

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EXECUTIVE SUMMARY

Today, the U.S. military relies heavily upon space-based technology for a myriad of functions from precision navigation to satellite communication and is thus vulnerable to potential adversaries cultivating the ability to attack the United States' space-based infrastructure. As a safeguard against such vulnerabilities, nanosatellites and cube satellites (CubeSats) are a low-cost and expedient method for building redundancy, offering unique options as an alternative to traditional satellite systems. This thesis provides such an alternative via the Software Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube): a software-defined radio (SDR) payload operating as a very high frequency (VHF) relay via a nanosatellite in low Earth orbit, as Figures ES-1 and ES-2 depict. This thesis demonstrates the depth of the problem a payload such as SAVIOR-Cube could solve, the applicability of nanosatellite solutions to U.S. forces today, and the results of extensive testing, culminating with a proof of concept high-altitude balloon (HAB) flight.

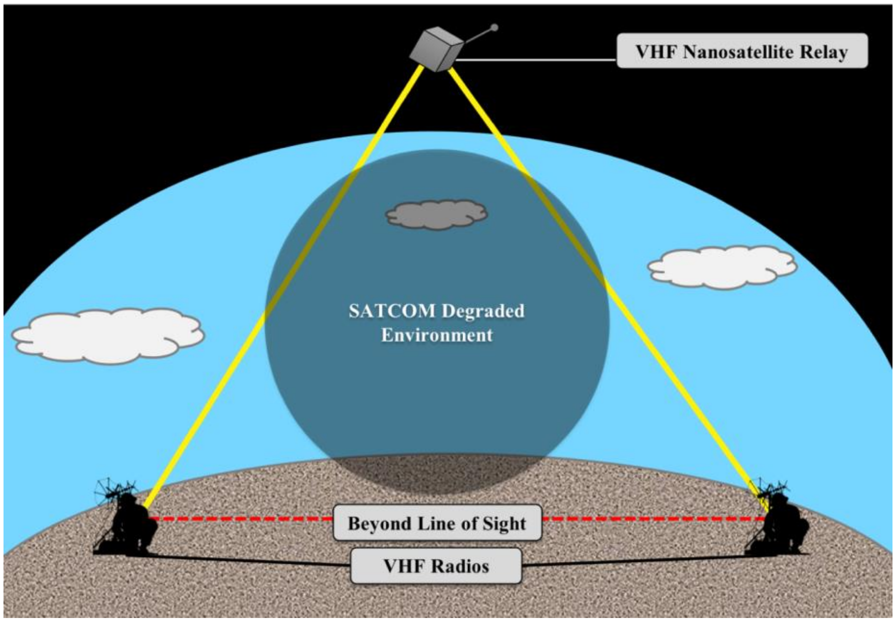

Figure ES-1. Concept of Operations

A. METHOD AND APPROACH

A research-based methodology coupled with in depth experimentation designed to:

- illuminate the vulnerability a dependence on space-based systems creates
- research potential nanosatellite solutions and build a model constellation and concept of operations for a VHF nanosatellite relay
- design, build, and iteratively test a prototype SAVIOR-Cube payload
- launch SAVIOR-Cube via a HAB to test it in a near-space environment

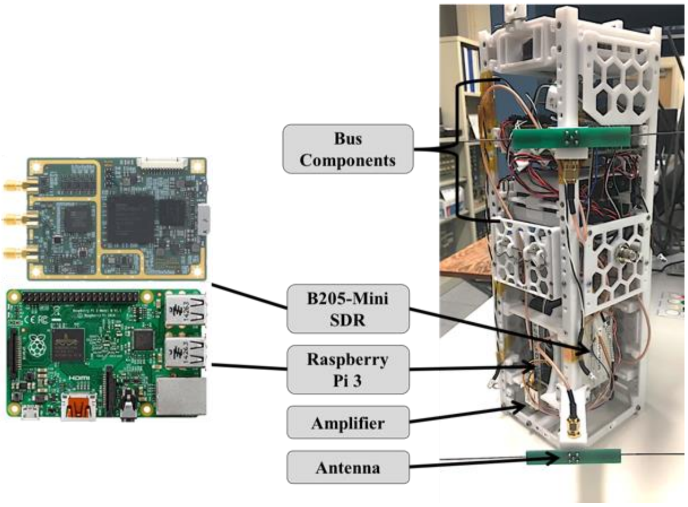

Figure ES-2. SAVIOR-Cube

B. TESTING AND RESULTS

Extensive research, experimentation, and testing resulted in:

- communication across a simulated distance of 100 km
- a maximum altitude of 21 km (70,000 ft) and communication over a maximum slant-range of 36 km
- thirty minutes of operations at altitude, successfully sending and receiving fourteen separate transmissions
- a successful proof of concept test and design for a VHF nanosatellite relay—a solution for a critical vulnerability

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Most importantly, I would like to thank my wife, Anna, and our son, Jack, for supporting me during this academic endeavor. They encouraged this Green Beret as I attempted to impersonate a scientist for a few months. As always, their continued support means the world to me.

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I. INTRODUCTION AND BACKGROUND

In the 1950s, the dawn of the space era led to scientific breakthroughs and technological innovations that forever changed the human way of life and still shape the way people connect across the globe. Today, modern governments and militaries are highly dependent on space technology to function, and the United States relies upon it to wage its modern style of war. Space technology enables the United States to conduct quick, decisive operations with decentralized units and precision weapons—the modern American way of war.[1] Furthermore, Special Operations Forces (SOF), the force of choice for America's Global War on Terrorism, often operate in remote locations and rely heavily on satellites to support a decentralized command structure, coordinating geographically disparate yet strategically connected operations. Though space-based technology greatly empowers U.S. SOF, the United States is teetering dangerously close to an overreliance on this technology. Access to space-based resources is finite, and every unit in the U.S. military, SOF included, does not have instantaneous access to this advanced technology for every mission. Beyond resource limitations, an adversary capable of jamming satellite signals, disabling U.S. ground stations, or attacking U.S. satellites could cause costly failures across the spectrum of operations. Moreover, the nature of special operations makes SOF particularly vulnerable to such anti-satellite attacks.

While the United States relies on space-based technology for a multitude of functions from positioning, navigation, and timing (PNT) to overhead imagery, nowhere is this high reliance more evident than in the use of satellite communication (SATCOM). Sophisticated communication systems such as SATCOM, coupled with decentralized command structures that inform and empower subordinates, have led to unprecedented awareness for commanders on the battlefield that greatly increases combat effectiveness.[2] Across the globe, U.S. forces use satellites to conduct encrypted video-teleconferences, to

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[1] Phillip S. Meilinger, "American Military Culture and Strategy," *Joint Forces Quarterly* 46 (October 2007): 85.

[2] Ryan Grauer, *Commanding Military Power: Organizing for Victory and Defeat on the Battlefield* (Cambridge: Cambridge University Press, 2016), 53.

access classified and unclassified networks, and to conduct real-time voice communication. U.S. SOF, in particular, utilize this paradigm to operate remote outposts in otherwise poorly connected and isolated regions of the globe, relying upon satellites orbiting the Earth to provide real-time links to higher headquarters on the other side of the planet. However, absent such capabilities, U.S. forces would be severely disadvantaged and U.S. SOF would find their current modus operandi—decentralized operations in remote regions—increasingly difficult to execute. Making matters worse, while safeguards exist for strategic assets like intercontinental ballistic missiles, little exists in the way of protection or contingency plans in the event of an attack on U.S. satellite infrastructure for tactical forces such as SOF detachments. This paints a stark reality: a high reliance on advanced communications technology is putting the U.S. military in a vulnerable position.

Despite the aforementioned vulnerabilities, it would be foolhardy for the U.S. military to divest itself from advanced technology such as SATCOM, as technological superiority gives U.S. forces, and in particular SOF, a clear edge on today's battlefield. However, redundant alternatives that build resiliency into existing space-based SATCOM architectures will help insulate against this critical vulnerability, while providing new options for communication techniques. Emerging technologies in miniature satellites and nanosatellites, for example, provide such alternatives.[3] Recent advances in these technologies have created unprecedented access to space at much lower costs, leading to innovations and unique payloads. Furthermore, software-defined radios (SDR)—simple programmable radios—allow for low-cost experimentation and payload development.

By utilizing nanosatellite technology in conjunction with SDRs, interesting possibilities with unique applications emerge. For the U.S. military, an SDR nanosatellite payload that builds redundant options for communication beyond traditional SATCOM would create much needed resiliency in the U.S. SATCOM architecture. Additionally, existing SATCOM systems generally do not support very high frequency (VHF) communication—transmissions from 30–300 MHz—yet most military forces rely heavily

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[3] The term "nanosatellite" will heretofore be used to refer to small satellites with a wet mass of less than 10kg to include CubeSats and picosatellites.

upon VHF radios for line of sight (LOS) communication.[4] Therefore, an SDR payload that augments existing VHF capabilities is quite valuable for military applications, potentially extending the range of VHF transmissions to SATCOM in lower orbits. While there are limitations for VHF transmissions supporting space-based communication, such as atmospheric scintillation, with enough power and the correct frequencies it is a viable alternative. With the current American way of war inexorably linked to space-based technology, and thus increasingly vulnerable, nanosatellites in low Earth orbit (LEO) provide interesting alternatives and redundancies that the United States should explore.[5] If the U.S. military does not recognize the importance of protecting against its potential space-based weaknesses, it will find itself crippled in its hour of greatest need.

A. PURPOSE AND SCOPE

The purpose of this thesis is to illuminate the depth of the U.S. military's reliance on space-based technology, understand the vulnerabilities this dependence creates, and design and test a payload to demonstrate the utility of using nanosatellites to mitigate these vulnerabilities. Developing a concept of operation (CONOP) for a constellation of nanosatellites serving as a VHF communications relay demonstrates the benefit of exploring nanosatellite applications. Subsequently building and testing a viable payload to prove the concept further emphasizes the utility of this emerging technology. Specifically, this thesis provides a feasible alternative to the U.S. military's high reliance on space-based technology by developing a low-cost substitute for traditional SATCOM architectures via an SDR VHF nanosatellite relay: The Software-Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube).

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[4] Gary D. Gordon and Walter L. Morgan, *Principles of Satellite Communications* (New York: John Wiley and Sons, Inc., 1993), 100.

[5] Low Earth orbit (LEO) is generally considered to be an orbit around the Earth with an altitude from approximately 150 km to 2,000 km above the Earth's surface.

B. RESEARCH QUESTION

Given the U.S. military's dependence on space-based technology, how can nanosatellites be utilized as an alternative to traditional SATCOM architectures to protect against adversaries capable of exploiting U.S. vulnerabilities?

C. LITERATURE REVIEW

An examination of the modern U.S. military quickly reveals that the United States is highly reliant on space-based technology to function and is thus increasingly vulnerable to potential attacks.[6] Examining the existing literature and theories on the cause of this high reliance, reviewing current SATCOM architectures, and understanding near-peer competitor anti-satellite capabilities identify the depth of the problem. The fundamentals of orbital mechanics as applied to emerging space technologies emphasize reasonable solutions that merit further research. Lastly, a brief examination of emerging nanosatellite applications and SDR technology highlights worthwhile solutions. Studying existing theories and methods helps in understanding the importance of finding an expedient solution to this critical vulnerability with a realistic safeguard.

1. The Depth of the Problem

Throughout history, military requirements and technological advances have been inexorably linked. Military necessities fostered by war and other crises led to competition between belligerents, and this competition frequently led to technological innovations that gave one side an edge on the battlefield. Often these innovations were in the form of advanced weapons such as nuclear bombs—new tools for killing.[7] However, many scientific advances less macabre in nature also owe their discovery to military needs. During World War II, for example, the first modern computer, known as a Turing machine, was created by Alan Turing, a British intelligence officer, as a counter to the German

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[6] Steven L. Bryant, "The Dangers of an Overreliance on Advanced Technology" (master's thesis, National Defense University, 2011), 2.

[7] Antoine J Bousquet, *The Scientific Way of Warfare: Order and Chaos on the Battlefields of Modernity* (New York: Columbia University Press, 2009), 99.

Enigma machine.[8] Communications technology has also seen many innovations thanks to military necessities. Electronic telegraphy, one of the first examples of humans sending information via electromagnetic signals, grew in prominence due to military forces using it as a means of communication.[9] American and Soviet competition during the Cold War led to the space race, which eventually resulted in the first man-made object orbiting the Earth—Sputnik.[10] Today, many advanced technologies, to include space-based technology, that developed out of necessity during wartime are now pervasive across the globe, enabling modern society.

However, the interconnected relationship between military needs and technological innovations created a military culture, and in particular the culture of the U.S. military, highly reliant upon advanced technology. Accordingly, there are extensive debates on the U.S. military's reliance on advanced technology. Critics argue that America used emerging technology to maintain an advantage over its adversary during the Cold War—the United Soviet Socialist Republic.[11] This created a culture of reliance on technology within the U.S. military since it was necessary for success. Some scholars make the case that necessity led to overreliance, and that the United States is now dangerously dependent on advanced technology. Though advanced technology gives the U.S. military a large advantage on the battlefield over its adversaries, it is becoming America's Achilles heel for the United States is deficient in ample technological protections.[12] Additionally, the problem is not easily solved because technology defines most aspects of U.S. military culture and doctrine.

Yet, some scholars argue that the American military can undo this dependence, but to do so the United States must make sweeping changes to its current doctrine, training, and operational procedures.[13] These recommended changes include properly adjusting

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[8] Bousquet, 98.

[9] Bousquet, 95.

[10] Bousquet, 134.

[11] Michael A VanPutte, *Walking Wounded: Inside the U.S. Cyberwar Machine* (CreateSpace Independent Publishing Platform, 2016), 3.

[12] VanPutte, 15.

[13] Bryant, "The Dangers of an Overreliance on Advanced Technology," 60.

command structures to prevent overly centralized command and control as well as not allowing information and communication saturation to overwhelm decision makers.[14] Other recommendations include updating U.S. military doctrine to address technological advances and to better incorporate the military in the procurement and training cycles for advanced technology.[15] Lastly, the argument is made for resiliency and redundancy in technology, particularly for communications technology, to insulate against a loss of command and control.[16] In other words, redundant communication systems help to reduce failure rates by building multiple pathways to the same target—a beneficial redundancy.[17] Though these arguments do not directly address a high reliance on space-based technology, they are a consequence of the same symptoms.

While much of the debate concerning the United States' use of advanced technology does not focus on space-based systems, recent actions by China and Russia shed new light on space-based vulnerabilities. China, for example, tested its ability to destroy a satellite in LEO in 2007.[18] General John Hyten, the Commander of U.S. Strategic Command, details the current danger China possesses as it continues to weaponize the space domain. He predicts that the same accuracy China demonstrated in LEO, could cripple the U.S. satellite infrastructure in geosynchronous orbit (GEO)—the orbit the United States relies on for much of its communication infrastructure.[19] Similarly, some scholars believe that in preparation for a potential future conflict with the United States, China will strike American space infrastructure in the first move of this hypothetical

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[14] Grauer, *Commanding Military Power*, 218.

[15] Bryant, "The Dangers of an Overreliance on Advanced Technology," 56.

[16] David S. Alberts, John J. Garstka, Richard E. Hayes, and David A. Signori, "Understanding Information Age Warfare," *Command and Control Research Portal Publication Series* (August 2001): 90.

[17] Leo J. Blanken and Jason J. Lepore, "Unpacking the Various Meanings of Redundancy: From Refining the Concept to Military Planning," *Defense & Security Analysis*, 28:4 (November 2012): 329.

[18] "US Must Deter Chinese Aggression In Space And Be Ready For War," *Science World Report*, February 9, 2017, http://www.scienceworldreport.com/articles/56959/20170209/deter-chinese-aggression-space-ready-war-general.htm.

[19] *Science World Report*.

conflict.[20] By attacking what it sees as a U.S. critical vulnerability, China would gain relative superiority over the United States and cripple its military absent space-based technology. Though the United States is not blind to this vulnerability, the steps to protect against such attacks at the tactical and operational levels and the capability to operate in contingency scenarios absent space technology are woefully lacking. The stark reality is that America is perilously deficient in the self-defense of its space-based assets.[21]

Beyond such vulnerabilities, the U.S. military—and SOF in particular—have allowed satellites to shape its modern standard operating procedures. This has been especially evident during America's Global War on Terrorism, as the United States' use of space-based technology has exponentially increased in recent decades. According to Air Force Space Command, the U.S. military's use of SATCOM increased from approximately 10 Mbps per 5,000 service members in 1990 to approximately 150 Mbps in 2010—a 15-fold increase.[22] In response to this surge in SATCOM demand, satellites now allow for real-time worldwide voice communication and access to data across all levels of classification in virtually any corner of the globe. For secure satellite voice communications, the U.S. military relies heavily upon the Mobile User Objective System (MUOS) constellation.[23] This system allows U.S. forces to communicate via ultra high frequency (UHF) bands—transmissions from 0.3-3 GHz—to send real-time updates and plan complex operations using encrypted voice transmissions.[24]

In addition to voice communication, the United States also uses SATCOM for various modes of data transmission, from sending simple reports to encrypted video-teleconferencing. The system that supports the majority of the U.S. military's data needs

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[20] Jim Sciutto, "US Military Readies for Next Frontier: Space War," CNN, November 29, 2016, http://www.cnn.com/2016/11/28/politics/space-war-us-military-preparations/index.html.

[21] Sciutto.

[22] Chuck Cynamon, "Military Satellite Communications," Air Force Space Command, February 2010, accessed April 14, 2017, https://afcea-la.org/sites/afcea-la.org/files/AFCEA%20Brief%20Feb2010.pdf.

[23] Christopher K. Matassa, "Comparing the Capabilities and Performance of the Ultra High Frequency Follow-On System with the Mobile User Objective System" (master's thesis, Naval Postgraduate School, 2011), 1.

[24] Gordon, *Principles of Satellite Communications*, 100.

is the Wideband Global SATCOM (WGS) constellation. WGS operates in the super high frequency (SHF) band—transmissions from 3–30 GHz—and greatly enables the United States to conduct decentralized and technologically advanced operations while still maintaining modern connectivity.[25] SOFs especially take advantage of the modern connectivity provided by SATCOM. With a simple laptop, a small satellite dish, and the appropriate terminals, U.S. forces have access to troves of data, and commanders have unprecedented command and control despite geographic isolation. The capabilities provided by MUOS, WGS, and their predecessors have enabled the United States to spread SOF across the globe despite disparate lines of operations. SATCOM truly enables the new American way of war.

Despite the state-of-the-art capabilities SATCOM provides, the U.S. military's primary communications constellations are unfortunately not without vulnerabilities to both traditional and non-traditional anti-satellite technology. MUOS consists of five satellites in GEO residing at approximately 35,000 km above the Earth.[26] WGS occupies the same orbital regime but with a few more satellites. For either constellation, a kinetic or cyber-attack or even a significant malfunction, would greatly limit the capacity of the systems. As an example, the loss of two MUOS satellites even with an on-orbit spare, would leave approximately a quarter of the Earth's surface without coverage.[27] Aside from traditional anti-satellite attacks, emerging technologies render these systems increasingly vulnerable. Directed energy lasers in development by both China and Russia will be capable of disabling and possibly destroying onboard computers and other hardware of satellites in orbit.[28] The strength of a constellation in GEO is that the orbit's high altitude

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[25] "Wideband Global SATCOM Satellite," U.S. Air Force, 2015, http://www.af.mil/About-Us/Fact-Sheets/Display/Article/104512/wideband-global-satcom-satellite/.

[26] "Mobile User Objective System: Revolutionizing Secure Communications for Mobile Forces," Lockheed Martin, accessed September 4, 2017, http://www.lockheedmartin.com/us/products/mobile-user-objective-system--muos-.html.

[27] Matassa, "Comparing the Capabilities and Performance of the Ultra High Frequency Follow-On System with the Mobile User Objective System," 21.

[28] Leonard David, "China, Russia Advancing Anti-Satellite Technology, U.S. Intelligence Chief Says," *Space.com*, May 18, 2017, https://www.space.com/36891-space-war-anti-satellite-weapon-development.html.

provides a large coverage area with a relatively small number of satellites. However, the small number of satellites also make MUOS, WGS, and other GEO-based communication satellites vulnerable because the loss of one satellite would degrade the system's capability by up to 20%.[29] Akin to the U.S. military's relationship with space-based technology, MUOS and WGS' technological advantages are also their weaknesses.

Fortunately, unique solutions may exist in the space domain due to emerging nanosatellite technology, but the U.S. military has yet to fully explore these options—it is still fighting with its heel exposed. Yet, the problem goes deeper than the U.S. military's use of communication satellites. Modern banking, transportation, and communications infrastructure requires PNT data that Global Positioning System (GPS) satellites provide. A cyber or kinetic strike that disabled the existing GPS constellation would incapacitate modern American life—not just the U.S. military. China is cultivating the expertise to conduct such an attack as a precaution for a potential future conflict.[30] These examples validate the frightening hypothesis that the U.S. military and way of life are exceedingly vulnerable due to a high reliance on space-based technology. While these vulnerabilities exist across the spectrum of space-based technologies, this thesis focuses on SATCOM and on developing a potential alternative to traditional communication architectures.

2. Emerging Solutions

Though little research on potential solutions to this dependence exist, there are several unique hypotheses. One school of thought advocates for a return to terrestrial-based technologies. While the United States must maintain a proficiency in non-space-enabled techniques and technology, it cannot completely divest itself from the space domain. Furthermore, traditional terrestrial-based methods are generally proven and tested; the United States simply needs to maintain them as a contingency. Other hypothetical solutions involve the unique use of emerging technologies in the stratosphere, replicating the

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[29] There are five MUOS satellites in orbit, four plus one on-orbit spare, with each representing 20% of the total system capacity.

[30] "US Must Deter Chinese Aggression In Space And Be Ready For War," *Science World Report*.

functions provided by satellites at a much lower cost and ease of replacement.[31] This idea, unfortunately, is largely untested and fraught with its own set of problems from environmental regulations to international law.[32] Just beyond the stratosphere and into LEO, however, some unique emerging space-based technologies provide more realistic solutions.

Specifically, nanosatellites and other small satellite technologies may hold the key to safeguarding against a high reliance on space-based technology. With the advent of the cube satellite (CubeSat), nanosatellite technology has dramatically increased over the last eighteen years.[33] In 1999, two California Polytech State University professors originally developed the CubeSat as a standard around which to base nanosatellite technology.[34] They intended to create a simple and low-cost form factor for designing CubeSats that would support experimentation and testing for graduate-level education.[35] Generally, CubeSats are segmented into 10x10x10 cm cubes referred to as unit or a U. In other words, a 1U CubeSat consists of one 10x10x10 cm cube, while a 2U cube is two 10x10x10 cm cubes.[36] With this basic form factor of a U, CubeSats are easily customized to fit various nanosatellite payloads at a relatively low-cost and risk. Their simple and easily replicated design also makes CubeSats ideal for testing via high-altitude balloons (HAB) and other experimental techniques. Since the first launch of a CubeSat into space in 2003, the field has only grown, and the number in orbit around the Earth increases each year due to their simplicity and applicability for research and testing purposes.[37] Consequently, the nanosatellite field today largely consists of CubeSats.

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[31] Jason Koebler, “Solar-Powered Blimps Are the New Satellites,” *Motherboard*, March 6, 2014, https://motherboard.vice.com/en_us/article/solar-powered-blimps-are-the-new-satellites.

[32] Koebler.

[33] “CubeSats in Brief,” Innovative Solutions in Space, accessed December 25, 2017, https://www.isispace.nl/cubesats/.

[34] Innovative Solutions in Space.

[35] Form factor refers to the physical dimensions of an object: length, width, and height.

[36] Innovative Solutions in Space.

[37] Innovative Solutions in Space.

Similar to nanosatellites, SDR technology has also bloomed in the last few decades. SDRs are essentially programmable radios in which software replaces traditional hardware such as amplifiers.[38] First developed in the 1980s, SDR technology exponentially grew in the 2000s in conjunction with advances in microchip technology.[39] While military radios, cell phones, and other technologies have utilized SDR technology for some time, the advent of a program called GNU Radio, which allows for much easier and intuitive programming, opened access to SDR technology to those not literate in computer programming languages.[40] It greatly opened the aperture for SDR experimentation. As such, amateur radio operators, students, and scientists use SDRs programmed with GNU radio for a myriad of purposes. In terms of designing the SAVIOR-Cube payload, SDRs and GNU Radio are critical for success. Absent this unique technology, a payload such as SAVIOR-Cube would be exponentially more difficult to design.

3. A Brief Foray in Orbital Mechanics

To truly understand the potential solutions nanosatellites and SDRs may provide, the fundamentals of the space environment require a basic understanding since that is where SAVIOR-Cube will hopefully operate one day. Fortunately, orbital mechanics, launch systems, and maneuvering in space are all thoroughly comprehended and widely tested. However, the basic constraints of the space domain merit a brief discussion prior to examining the potential of nanosatellites as a safeguard. A number of complex factors affect objects orbiting the Earth, ranging from space weather to gravity. Orbital perturbations, for example, cause a satellite to deviate from its orbit due to third body gravitational effects, the Earth's oblateness, and numerous other factors.[41] Furthermore, due to the low altitude of LEO, satellites in this orbit are subjected to a large force of drag from the Earth's atmosphere, in addition to about 80% of the force of gravity experienced

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[38] "Software Defined Radio: Past, Present, and Future," National Instruments, March 30, 2017, accessed December 2, 2017, http://www.ni.com/white-paper/53706/en/.

[39] National Instruments.

[40] National Instruments.

[41] Jerry Jon Sellers, et al., *Understanding Space: An Introduction to Astronautics*, 3rd ed. (New York: McGraw-Hill Companies, 2005), 273.

on the Earth's surface (altitude dependent).[42] Space is also bursting with radiation and numerous anomalies that make the environment harsh for both manned and unmanned spaceflight.[43] Moreover, payloads are subject to the harshness of this environment and require intense radiation hardening, temperature survivability, and a multitude of other protections. Beyond the challenges of maintaining a constellation of LEO spacecraft, space launch is not trivial, and both launch and on-orbit maintenance budgets are complex in terms of money and fuel. These constraints demonstrate the multitude of complex challenges associated with the space environment.

4. Utility of Nanosatellites

Despite these limitations, the low-cost and small mass of nanosatellites still provide unique solutions for the vulnerability created by the U.S. reliance on space-based technology. Though they are a relatively new system for military applications, academic institutions and some aerospace companies widely use nanosatellites and CubeSats. Furthermore, the field is swiftly growing, and the technology to build, launch, and maintain such technologies continues to improve rapidly.[44] Their small size and quick production make them uniquely equipped to meet short-term, operationally responsive needs.[45] While it would be difficult to replicate the capabilities provided by the massive MUOS or WGS satellites in a nanosatellite, the United States could specialize constellations to focus on specific capabilities to both build redundancy and serve as a safeguard in the event of an attack. Admittedly, LEO lacks many of the advantages provided by GEO for SATCOM, but the low-cost and quick production of nanosatellites make them an ideal solution for building resiliency. At the very least, the U.S. military would benefit from exploring these types of alternative options.

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[42] Sellers, 134.

[43] Sellers, 85.

[44] Mark Holmes, "LEO: Two Generations Share Their Outlooks," *Via Satellite*, February 2017, http://interactive.satellitetoday.com/via/february-2017/low-earth-orbit-two-generations-share-their-outlooks/.

[45] Anne Marinan and Kerri Cahoy, "From CubeSats to Constellations: Systems Design and Performance Analysis" (master's thesis, Massachusetts Institute of Technology, 2013), 7.

Several existing studies regarding potential solutions to protect against America's critical vulnerability in the space domain shed led on the utility of using nanosatellites. Specifically, the Navy's Space and Naval Warfare Systems Command (SPAWAR) conducted a feasibility study regarding the use of small satellites in LEO to serve as a communications relay for VHF radios.[46] This study built upon a concept developed by the U.S. Army Space and Missile Defense Command entitled the Army Resilient Global On-the-move SATCOM (ARGOS) System.[47] Both studies discuss the utility of using nanosatellites as a means to greatly increase the range and scope of non-SATCOM capable VHF radios. Each study suggests that by building a constellation of nanosatellites in LEO, the existing infrastructure of U.S. military ground-based radios would be exponentially more powerful. While both the SPAWAR and ARGOS studies require further research, they provide insight into forming a hypothesis for the way such a system may function in supporting U.S. military needs. SAVIOR-Cube intends to take these concepts one step further with a nanosatellite payload that consists of an SDR programmed as just such a VHF relay.

D. METHODOLOGY AND APPROACH

To fully develop a potential solution to this vulnerability, the depth of the problem requires understanding, which this chapter articulates throughout. However, designing a worthwhile payload requires further analysis and testing. Prior to developing SAVIOR-Cube, model constellations and CONOPs, discussed in Chapter II, highlight the payload's applicability for the U.S. SOF today. Next, the trade space analysis in Chapter III highlights how examining the various hardware options contributes to an orderly design. Lastly, laboratory tests ensure functionality and the results of a high-altitude balloon (HAB) flight, discussed in Chapter IV, simulate near-space conditions, short of an actual technology demonstration in LEO. By coupling a research-based methodology with scientific development, modeling, and testing, SAVIOR-Cube emerges as a redundant safeguard to traditional military SATCOM.

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[46] Austin Mroczek, email message to author, May 23, 2017.

[47] Darin Lindon, email message to author, May 24, 2017.

1. SAVIOR-Cube in Action

Prior to an evaluation of the available SDR technology, potential applications for SAVIOR-Cube require analysis. First, a CONOP and operational view-1 (OV-1) for utilizing the payload highlights the applicability of SAVIOR-Cube for SOF detachments operating in remote areas, emphasizing the utility to today's conflicts. Next, using the principles of orbital mechanics in conjunction with data from existing constellations, a model constellation built in Analytical Graphics Inc. Systems Tool Kit (STK) demonstrates coverage and potential orbital regimes. This simulation helps to determine whether or not the constellation provides the requisite coverage and whether or not it is a feasible concept. Finally, communications link budgets for the uplink and downlink from a VHF radio to the payload in orbit—calculated and modified for specific environmental effects, distances, and scenarios—provide insight into signal quality and build realistic grounding into this study. These steps demonstrate potential applications not just for SAVIOR-Cube, but also for nanosatellites writ large.

2. Designing SAVIOR-Cube

A concise and unbiased trade space analysis of payload hardware and testing conditions lays the foundation for experimentation. First, an analysis of the frequencies available for use within the VHF range helps to determine which SDRs and ancillary equipment support the objectives of this payload. Next, a comparison of man-portable radios that U.S. SOF currently use on today's battlefield demonstrates options for the ground-based segment of testing. Examining low-cost and light-weight SDRs that can both receive and transmit in the VHF range outlines the heart of SAVIOR-Cube's payload. Lastly, a similar comparison of available single board computers, amplifiers, and antennas completes the design. An analysis of these key variables is paramount to building a functioning and realistic payload.

3. Testing SAVIOR-Cube

With model constellations and CONOPs built, a prototype payload validates the applicability of nanosatellites with an SDR payload through testing in both the laboratory and on a HAB. The payload—an SDR with slight modifications—is designed to function as a simple VHF voice relay capable of storing messages or executing real-time retransmissions that increase the effective range for otherwise distance-limited line-of-sight radios. Laboratory bench tests and further environmental tests allow for multiple iterations of testing under different simulated conditions. Next, the HAB flight demonstration of the SDR payload provides a reference for any capabilities that may be implemented on a future nanosatellite mission, while simultaneously testing the payload in a realistic near-space environment. In conjunction with ground forces simulated in a testing environment, the HAB platform replicates potential applications for nanosatellites in a denied-space environment. The results of the research and testing derived from this thesis demonstrate techniques and methods to defend against a critical vulnerability in the space domain.

E. CHAPTER CONCLUSION

Undoubtedly, the U.S. military is vulnerable due to its high reliance on space-based technology, and nanosatellites are a low-cost and expedient near-term solution to support U.S. forces that rely on satellites to wage the modern American way of war. Furthermore, they offer unique solutions in a degraded space environment as an alternative communication architecture. Specifically, a constellation of nanosatellites in LEO with a payload consisting of a simple software-defined VHF radio relay provides an unconventional method for satellite voice and data communication. An infrastructure of space-based nanosatellite safeguards will help protect the U.S. military from its current vulnerabilities—precisely what SAVIOR-Cube aims to do. Prior to further discussing any CONOPs and experimental results for SAVIOR-Cube, Chapter II analyzes its applicability and feasibility.

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II. SAVIOR-CUBE IN ACTION

As the action arm of U.S. foreign policy, U.S. Special Operations Forces (SOF) are spread across the globe and thus rely highly upon satellite communication (SATCOM) for command and control, the vulnerability of which Chapter I covers. Solutions for this vulnerability derived from emerging technology in nanosatellites merit further exploration. One example is a nanosatellite software-defined radio (SDR) very high frequency (VHF) relay, such as the Software Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube). This chapter focuses on the applicability of SAVIOR-Cube and demonstrates that nanosatellites may help build resiliency into the U.S. SATCOM infrastructure. First, a credible scenario in which a special operations detachment could benefit from SAVIOR-Cube demonstrates its applicability for U.S. SOF. Next, a model constellation validates that nanosatellites in low Earth orbit (LEO) can feasibly support decentralized SATCOM. Lastly, a communication link budget shows that a VHF link from LEO will have a positive margin; it demonstrates that it is a realistic solution. Most importantly, the analysis in this chapter illustrates that SAVIOR-Cube has both realistic and direct applications for U.S. SOF across the globe.

A. A WORLD WITHOUT SAVIOR-CUBE

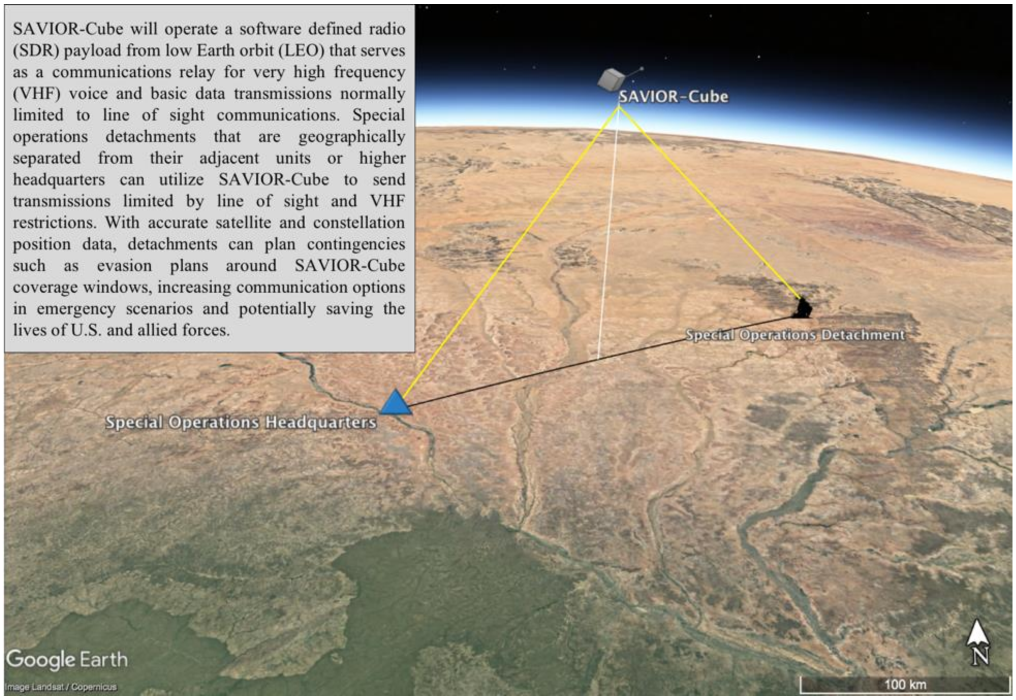
An illustrative fictional example of SAVIOR-Cube in action shows the potential applicability for U.S. forces in the field. As Chapter I illustrates, the decentralized nature of many special operations leads to large geographic distances between units, requiring SOF to rely upon SATCOM for much of their communication needs. The following scenario illustrates what a SOF detachment could face in an emergency scenario absent SATCOM capabilities. More specifically, the scenario shows the startling vulnerability U.S. forces may find themselves in absent SATCOM capabilities on the battlefield. It demonstrates the role SAVIOR-Cube could play in building resiliency into U.S. space-based infrastructure.

> Special Forces Operational Detachment-Alpha (SFOD-A) 0425 is on a routine mission to the remote village of Amaloul—located in the Tahoua region of the sub-Saharan country of Niger—to provide medical support to the otherwise isolated

> village. They are approximately 400 km northeast of their higher headquarters in the Nigerien capital of Niamey; this large geographic distance forces the detachment to use SATCOM for voice and data communication. On today's mission, they are relying upon Harris PRC117 radios for SATCOM with Niamey and Harris PRC152 radios for team internal line of sight (LOS) communication. Despite the peaceful nature of the mission—medical support—the prevalence of violent extremist organizations in the area, such as Al Qaeda in the Islamic Maghreb (AQIM), endangers the detachment.
>
> As SFOD-A 0425 is traveling north along a sandy desert road from Tahoua City to Amaloul, they notice movement to the east of road, but civilian traffic in the area is not uncommon. Yet, the possibility of a catastrophic attack by AQIM puts the detachment on edge. Their intuition is not misplaced, for the movement to the east increases. Before they know it, a small improvised explosive device disables the lead vehicle and a massive force numbering close to one hundred fighters ambushes the detachment. The ferocity of the initial attack disables all of the detachment's vehicles, trapping them in the kill zone. SFOD-A 0425 relies upon their extensive training and counterattacks the AQIM force to provide enough suppressive fire for the detachment to break contact to the west.
>
> Unfortunately, the initial violent attack that disables the detachment's vehicles also destroys the SATCOM capable PRC117 radios. SFOD-A 0425 does not have a form of SATCOM and is unable to call for air support or reinforcements—they are on their own. The detachment thus executes their evasion plan: a plan to evade enemy forces and safely reach their headquarters in Niamey. The large distance and harsh desert terrain between the Tahoua region and Niamey makes for a rough and perilous journey that takes days on foot. Due to a lack of SATCOM, the detachment is absent the ability to communicate with friendly forces and request much needed supplies or exfiltration. Furthermore, the headquarters in Niamey and U.S. Special Operations Command Africa (SOCAF) in Stuttgart, Germany is helpless to support the detachment.
>
> In an effort to aid the detachment, SOCAF flies manned and unmanned aircraft and uses remote sensing satellites to locate SFOD-A 0425. After three long days of searching overhead and evading AQIM forces on the ground, a tired, dehydrated, and hungry detachment is located in the desert, moving west toward Niamey. SOCAF arranges for a safe exfiltration, and the exhausted detachment is returned to safety.

While this vignette raises a number of questions, the key question as it relates to this study is: what if the detachment had a resilient form of SATCOM that enabled their VHF radios to communicate with satellites overhead? With SAVIOR-Cube overhead, SFOD-A 0425 could have requested much needed support from Niamey and SOCAF. Furthermore, imagine if there had been constellation of SAVIOR-Cube nanosatellites that provides daily coverage to every place on the planet at least twice a day for a minimum of a two-minute window (similar to what many remote sensing constellations provide from LEO). If this hypothetical constellation was flying an SDR as its payload, serving as a VHF radio relay, it could have been useful for the evading detachment, providing SATCOM to the detachment despite their lack of SATCOM-capable radios. With accurate two-line element (TLE) data available for satellites—predicating orbits months and years in advance—the detachment could have built the coverage windows of this constellation into their evasion plan. If they knew one of the satellites would have been overhead a specific location along their planned evasion route, they could have traveled to a known coverage location, established a safe site, and waited for coverage. During the coverage window, the detachment could have used simple VHF LOS radios to broadcast a message containing their location, plan of action, and status to any friendly forces also within range of the satellite during their transmission. While this would have only increased the range of the radio from tens to hundreds of kilometers, it would have still greatly expanded their VHF communication range.

In addition to a real-time SATCOM relay, if the payload would have been capable of recording and forwarding the detachment's voice transmissions, the distance limitation would have been moot. The payload would have recorded the detachment's transmission and retransmitted it on a loop, eventually reaching the headquarters in Niamey or SOCAF in Stuttgart, Germany. Thus, rather than evading without command and control from their higher headquarters for 375 km, the detachment could have sent and received transmissions to a simple nanosatellite in LEO and coordinated a much quicker exfiltration—a low-cost solution to a complex problem. Figure 1 depicts an operational view-1 (OV-1) for SAVIOR-Cube as it relates to this vignette.



SAVIOR-Cube will operate a software defined radio (SDR) payload from low Earth orbit (LEO) that serves as a communications relay for very high frequency (VHF) voice and basic data transmissions normally limited to line of sight communications. Special operations detachments that are geographically separated from their adjacent units or higher headquarters can utilize SAVIOR-Cube to send transmissions limited by line of sight and VHF restrictions. With accurate satellite and constellation position data, detachments can plan contingencies such as evasion plans around SAVIOR-Cube coverage windows, increasing communication options in emergency scenarios and potentially saving the lives of U.S. and allied forces.

Figure 1. SAVIOR-Cube Operational View-1

This fictional yet realistic vignette in Niger highlights SAVIOR-Cube's applicability for U.S. SOF across the globe. Furthermore, the potential applications for a VHF relay across the U.S. military are numerous. Aside from an evasion scenario, SAVIOR-Cube could also support communication in an unconventional warfare campaign such as the U.S. campaign to overthrow the Taliban across Afghanistan in late 2001. Additionally, it could provide SATCOM to forces lacking UHF capabilities due to resource constraints or support forces in a degraded space domain absent traditional SATCOM. Undoubtedly, there are many applications for a payload that increase U.S. SATCOM capabilities via resilient and unconventional approaches beyond traditional SATCOM.

B. SAVIOR-CUBE IN ORBIT

Simply because there are applications for SAVIOR-Cube to support U.S. SOF does not mean the concept of a VHF radio in LEO is feasible to implement. For example, 24-hour global coverage—the gold standard for SATCOM—would require a massive constellation from LEO. The Iridium satellite constellation, for example, accomplishes this amount of coverage with 66 satellites from an altitude of approximately 700 km and an inclination of approximately 86.4°.[48] This constellation provides continuous global satellite phone coverage from LEO. However, an architecture at a lower altitude would entail a larger constellation to provide such coverage—potentially demanding over a hundred satellites. These limitations of a VHF link complicate the use of VHF for SATCOM. Yet, as the SAVIOR-Cube scenario conveys, SOF could benefit from a constellation that provides coverage long enough for simple voice transmissions (approximately two minutes) at least twice each day. Fortunately, if utilizing nanosatellites such a constellation is not beyond reasonable.

Thus, to build a nanosatellite constellation for SAVIOR-Cube, this type of global coverage is the goal. Further aiming for global coverage to include the poles, a polar orbit with streets of coverage is the most reasonable method for designing such a constellation. Polar orbits inclined at approximately 90° orbit the Earth from the North Pole to the South Pole, moving north to south above the Earth at a right angle to the equator.[49] Figure 2 depicts a 90° orbit with a satellite crossing over the north pole, illustrating this concept.

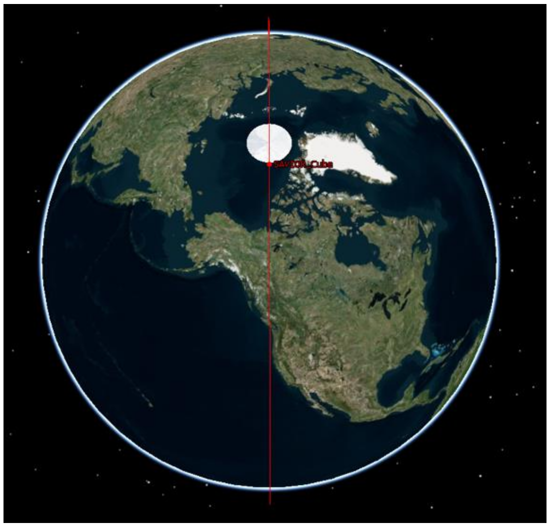


Figure 2. Polar Orbit

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[48] "Iridium Next," eoPortal Directory, accessed 03 December 2017, https://directory.eoportal.org/web/eoportal/satellite-missions/i/iridium-next.

[49] Sellers, *Understanding Space: An Introduction to Astronautics*, 157.

This orbital pattern allows a satellite plane to provide equitable coverage to the entire surface of the Earth rather than focusing on the equator or targeting a specific area such as a U.S. combatant command (COCOM). For these reasons, a polar orbit is a sound starting point for designing a SAVIOR-Cube constellation that aims to provide frequent revisit times across the globe.

Furthermore, in order to equalize the coverage as much as possible, streets of coverage constellations are best.[50] Streets of coverage constellations include multiple planes of continuous bands of satellites spread equally around the Earth. They allow for frequent revisit time and predictable coverage; it is the most efficient way to maximize global coverage.[51] A polar inclination and a streets of coverage design provide a baseline for designing a SAVIOR-Cube constellation, an example of which Figure 3 depicts.

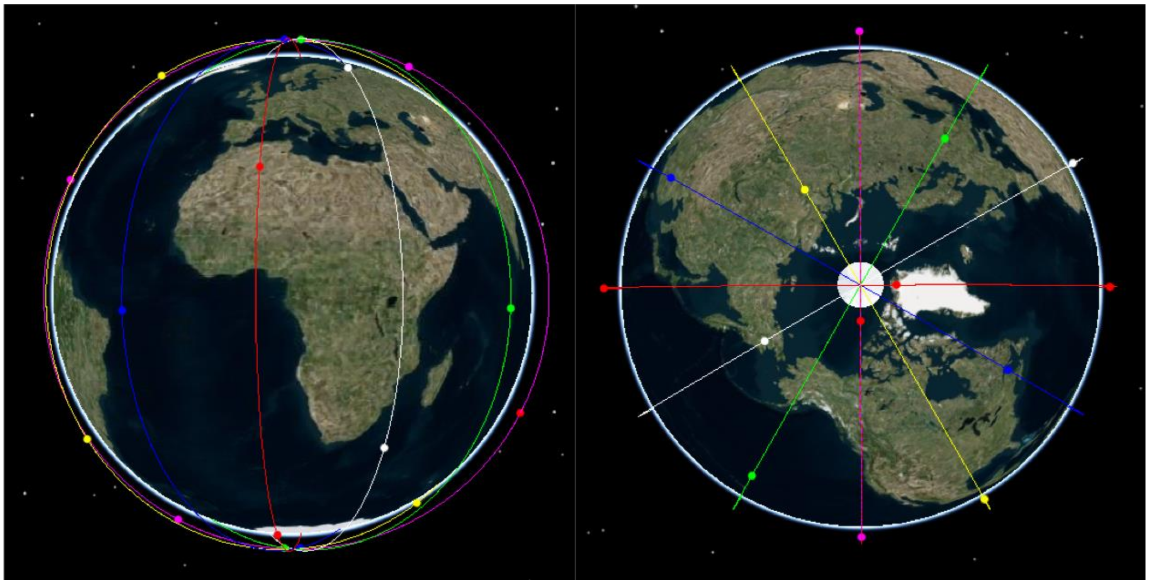

Figure 3. Polar Streets of Coverage Design

Though orbital mechanics—the physical laws that govern orbits—are incredibly complex, useful tools such as the Analytic Graphic Inc.'s (AGI) Systems Tool Kit (STK)

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[50] Olivier L. de Weck, Uriel Scialom, and Afreen Siddiqi, "Optimal Reconfiguration of Satellite Constellations with the Auction Algorith," *Acta Astronautica* 62 (February 2008): 113.

[51] Weck, 113.

provide a means to model constellations. STK's tools provide numerous options for constellation modeling, which can be applied to a baseline SAVIOR-Cube constellation. Rather than dissecting all of the classical orbital elements for the constellation, a few basic elements provide the details required to understand the orbital regime. Specifically, the inclination, altitude, number of orbital planes, and number of satellites per plane reveal the key orbital elements for designing this constellation.

Examining Planet Labs'—an innovative small satellite company—Sky Sat constellation provides a reference for designing a SAVIOR-Cube constellation due to the orbit's altitude and inclination. While Sky Sat is a remote sensing imagery constellation, its orbital regime is similar to a constellation that could support SAVIOR-Cube's mission. Sky Sat's constellation consists of thirteen satellites at an approximate altitude of 500 km and a sun-synchronous orbit of 97.8°, similar to a polar orbit.[52] With this small constellation and relatively low altitude, Sky Sat provides a new image of every place on the Earth's surface multiple times a day.[53] To shorten the distance for the communication link and simplify the inclination for analytical purposes, SAVIOR-Cube utilizes an altitude of 450 km and an exact polar orbit of 90°. Applying this concept to a streets of coverage design at 450 km and a 90° inclination, six planes of four satellites offer a robust amount of coverage with twenty-four total satellites. Figure 4 graphically depicts such a constellation and Table 1 summarizes the orbital parameters.

Table 1. SAVIOR-Cube Orbital Parameters

Altitude	450 km
Inclination	90°
Number of Planes	6 planes
Satellites per Plane	4 satellites

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[52] "SkySat Constellation of Terra Bella - Formerly SkySat Imaging Program of Skybox Imaging," eoPortal Directory, accessed February 28, 2018, https://directory.eoportal.org/web/eoportal/satellite-missions/s/skysat.

[53] eoPortal Directory.

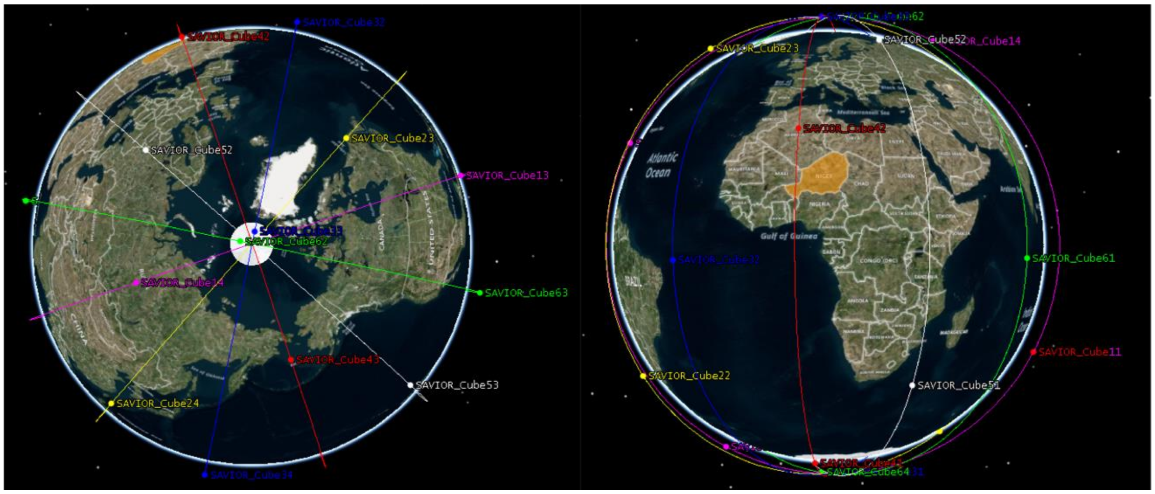

Figure 4. SAVIOR-Cube Constellation

In terms of global coverage, a six-plane four-satellite polar constellation does not disappoint. However, there are constraints on the amount of coverage it provides. For example, terrain, elevation, urban areas, and other factors surrounding a ground-based user will limit a signal's ability to reach a satellite in orbit. Furthermore, as a satellite reaches the limit of the horizon, its coverage will eventually degrade beyond repair. A standard estimate to the limit of coverage and elevation angles for maritime VHF is 5–10˚.[54] Yet to account for the aforementioned terrain-based constraints and to provide conservative estimates of this constellation's coverage, a minimum elevation angle of 20° provides a more realistic estimate of coverage definitions. With this constraint, the global SAVIOR-Cube mean access duration—the average amount of time each coverage window lasts—is approximately four minutes. The mean revisit time—the average amount of time between satellite coverage windows—is approximately twenty-one minutes. In other words, on average, every place on the Earth's surface will have approximately four minutes of coverage every twenty-one minutes; this constellation could support a resilient form of SATCOM.

However, the SAVIOR-Cube constellation coverage is not equal across all latitudes. Due to the shape and rotation of the Earth, the Earth rotates fastest at the equator

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[54] Lars Loge, "Arctic Communications System Utilizing Satellites in Highly Elliptical Orbits" (doctoral thesis, Norwegian University of Science and Technology, 2013), 62.

and slowest at the poles. Therefore, olar regions will have more coverage because the satellite will dwell longer over those regions due to the lower velocity of the Earth's rotation near the poles. Additionally, as a satellite descends and ascends over the North and South Poles, the coverage over those regions will be longer due to the shape of the Earth in respect to the 90° plane.[55] Regardless of these differences in coverage across the Earth, the coverage definitions globally are sound. Table 2 breaks down STK-based analysis that provides the minimum, maximum, and mean access duration and revisit time globally and for each of the U.S. COCOMs, providing a comparison of coverage across the globe.

Table 2. Global Coverage

	Minimum (minutes)	**Maximum (minutes)**	**Mean (minutes)**
	Global		
Access Duration	4.00	5.68	4.35
Revisit Time	1.44	29.9	21.1
	U.S. Africa Command (AFRICOM)		
Access Duration	4.05	4.52	4.32
Revisit Time	5.04	29.9	23.9
	U.S. Central Command (CENTCOM)		
Access Duration	4.19	4.53	4.35
Revisit Time	15.3	29.9	23.6
	U.S. European Command (EUCOM)		
Access Duration	4.10	4.53	4.37
Revisit Time	2.40	27.1	14.6
	U.S. Northern Command (NORTHCOM)		
Access Duration	4.13	4.51	4.35
Revisit Time	2.72	28.4	17.3
	U.S. Pacific Command (PACOM)		
Access Duration	4.06	4.51	4.33
Revisit Time	2.68	29.2	22.1
	U.S. Southern Command (SOUTHCOM)		
Access Duration	4.08	4.48	4.33
Revisit Time	2.52	29.2	23.0

For SAVIOR-Cube, STK helps in not only building constellations, but it also determines the coverage over the two locations in the scenario: Niamey and Tahoua, Niger. While COCOM and global coverage definitions are useful, more specific locations provide

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[55] Sellers, *Understanding Space: An Introduction to Astronautics*, 157.

more realistic expectations of coverage. Table 3 depicts the minimum, maximum, and mean access duration and revisit time for all of Niger, Niamey, and Tahoua separately, while Figure 5 graphically depicts simultaneous coverage for Niamey and Tahoua.

Table 3. Niger Coverage

	Minimum (minutes)	Maximum (minutes)	Mean (minutes)
	Niger		
Access Duration	0.199	5.51	4.34
Revisit Time	n/a	73.4	24.3
	Tahoua		
Access Duration	1.01	5.48	4.17
Revisit Time	n/a	58.7	28.9
	Niamey		
Access Duration	0.901	5.49	4.20
Revisit Time	n/a	58.8	29.7

Figure 5. SAVIOR-Cube over Niger

As Table 3 confirms, both Niamey and Tahoua have approximately four minutes of coverage every twenty-nine minutes—a reasonable amount of coverage for the service SAVIOR-Cube aims to provide.

This example constellation for SAVIOR-Cube and the subsequent analysis demonstrate the type of constellation required for a VHF nanosatellite relay and the coverage it would provide. Furthermore, accurate TLE data for the constellation would allow a SOF detachment or any ground-based user to plan missions around coverage windows. Absent access to TLE data, the frequent revisit time of the SAVIOR-Cube constellation affords enough predictability for approximation. While future analysis and modeling in STK would highlight additional constellations that support SAVIOR-Cube's mission, this constellation provides a baseline from which to design and validate initial testing.

C. CALCULATING SAVIOR-CUBE

While a concept of operations (CONOP) provides relevance to this payload and a model constellation further solidifies SAVIOR-Cube as feasible, a communication link budget adds additional weight to the concept; it confirms that it is a realistic hypothesis. In terms of a communication link budget, the key components are the uplink and the downlink. The uplink is the transmission from a ground-based radio to a satellite in orbit; the downlink is the transmission from a satellite in orbit to a separate ground-based radio. Figure 6 illustrates this concept, with a communication link connecting two ground-based radios to a satellite overhead.

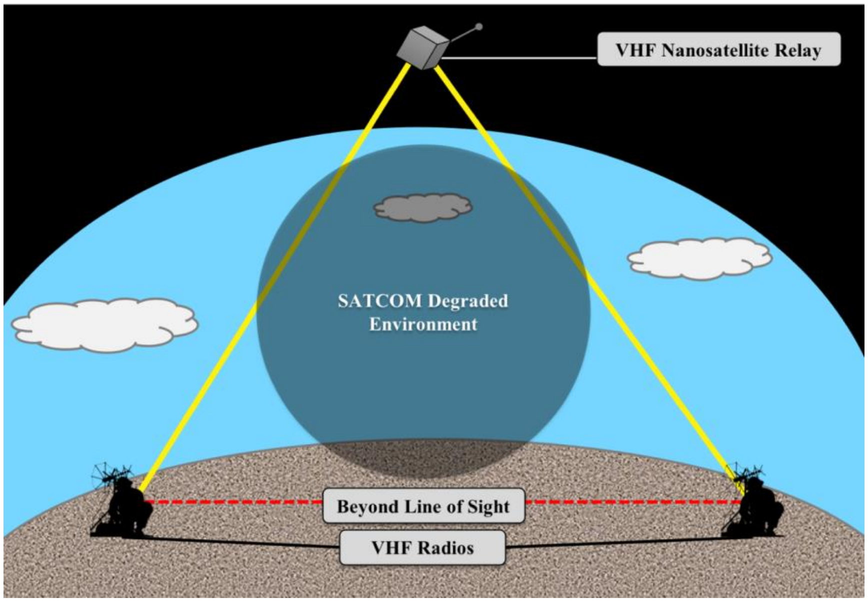

Figure 6. Satellite Uplink and Downlink

Though there are constraints to using VHF to communicate from space, these challenges are not insurmountable, as discussed further in Chapter III. With enough power and amplification, for example, VHF transmissions tuned to the appropriate frequencies can successfully penetrate the Earth's atmosphere. In fact, the International Space Station's amateur radio program attests to this fact, sending and receiving transmissions from LEO to ground-based users in VHF.[56] A worthwhile analog for what SAVIOR-Cube aims to provide.

However, in order to dissect the specific VHF link budget for SAVIOR-Cube, certain parameters require clarification to understand the mathematics, starting with the downlink. First, the power for the ground terminal and the receive threshold are based on Harris Radio's PRC117 radio—the radio of choice for many U.S. SOF operating across the globe. The maximum transmit power for this radio is 10 W (40 dBm), and the receive threshold—the weakest signal the radio is rated to receive—is -118 dBm.[57] For the ground antenna, the gain is 2 dBi based on standard gain parameters for Harris VHF antennas. Next, for the downlink from SAVIOR-Cube, the payload is assumed to have 1 W (30 dBm) of transmit power—not unreasonable for a CubeSat with the appropriate electrical power system (EPS). The receive threshold for an SDR in orbit is arbitrarily set at -95 dBm, since the actual margin is unknown. Nevertheless, -95 dBm is a reasonable margin for VHF communications. Similar to the ground antenna, the SAVIOR-Cube antenna gain is 2 dBi. In order to add realistic loss into the equation, transmitter losses are 2 dB; miscellaneous losses are 5 dB; and receiver losses are 2 dB. Given this scenario, an altitude of 450 km is used for free-space path loss calculations and other link budget factors, based upon the model SAVIOR-Cube constellation. With that information, Equation 1 easily provides power received.[58]

$$P_r = P_t + G_t - L_t - L_{fs} - L_m + G_r - L_r \qquad \text{(Equation 1)}$$

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[56] "Contact the ISS," Amateur Radio on the International Space Station, accessed November 3, 2017, http://www.ariss.org/contact-the-iss.html.

[57] "Harris III AN/PRC-117G(V)1(C)," Harris Corporation, 2017, https://www.harris.com/sites/default/files/downloads/solutions/an-prc-117g-multiband-networking-manpack-radio-datasheet.pdf.

[58] Gordon, *Principles of Satellite Communications*, 43.

In this equation, P_r is the power received, Gt is the gain of the transmitter, L_t is transmitter losses, L_{fs} is free-space path loss, L_m represents miscellaneous losses, G_r is the receiver gain, and finally L_r is receiver losses. Each of these variables is in decibels to allow for easy computing using simple addition and subtraction. Furthermore, free-space path loss, the reduction of an electromagnetic signal's strength as it travels over distance, is determined using Equation 2.[59]

$$L_{fs} = 20\log_{10}S + 20\log_{10}f + 92.45 \qquad \text{(Equation 2)}$$

L_{fs} once again represents free-space path loss, S represents the distance or range from a ground-based radio to the satellite in kilometers, and f is the frequency in gigahertz. The other values in the equation convert the free-space path loss values into decibels. Table 4 summarizes the downlink budget for SAVIOR-Cube based on the orbital parameters outlined in Table 1.

Table 4. Downlink Budget

Term	Variable	Value
Transmitter Power	P_t	30.0 dBm
Transmitter Gain	G_t	2.00 dBi
Transmitter Losses	L_t	2.00 dB
Free-Space Path Loss	L_{fs}	128.7 dB
Miscellaneous Losses	L_m	5 dB
Receiver Gain	G_r	2 dBi
Receiver Losses	L_r	2 dB
Power Received	P_r	-103.7 dBm
Receive Threshold	n/a	-118 dBm
Receive Margin	n/a	**14.3 dBm**

As stated previously, the minimum receive threshold for the radio in this scenario is -118 dBm. With a calculated received power of -103.68 dBm, there is a margin of 14.32 dBm. Given that the link will close with the lower 30 dBm transmit power of the satellite payload, the link should also close with the 40 dBm transmit power of the radio on the ground. However, the estimated receive threshold for the SDR is a bit smaller than the

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[59] Gordon, 39.

margin for the Harris PRC117 radio. Thus, for thoroughness, Table 5 calculates the uplink budget.

Table 5. Uplink Budget

Term	Variable	Value
Transmitter Power	P_t	40.0 dBm
Transmitter Gain	G_t	2.00 dBi
Transmitter Losses	L_t	2.00 dB
Free-Space Path Loss	L_{fs}	128.7 dB
Miscellaneous Losses	L_m	5.00 dB
Receiver Gain	G_r	2.00 dBi
Receiver Losses	L_r	2.00 dB
Power Received	P_r	-93.7 dBm
Receive Threshold	n/a	-95.0 dBm
Receive Margin	n/a	**1.30 dBm**

With an estimated receive margin of -95 dBm and an uplink signal strength of -93.68 dBm, there is a slight margin of 1.32 dBm. Yet, -95 dBm is a hypothetical threshold for a SAVIOR-Cube payload. If fully designed and tested for spaceflight, a payload could be built with efficient antennas, robust low noise amplifiers, and adequate receive margins, similar to how the PRC117 is designed for the ground segment. Consequently, the two link budgets demonstrate that the concept of a VHF radio relay in LEO is theoretically possible for both the uplink and the downlink—the communications link will close.

While these link budgets suffice for the purposes of this thesis, future research and testing will need to account for certain constraints beyond the scope of this thesis. For example, antenna angles for VHF dipole antennas as well as changes to the Earth's atmosphere throughout the day may add additional complexity to the link budget. Furthermore, a value of 450 km when calculating free-space path loss—based on the proposed SAVIOR-Cube altitude—does not account for slant range. The altitude of SAVIOR-Cube, used to compute the downlink and uplink margins, accounts for the satellite range at nadir. In other words, when the satellite is directly overhead. Slant range, however, is the actual range between a radio on the ground and the satellite overhead.[60] It

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[60] Gordon, 10.

accounts for actual distance between the two radiating antennas. Thus, slant range will increase the free-space path loss. Yet, for this initial SAVIOR-Cube concept and test, the positive margins in the downlink and uplink budgets suffice for demonstrating that a VHF communications link will realistically close from LEO.

D. CHAPTER CONCLUSION

U.S. SOF across the globe would benefit greatly from a resilient form of communications that expands current SATCOM capabilities, such as SAVIOR-Cube: a VHF nanosatellite relay. The focus of this chapter demonstrates that a VHF nanosatellite relay is applicable, feasible, and realistic for U.S. forces today. A concept of operations for SAVIOR-Cube supporting SOF in the field demonstrates applicability, while a model SAVIOR-Cube constellation depicts its feasibility. Lastly, a communication link budget proves that SAVIOR-Cube is a realistic concept. To truly validate the concept, further testing is required in both the lab environment and the near-space environment, the results of which are discussed in Chapter IV. Prior to discussing test results, however, the next chapter contains a detailed trade space analysis for building a prototype payload for testing purposes.

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III. DESIGNING SAVIOR-CUBE

Today, space technology greatly enables the modern American way of war—quick, decisive, and decentralized operations—and U.S. Special Operations Forces (SOF) particularly rely upon satellite communications (SATCOM) for all facets of operations. While Chapter I discusses the causes and dangers of this reliance, Chapter II demonstrates that emerging technology in nanosatellites provides applicable, feasible, and realistic solutions to this critical vulnerability, such as a very high frequency (VHF) software-defined radio (SDR) relay. Analysis regarding the results of testing such a prototype payload validates the feasibility of this concept, which is further discussed in Chapter IV. In this chapter, however, a trade space analysis of the frequency spectrum, man-portable radios, SDRs, single-board computers, antennas, and amplifiers available for testing on the high-altitude balloon (HAB) platform lays the foundation for experimentation. A thorough trade space analysis, a comparison of the hardware and resources available for a design, compares the relative advantages and disadvantages of various components. In this case, it defines the requirements for building an engineering design unit (EDU) for the Software-Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube) payload in a HAB. While the payload design will change slightly if installed on a nanosatellite for space flight, this trade space analysis ensures the payload is not only adequately designed for success, but it also lays the foundation for future iterations of testing—both terrestrial and space-based.

A. WHAT IS SAVIOR-CUBE?

While this chapter’s trade space analysis compares the best hardware for designing an EDU for SAVIOR-Cube, a general description of the payload itself first provides clarity. First and foremost, the heart of the payload is an SDR that receives, transmits, and modulates radio signals. Next, the SDR requires a payload computer for processing and commanding—it needs a driver. To receive and transmit electromagnetic signals, the SDR requires two external antennas: a receive antenna (Rx) and a transmit antenna (Tx). In other words, it must be a full-duplex SDR, capable of simultaneously receiving and transmitting electromagnetic signals from two separate antennae. Lastly, an amplifier attached to the transmit antenna ensures the SDR transmits a strong signal. These four basic pieces of hardware (SDR, computer, antenna, and amplifier) are the building blocks for SAVIOR-Cube. Figure 7 depicts a signal flow diagram of a rudimentary payload.

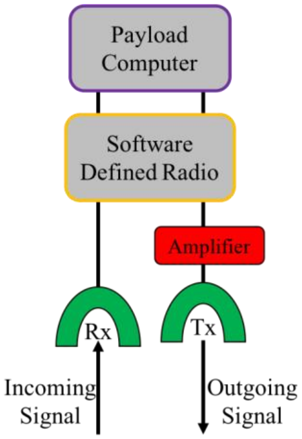

Figure 7. Rudimentary SAVIOR-Cube Design

As Figure 7 depicts, the receive antenna receives signals transmitted in the frequency to which the payload is tuned. From the receive antenna, the SDR receives and modulates the received signal from analog to digital. With the help of the payload computer, the SDR filters and appropriately modifies the signal per software parameters. Once modified, the payload computer commands the SDR to demodulate the signal from digital to analog and transmit the signal to the amplifier, increasing the signal strength. Beyond the amplifier, the signal travels to the transmit antenna which radiates the signal from SAVIOR-Cube to its intended target. Akin to traditional communication satellites, it receives a signal and retransmits it on a different frequency to ground-based users. Simply put, SAVIOR-Cube is a bent-pipe VHF relay.

B. WHAT IS THE FREQUENCY CUBE?

Discussing any specific hardware for building the SAVIOR-Cube payload first requires a clear understanding of the frequency spectrums available for testing. There are various naming conventions for delineating bands within the electromagnetic spectrum that support voice and data communication via radio waves. This thesis, however, utilizes the International Telecommunication Union convention of naming frequency ranges from very low frequency (VLF) at the low end of the spectrum to extremely high frequency (EHF) at the high end.[61] The terms VLF, low frequency (LF), and medium frequency (MF) refer to the range of frequencies from 3 kHz to 3 MHz, but they are below the frequencies relevant to the experimentation for this thesis.[62] High frequency (HF), which ranges from 3–30 MHz, supports many amateur and maritime radio communications.[63] Military and civilian radios widely use VHF, transmissions from 30–300 MHz, for line of sight (LOS) communications.[64] Ultra high frequency (UHF), which is from 0.3-3 GHz, and super high frequency (SHF), which is from 3–30 GHz, primarily support SATCOM voice and data transmissions.[65] Lastly, extremely high frequency (EHF) supports limited SATCOM transmissions, but certain constraints such as nuclear blackouts affect it less.[66] This naming convention provides a basic method for delineating which frequencies support specific functions—a useful tool for this study. For ease, Table 6 further breaks down these bands.

Table 6. Frequency Bands[67]

Frequency Spectrum	Designation	Acronym
3-30 kHz	Very Low Frequency	VLF
30-300 kHz	Low Frequency	LF
0.3-3 MHz	Medium Frequency	MF
3-30 MHz	High Frequency	HF
30-300 MHz	Very High Frequency	VHF
0.3-3 GHz	Ultra High Frequency	UHF
3-30 GHz	Super High Frequency	SHF
30-300 GHz	Extremely High Frequency	EHF

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[61] Gordon, *Principles of Satellite Communications*, 100.

[62] Gordon, 100.

[63] Gordon, 100.

[64] Gordon, 100.

[65] Gordon, 100.

[66] "The Army Satellite Communications Architecture Book," (Fort Gordon, GA: U.S. Army Signal Center of Excellence, 2013), 2–25.

[67] Gordon, *Principles of Satellite Communications*, 100.

While UHF bands are used for the majority of SATCOM voice communication—from the commercial Iridium satellite phone system in low Earth orbit (LEO) to the massive military communication satellites in geosynchronous orbit (GEO)—VHF is the band of choice for military LOS communications. However, for most military SATCOM, VHF is typically insufficient due to a number of constraints. First, VHF communications in the lower end of the frequency spectrum typically reflect off the ionosphere and never reach satellites in orbit.[68] Second, any VHF signals that penetrate the Earth's dense atmosphere will have a difficult time reaching satellites beyond LEO due to exponential free-space path loss—signal attenuation caused by the distance a signal travels from transmitter to receiver.[69] Finally, because of the long wavelength of radio waves in the VHF spectrum, the antenna size, both on the ground and in orbit, will be much larger than an antenna in the UHF spectrum.[70] Antenna size is a very important factor given that man-portable radios rely upon VHF for voice communications. With the small size and mass of the CubeSat form factor, a large antenna may be problematic if the intent is to keep SAVIOR-Cube relatively small. These constraints, though not insurmountable given some ingenuity and access to emerging technologies, have limited the utility of VHF testing for SATCOM to date.

Since most LOS radio communication utilizes VHF frequencies, the U.S. military has a massive inventory of VHF capable radios as a result. These range from rudimentary Vietnam-era radios to state-of-the-art radios used by U.S. SOF across the globe today. In terms of the U.S. military, VHF voice communications are traditionally conducted between 30 MHz and 250 MHz depending on the radio. Furthermore, the military refers to the range from 30 MHz to 90 MHz as the Single Channel Ground and Airborne Radio System (SINCGARS), a common radio network that has supported U.S. military operations for decades. Thus, almost all VHF LOS radios have a SINCGARS mode, but modern military

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[68] U.S. Army Signal Center of Excellence, "The Army Satellite Communications Architecture Book," 2–23.

[69] Gordon, *Principles of Satellite Communications*, 11.

[70] U.S. Army Signal Center of Excellence, "The Army Satellite Communications Architecture Book," 2–23.

radios are capable of pushing into the upper spectrum of VHF beyond SINCGARS. While the U.S. military can allocate specific bands within VHF through a formal request process to support testing and operations, amateur radio bands support quick turnaround and development since they are always available to those with the appropriate licenses. Therefore, in terms of this specific experiment, amateur radio license constraints limit the available frequencies. VHF transmissions for SAVIOR-Cube are thus limited to the primary VHF frequencies allowed with an amateur radio license in the United States: 50–54 MHz and 144–148 MHz.[71] A further comparative analysis of these two frequency bands demonstrates which of these ranges is best suited for testing.

In evaluating the tradeoff between 50 MHz and 144 MHz, there are a number of key factors to consider, but ionospheric reflection is of chief importance due to its implications for HF and VHF communications. The ionosphere is a region of the Earth's atmosphere consisting of charged particles (ions) residing approximately 50–650 km above the Earth's surface.[72] Most layers of the Earth's atmosphere possess a neutral charge, but the charged nature of the ionosphere makes it unique. Energy from the sun, in the form of radiation, interacts with the gaseous atoms and molecules in the ionosphere, which forces the release of electrons. This results in positively charged gas ions and free electrons throughout the layer—hence, the name ionosphere.[73] The ionosphere is further divided into sublayers, each with its own properties of charge, density, and temperature. These sublayers change with solar and terrestrial weather patterns as well as the time of day.[74] Regardless of any fluctuations, the charged nature of the ionosphere makes it unique amongst the layers of the atmosphere. For example, ionosphere's charge, coupled with the length of HF and VHF waves, allow the radio waves to reflect off the ionosphere and travel great distances.[75] This is the principle ham radios and other HF radios use to send radio

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[71] "US Amateur Radio Frequency Allocations," The National Association for Amateur Radio, accessed 03 December 2017, http://www.arrl.org/frequency-allocations.

[72] Ian Poole, "Radio Waves and the Ionosphere," *QST* (November 1999): 1, accessed December 14, 2017, https://www.arrl.org/files/file/Technology/pdf/119962.pdf.

[73] Poole, 1.

[74] Poole, 2.

[75] Poole, 1.

transmissions to the other side of the world. For VHF, there are conflicting theories regarding the upper limit of VHF transmissions that reflect off the ionosphere, and the limits are also subject to the varying nature of the ionosphere's layers. Regardless, lower frequencies have longer wavelengths and thus a higher the chance of reflection.

While ionospheric reflection will be of utmost importance when trying to reach a nanosatellite in LEO, a number of key factors merit consideration for this initial test. For both a HAB flight and a satellite in orbit, a thorough frequency trade space analysis requires a breakdown of antenna size, antenna availability, and SINCGARS compatibility because they play an important role in the payload design; Table 7 further breaks this comparison down. Frequency considerations greatly affect antenna size and availability while SINCGARS compatibility influences the range of applications for SAVIOR-Cube. Rather than attempting to weight criteria—fraught with challenges associated with any ordinal grading system—the trade space comparison simply outlines the relative advantages and disadvantages of each and determines if one has a clear categorical advantage. The frequency with the advantage is awarded one point for that category with the number of points for each summed at the bottom of Table 7. Accordingly, the frequency with the highest number of total points has the overall advantage.

Table 7. Frequency Trade Space Comparison

	50-54 MHz	144-148 MHz	Implications
Ionospheric Reflection	Long wavelengths make lower frequencies more susceptible to reflection.	Higher Frequencies are less affected by ionospheric reflection.	Higher frequencies are less susceptible to reflection and 144 MHz is thus better.
Antenna Size	Larger wavelengths require larger antennas	Shorter wavelengths require smaller antennas.	144 MHz antennas have less mass, are shorter, and are more portable.
Antenna Availability	Due to the popularity of amateur radio use, antennas in the 50 MHz range are widely available.	Antennas are widely available due to amateur radio allocations and automatic packet reporting system radios.	Additional antennas make designing the experiment easier and drives costs down; 144 MHz is better.
SINCGARS Compatibility	50 MHz is within the SINCGARS range.	144 MHz is not within the SINCGARS range.	50 MHz is better due to its compatibility.
Results	1 Point	3 Points	144 MHz is best in three of the four categories.

Fortunately, the results of the trade space comparison are clear: 144 MHz is better suited for testing a VHF nanosatellite relay onboard a HAB. The smaller wavelengths associated with 144 MHz positively influence ionospheric reflection, antenna size, and antenna availability. While the lack of SINCGARS compatibility for 144 MHz is negative, the trade space analysis in the following section reveals that most man-portable radios in use by U.S. military forces across the globe operate in the full range of VHF communications; SINCGARS bands do not limit this test. Thus, in terms of the VHF bands available for testing with an amateur radio license, 144 MHz is best. Regardless of the frequency used for the initial concept test, the experimental conditions are adjustable to support a range of frequencies within VHF for subsequent SAVIOR-Cube tests.

C. PAGING SAVIOR-CUBE

Beyond the frequency spectrum, the next step to define in a SAVIOR-Cube test is which radio to use for communicating with the SDR. Traditionally, frequencies within the VHF range support LOS communication for mobile ground forces, so this experiment thus utilizes man-portable VHF capable radios currently employed by U.S. forces. Furthermore, the decentralized nature of most special operations makes U.S. SOF the most likely candidate to benefit from SAVIOR-Cube. The most commonly used VHF radios by U.S. SOF today are the Harris PRC117 and the Harris PRC152. Both are similar in capacity—capable of a range of voice and data transmission from VHF to UHF—with the biggest differences being size and power. The PRC117 is simply a larger version of the PRC152, which means more mass but also more transmit power. Some slight differences exist between the two radios’ data rates and advanced capabilities, but for simple VHF voice transmissions they are virtually the same in terms of capability. Figure 8 is a side-by-side comparison of the two radios.

Figure 8. Harris' PRC117 (left) and PRC152 (right)[76]

Analyzing the two similarly matched radios by comparing mass, transmit power, frequency range, and receive threshold helps in judging which radio meets the needs of this experiment. Since the payload is designed to support man-portable radios, less mass equates to greater portability. Transmit power, frequency range, and receive threshold all affect the strength of the communication link. Table 8 lays out the relative advantages and disadvantages of each radio in the same manner as Table 7.

Table 8. Man-Portable Radio Trade Space Comparison

	PRC117[77]	**PRC152**[78]	**Implications**
Mass	5.44 kg (with battery)	1.20 kg (with battery)	The PRC152 is lighter and more mobile; it has the advantage.
Transmit Power	10.0 W	5.00 W	The PRC117 has a larger transmit power, but the budgets in Chapter II demonstrate 5 W will reach LEO; neither has an advantage.
Frequency Range	30-2000 MHz	30-870 MHz	While the PRC 117 has a larger range, anything beyond VHF is moot for this experiment; the two are equal in this category.
Receive Threshold	-118 dBm	-116 dBm	The extra margin of 2 dBm provided by the PRC117 may prove the difference in closing a downlink; the PRC 117 is best.
Results	1 Points	1 Point	The two radios are tied.

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[76] Source: Harris Corporation, "Harris III AN/PRC-117G(V)1(C)"; "Harris Falcon III AN/PRC-152A," Harris Corporation, 2017, https://www.harris.com/sites/default/files/downloads/solutions/harris-falcon-iii-an-prc-152a-wideband-networking-handheld-radio.pdf.

[77] Harris Corporation, "Harris III AN/PRC-117G(V)1(C)."

[78] Harris Corporation, "Harris Falcon III AN/PRC-152A."

Unlike the frequency comparison, the results of comparing the man-portable radios are not precisely clear as each has obvious advantages in certain categories. However, due to the portability of the PRC152, it serves as the primary form of communication for the HAB test. Yet the PRC117 still aids as a secondary method for payload communication due to its higher transmit power and larger receive threshold. In other words, it receives weaker signals than the PRC152. While later testing may only require smaller radios with less power, the initial proof of concept requires ground-based communication redundancy to ensure a successful test. Accordingly, the PRC152 is the primary man-portable radio for communicating with SAVIOR-Cube, with augmentation by the PRC117 as necessary.

D. THE HEART OF SAVIOR-CUBE

With a clear understanding of the frequency spectrum and ground-based radios, the next and most important parameter in the trade space analysis is determining which SDR best functions as a VHF relay. While the SDR field is burgeoning with experimentation and innovation, it primarily focuses on commercial and amateur applications. Fortunately, Ettus Corporation (a branch of National Instruments) makes a number of VHF-capable SDRs that could support military requirements. The two most suited for testing in a HAB are Ettus Corporation’s B205-Mini and the E310. Both function in VHF ranges, are relatively light weight, and do not require massive amounts of power to function. Figure 9 provides a side-by-side comparison of both SDRs.

Figure 9. Ettus Corporation’s B205-Mini (left) and E310 (right)[79]

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[79] Source: “USRP B200mini Series,” Ettus Research, 2017, https://www.ettus.com/content/files/ USRP_B200mini_Data_Sheet.pdf; “USRP E310,” Ettus Research, 2017, https://www.ettus.com/content/ files/ USRP_E310_Datasheet.pdf.

As with frequency and man-portable radios, a trade space analysis helps outline the relative advantages and disadvantages of each. Specifically for these two radios, an analysis of mass, power consumption, signal strength, temperature survivability, and the SDR form factor assists in comparing these similar radios. Mass affects the overall weight of the HAB; power consumption influences the HAB power requirements and estimated operating time. Temperature survivability obviously influences the ability of SAVIOR-Cube to function in a range of environments, and the dimensions of each form factor affect the HAB bus mechanical interface and volume. Lastly, the output signal strength directly influences the margin of the downlink. Table 9 makes this comparison in the same manner as Tables 7 and 8.

Table 9. Software-Defined Radio Trade Space Comparison

	B205-Mini[80]	**E310**[81]	**Implications**
Mass	90.0 g (with enclosure)	375 g	Less mass in a HAB is an advantage; the B205-Mini is better.
Power Consumption	5.00 V (USB powered)	5.00-15.0 V	The lower power requirements and the USB powered option of the B205-Mini are advantageous.
Signal Strength	10 dBm	10 dBm	Neither has an advantage.
Temperature Survivability	-40.0 to 75.0˚C (with enclosure)	0 to 45.0˚C	With the enclosure, the B205-Mini has a larger temperature range, giving it better survivability.
Dimensions	83.3 x 50.8 x 8.4 mm	133 x 68 x 26.4 mm	The smaller size of the B205-Mini is an advantage.
Results	4 Points	0 Points	The B205-Mini has the advantage in four of the five categories.

The results of Table 9 demonstrate that Ettus Corporation's B205-Mini is best suited to test the SAVIOR-Cube concept in either a HAB or as a prototype in LEO. Its smaller mass, low power requirements, and small dimensions are ideal for this testbed. Additionally, its increased temperature survivability with the enclosure makes it the mostly

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[80] Ettus Research, "USRP B200-Mini Series."

[81] Ettus Research, "USRP E310."

likely candidate for surviving a test flight. Thus, the B205-Mini meets the key requirements for building the payload; it will serve as the heart of SAVIOR-Cube.

E. A RASPBERRY PI IN THE SKY

After the SDR, a payload computer is the next component of SAVIOR-Cube's design. While the B205-Mini is the appropriate SDR for the payload, it still requires a computer for sending and receiving commands and processing GNU Radio. Fortunately, the requirements are relatively low, and a single board computer—a computer built on a single circuit board—provides enough power and processing speed. The most widely available single board computers are Raspberry Pi computers; these small single board computers support a myriad of tasks from video gaming to file storage. Specifically for SAVIOR-Cube, the Raspberry Pi 2 and the Raspberry Pi 3 are appropriate because the less sophisticated models of the Raspberry Pi do not have the processing power to drive an SDR. Therefore, they cannot support the demands of this payload. Figure 10 depicts a standard Raspberry Pi computer.

Figure 10. Raspberry Pi Single-Board Computer[82]

For this next comparison, the familiar categories of dimensions (form factor) and mass arise, in addition to processing speed and random-access memory (RAM). Form factor and mass are important for the obvious reasons of HAB weight and size. For a computer, processing power is key. Faster processing speed equates to more horsepower driving the SDR; it lowers the chance of the SDR and the computer crashing. Lastly,

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[82] Source: "Raspberry Pi Hardware Guide," Raspberry Pi Learning Resources, accessed January 8, 2018, https://www.raspberrypi.org/learning/hardware-guide/.

random access memory (RAM) assists in running multiple complex programs and operations simultaneously. Table 10 makes this comparison for the two computers in the same manner as the previous tables.

Table 10. Raspberry Pi 3 Trade Space Comparison

	Raspberry Pi 2[83]	**Raspberry Pi 3**[84]	**Implications**
Dimensions	85.6 x 56.5 x 17 mm	85.6 x 56.5 x 17 mm	Neither has the advantage.
Mass	45.0 g	45.0 g	Neither has the advantage.
Processing Speed	0.9 GHz	1.2 GHz	The greater processing speed of the Raspberry Pi 3 increases payload reliability; it is better.
RAM	1 GB at 450 MHz	1 GB at 900 MHz	The higher RAM speed of the Raspberry Pi 3 supports complex operations; it has the advantage.
Results	0 Points	2 Points	The Raspberry Pi 3 has the advantage in the two remaining categories.

As Table 10 demonstrates, the Raspberry Pi 3 is best suited to serve as the payload computer. Its faster processing speed provides a more robust payload with a lower probability of computer and SDR crashes. While the RAM size of the Raspberry Pi 2 and Pi 3 are the same, the faster RAM speed of the Pi 3 provides an advantage for functioning speeds. With this single board computer comparison complete, an important piece of the payload—a Raspberry Pi 3—adds to the design of SAVIOR-Cube.

F. RECEIVING AND TRANSMITTING

Next, antennas are an important aspect to the design, as the payload will require an antenna to receive and transmit signals. However, antenna theory is an often debated and complex topic. Providing the most efficient method of communication requires a specific antenna length as it relates to a frequency's wavelength. For example, 144 MHz signals

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[83] Andrew Williams, "Raspberry Pi 3 vs Pi 2: What's the Difference," *Trusted Reviews*, February 29, 2016, accessed January 8, 2018, http://www.trustedreviews.com/opinion/raspberry-pi-3-vs-pi-2-2936374.

[84] Williams.

have a wavelength of approximately 2 m.[85] This principle is based on a conversion between wavelength and frequency, which Equation 3 demonstrates.[86]

$$\lambda = c/f \qquad \text{(Equation 3)}$$

Where lambda (λ) represents the wavelength in meters, c is the velocity of light in meters per second, and f represents the frequency in gigahertz. Using the principles behind this equation antennas are constructed to correspond to frequency's wavelength. Generally, this results in antenna length that roughly corresponds to approximately ½ or ¼ of that signal's wavelength in order to maximize antenna gain and minimize loss.[87] Additionally, antenna material affects gain as do a number of other factors such as antenna radiation patterns.[88] As a result, picking the correct antenna to support a HAB test is key.

For SAVIOR-Cube, the two most widely available and cost-effective antennas that support transmissions in the 144 MHz range are the Byonics Company's V6 Dipole Antenna and the V2 Whip Antenna. Both are tuned for 144 MHz and have the appropriate gain, mass, and flexibility to support SAVIOR-Cube's intended purpose. Figure 11 is a side-by-side comparison of the two antennas.

Figure 11. Byonics V2 Whip Antenna (left) and V6 Dipole Antenna (right)[89]

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[85] The National Association for Amateur Radio, "US Amateur Radio Frequency Allocations."

[86] Gordon, *Principles of Satellite Communications*, 98.

[87] "Antenna Basic Concepts," Pulse Electronics, 2018, accessed 04 February 2018, https://www.pulseelectronics.com/antenna_basic_concepts/.

[88] Pulse Electronics.

[89] Source: "MicroTrak VHF Antennas," Byonics LLC, accessed February 4, 2018, http://www.byonics.com/antennas.

Specifically for making this trade space comparison, the factors to consider are antenna length, gain, mass, and structural flexibility. Length is important because the actual length of the antenna affects the shape of the HAB design. In terms of a HAB, for example, a longer antenna may impede the deployment of parachutes. Gain is important for ensuring the communications link closes. Mass will affect the overall HAB mass, and less mass is therefore advantageous. The antenna material's structural flexibility must allow the antenna to be manipulated during transit, to be placed on the most advantageous location of the HAB, and to survive a parachute deployment. Table 11 makes the trade space comparison for the two antennas in the same manner as the previous tables.

Table 11. Antenna Trade Space Comparison

	V2 Whip Antenna[90]	**V6 Dipole Antenna**[91]	**Implications**
Antenna Length	37.0 cm	94.0 cm	The shorter length of the V2 antenna is best.
Gain	2.15 dB	2.15 dB	While the V6 is touted to have better gain than the alternative Byonics' antennas, the company lists 2.15 dB as the gain for each; neither has a clear advantage.
Mass	34.0 g	11.3 g	The lighter mass of the V6 antenna makes its best for a HAB.
Flexibility	A sturdy whip with a rubber coating.	Flexible spring steel music wire.	The described flexibility of the V6 gives it a better chance of surviving a HAB flight; it has the advantage.
Results	1 Points	2 Points	The V6 Dipole Antenna has the advantage in two the categories.

To support a HAB test, the V6 dipole antenna is best. While its length is slightly cumbersome, the lower mass assists in minimizing launch budgets. Additionally, the antenna's flexibility facilitates payload transportation and gives it the best chance of surviving a test flight. This antenna serves as both SAVIOR-Cube's receive and transmit antenna—supporting uplink and downlink communications. While later tests will require

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[90] Byonics LLC.

[91] Byonics LLC.

custom-designed antennas that survive launch and orbit, this antenna suffices for initial HAB experimentation.

G. AMPLIFYING THE SIGNAL

In order to increase the margin of the communication downlink and ensure a successful test, an amplifier is the final piece of SAVIOR-Cube's design. It strengthens the signal the B205-Mini SDR transmits. While Chapter IV further discusses the communication link budgets specific to the HAB flight, SAVIOR-Cube's communication link margin requires a small amplifier in the 144 MHz range. Specifically, SAVIOR-Cube requires an amplifier that increases the transmit signal above the B205-Mini's advertised signal strength of 10 dBm, easily fits in a HAB, and requires approximately 5 volts or less of power. Few commercially available amplifiers fit these criteria because most require 12 volts or more of power. However, the two that seem best suited for SAVIOR-Cube testing are Mini-Circuits' ZX60-V82+ Wideband Amplifier and ZX60-63+ Wideband Amplifier. While voice transmissions are generally narrowband, these amplifiers are considered wideband because they support a wide range of frequencies. However, they also support narrowband voice transmissions. Both also meet the strict power requirements of a HAB, are small in terms of form factor, can survive a wide-range of temperatures, and increase the signal beyond that of the B205-Mini. Figure 12 depicts a Mini-Circuits amplifier.

Figure 12. Mini-Circuits Wideband Amplifier[92]

In terms of these two amplifiers, there are a number of factors to consider. First, the dimensions of the amplifier are key because a smaller amplifier will fit easier into a HAB.

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[92] Source: "ZX60-V63+ Wideband Amplifier," Mini-Circuits, 2017, accessed February 4, 2018, https://www.minicircuits.com/pdfs/ZX60-V63+.pdf.

Next, operating temperature is important because it affects the amplifier's survivability for a HAB flight. Output power at approximately 144 MHz is crucial for closing the communication downlink. Lastly, voltage and power consumption determine how well each function with the limited power supply onboard a HAB. Table 12 makes this comparison for the two amplifiers in the same manner as the previous tables.

Table 12. Amplifier Trade Space Comparison

	ZX60-V82+[93]	**ZX60-63+**[94]	**Implications**
Dimensions	1.91 x 1.91 cm	1.91 x 1.91 cm	Neither has the advantage.
Temperature Survivability	-40.0 to 85.0˚C	-40.0 to 85.0˚C	Neither has the advantage.
Power Output	19 dBm	18.4 dBm	The ZX60-V82+ signal output is larger by .6 dBm; it is better.
Voltage	5.50 V	5.70 V	The ZX60-V82+ requires less voltage and thus has the advantage.
Power Consumption	0.84 W	0.50 W	The ZX60-63+ has a lower power consumption and is thus better.
Results	2 Points	1 Points	The ZX60-V82+ amplifier has the advantage in two of the categories.

Based on the results shown in Table 12, the ZX60-V82+ Wideband Amplifier is marginally better suited for testing SAVIOR-Cube during a HAB flight. The slightly larger dBm margin it provides assists with closing the downlink and the lower voltage helps to minimize power requirements. This amplifier is crucial for boosting SAVIOR-Cube transmissions at a relatively low power cost. More importantly, it is the final piece of SAVIOR-Cube's initial EDU.

H. CHAPTER CONCLUSION

From the trade space analyses of frequencies, man-portable radios, SDRs, computers antennas, and amplifiers, the best parameters and hardware for initial SAVIOR-Cube testing are clear: a PRC152 (augmented by a PRC117 if necessary) broadcasting in

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[93] "ZX60-V82+ Wideband Amplifier," Mini-Circuits, 2017, accessed February 4, 2018, https://www.minicircuits.com/pdfs/ZX60-V82+.pdf.

[94] Mini-Circuits, "ZX60-V63+."

the 144 MHz range to a B205-Mini SDR with a Raspberry Pi 3, dipole antenna, and wideband amplifier. 144 to 148 MHz is better suited than 50 MHz due to its advantages in ionospheric reflection, antenna size, and antenna availability. The PRC152 is easily portable, and it has enough power to reach a HAB in flight. Ettus Corporation’s B205-Mini is better suited than the E310 due to its smaller size and weight, as well as better temperature survivability. A Raspberry Pi 3’s faster processing speeds and RAM support the payload better than a Raspberry Pi 2. Finally, a V6 dipole antenna and the ZX60-V82+ amplifier increase the chances of the downlink closing. Figure 13 depicts the initial EDU for SAVIOR-Cube.

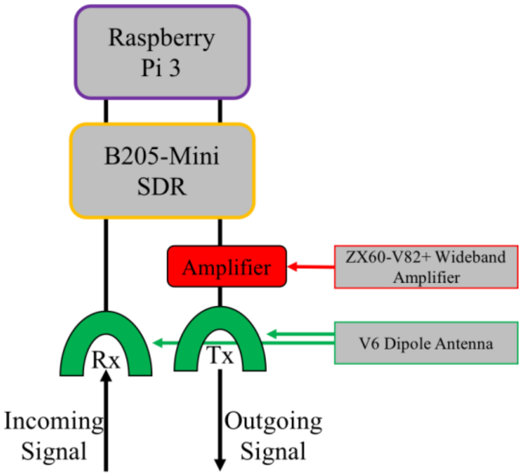

Figure 13. Initial SAVIOR-Cube EDU

These conditions and hardware are the most conducive for testing in a HAB and the most likely conduits for success. This trade space analysis lays the groundwork for SAVIOR-Cube by outlining its appropriate design for a HAB. While this chapter focuses on the trade space analysis for building an EDU that supports testing the payload in a HAB, the next chapter discusses the parameters and results from environmental and operational testing in the lab, outdoors, and onboard a HAB.

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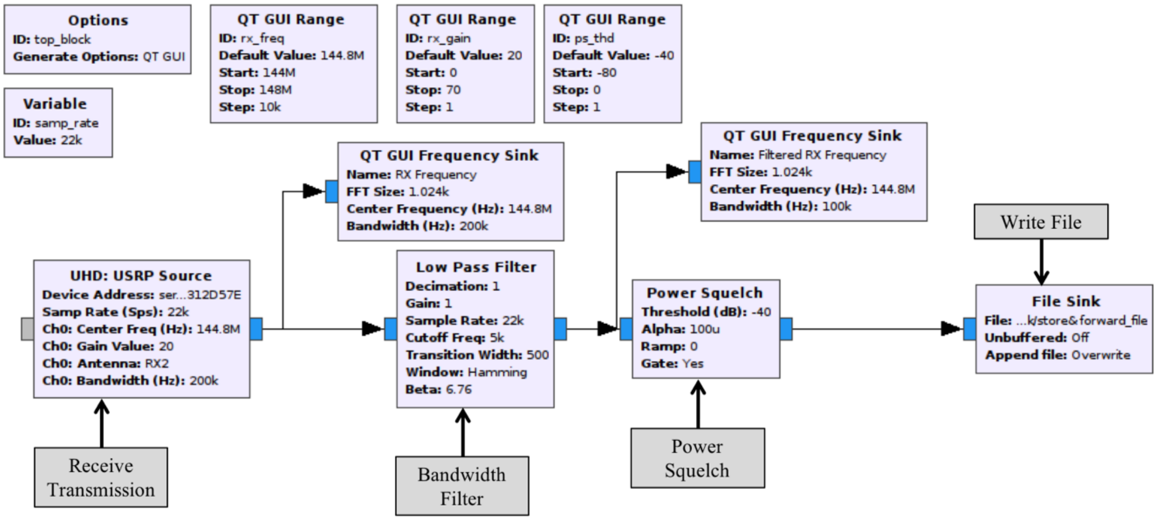
IV. TESTING SAVIOR-CUBE

As the previous chapters of this thesis demonstrate, the U.S. military is highly reliant upon space-based technology, and this is particularly the case with satellite communication (SATCOM). Consequently, alternative forms of SATCOM that leverage existing communication capabilities such as very high frequency (VHF) line of sight (LOS) transmissions, coupled with nanosatellite technology, will build resiliency into the U.S. infrastructure, much like the Software Assisted VHF Information Overhead Relay-Cube Satellite (SAVIOR-Cube). Fortunately, with the initial engineering design unit (EDU) from the trade space analysis in the previous chapter complete, the results of numerous iterations of SAVIOR-Cube testing now merit discussion and analysis. Initial testing occurred on the laboratory bench, improving the payload design, monitoring power, and measuring signal strength. Next, SAVIOR-Cube underwent outdoor operational testing to help finalize the design and identify any hardware or software shortfalls, after which the final EDU was constructed. The software coding that commands SAVIOR-Cube was also finalized, completing the design. With a final EDU in hand, environmental testing ensured that SAVIOR-Cube would survive a high-altitude balloon (HAB) flight. Finally, the payload flew in a HAB as a proof concept test for an overhead VHF relay. The results of these numerous iterations of testing, in the lab and in the field, show that not only is a software-defined radio (SDR) VHF relay possible, but it is a viable low-cost, near-term solution for building resilient and redundant pathways into the U.S. military SATCOM infrastructure.

A. DIVING INTO GNU RADIO

Prior to a discussion of the tests conducted, a brief description of the programming behind SAVIOR-Cube's software design provides clarity. As Chapter I briefly discusses, the payload utilizes GNU Radio—an open-source program for programing SDRs. In this instance, the payload is programmed to function as a bent-pipe relay: receiving an analog signal, modulating the signal into a digital form, filtering as necessary, modulating the signal back to an analog form, and broadcasting it on a different frequency. Beyond the hardware required to perform these functions, the payload software must adequately support such operations. The flowchart in Figure 14 graphically depicts the initial GNU Radio receive flow graph prior to extensive testing.



Options
ID: top_block
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 22k

QT GUI Range
ID: rx_freq
Default Value: 144.8M
Start: 144M
Stop: 148M
Step: 10k

QT GUI Range
ID: rx_gain
Default Value: 20
Start: 0
Stop: 70
Step: 1

QT GUI Range
ID: ps_thd
Default Value: -40
Start: -80
Stop: 0
Step: 1

QT GUI Frequency Sink
Name: RX Frequency
FFT Size: 1.024k
Center Frequency (Hz): 144.8M
Bandwidth (Hz): 200k

QT GUI Frequency Sink
Name: Filtered RX Frequency
FFT Size: 1.024k
Center Frequency (Hz): 144.8M
Bandwidth (Hz): 100k

UHD: USRP Source
Device Address: ser...312D57E
Samp Rate (Sps): 22k
Ch0: Center Freq (Hz): 144.8M
Ch0: Gain Value: 20
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 200k

Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 22k
Cutoff Freq: 5k
Transition Width: 500
Window: Hamming
Beta: 6.76

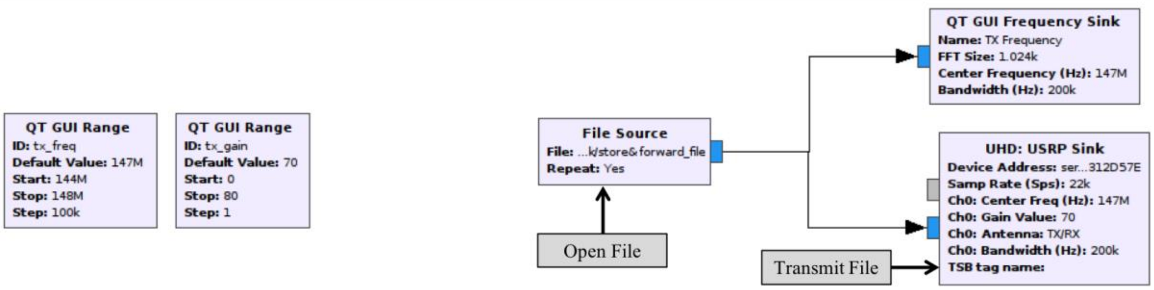
Power Squelch
Threshold (dB): -40
Alpha: 100u
Ramp: 0
Gate: Yes

File Sink
File: ...k/store&forward_file
Unbuffered: Off
Append file: Overwrite

Figure 14. Initial GNU Radio Receive Flow Graph

The initial block on the far left of the flow graph in Figure 14 is the receive block, entitled UHD: USRP Source. It defines the frequency, gain, and media access control (MAC) address of the device receiving the signal; it tells the payload how to listen for a signal. In this case, the Raspberry Pi 3 uses the information in the receive block to communicate with the B205-Mini SDR. The next block, Low Pass Filter, narrows the bandwidth of the received signal to a specified range centered on the desired receive frequency. After that, the subsequent box in the flow graph is Power Squelch, which essentially mutes frequencies below a certain threshold (a minimum number of dBm), i.e., weak signal sources. Lastly, the File Sink block writes the received transmissions to a binary file on the Raspberry Pi 3 for rebroadcasting when recalled.

Upon receipt of the transmissions, the payload is also programmed to transmit a recently recorded transmission. Figure 15 contains the initial transmit flow graph.


QT GUI Range
ID: tx_freq
Default Value: 147M
Start: 144M
Stop: 148M
Step: 100k

QT GUI Range
ID: tx_gain
Default Value: 70
Start: 0
Stop: 80
Step: 1

File Source
File: ...k/store&forward_file
Repeat: Yes

QT GUI Frequency Sink
Name: TX Frequency
FFT Size: 1.024k
Center Frequency (Hz): 147M
Bandwidth (Hz): 200k

UHD: USRP Sink
Device Address: ser...312D57E
Samp Rate (Sps): 22k
Ch0: Center Freq (Hz): 147M
Ch0: Gain Value: 70
Ch0: Antenna: TX/RX
Ch0: Bandwidth (Hz): 200k
TSB tag name:

Figure 15. Initial GNU Radio Transmit Flow Graph

The far-left block in Figure 15 is the File Source block. It simply tells the SDR to open a specific file, in this case the previously recorded transmission. That block leads into the USRP Sink, which is a transmission block that acts similarly to the USRP Source, but simply transmits rather than receives. It specifies the frequency, transmit gain, device address, and a few other parameters. There are also numerous variable and graphical user interface (GUI) blocks around the periphery of the flowchart. These are simply used to visualize the process and modify certain values quickly, such as receive and transmit frequencies, gain, power squelch, and other customizable features for testing. This simple flow graph depicts how the payload receives a transmission on a specific frequency and subsequently filters, saves, and replays it on a different frequency—serving as an initial software design for SAVIOR-Cube.

B. LABORATORY TESTING

With the initial hardware and software designs complete, SAVIOR-Cube endured extensive bench testing. Iterative bench testing began with simple tests to ensure the payload functioned and the transmitted signal remained strong. In the lab, a spectrum analyzer tuned to the same frequency range as the payload's receive and transmit frequencies (144-148 MHz) allowed signal pattern and strength analysis. SAVIOR-Cube was assembled as designed with the SDR, Raspberry Pi 3, amplifier, and antennas. Additionally, the payload, via the Raspberry Pi 3, had a computer monitor, a keyboard, and a mouse to allow for easy manipulation while testing, as depicted in Figure 16. The test consisted of setting up the payload and adjusting the software design while the payload functioned. This supported fine-tuning of the various payload parameters such as the receive and transmit gain and power squelch. In addition, bench testing allowed for iterative testing of the software design for the payload, eventually leading to the most advantageous software design for SAVIOR-Cube.

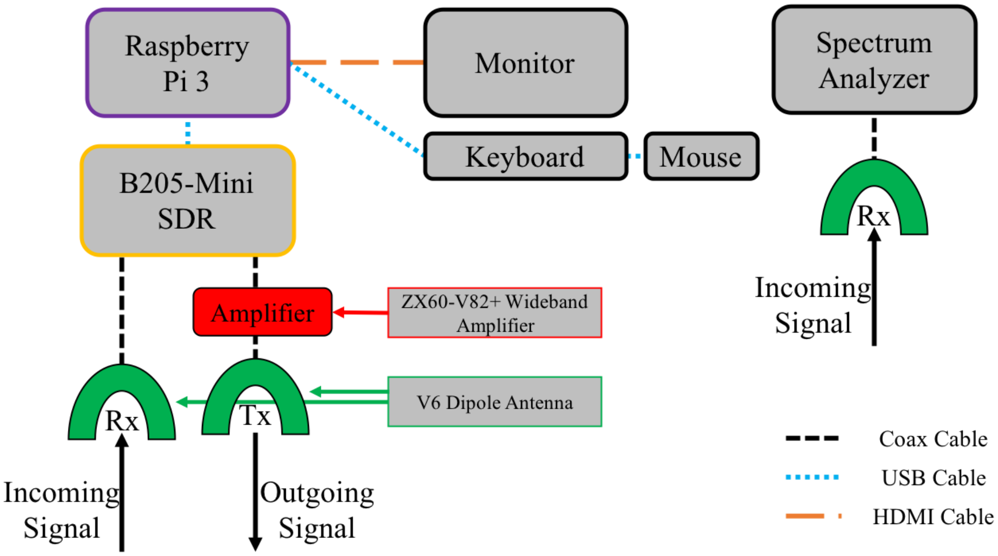


Figure 16. Bench Testing Set-up

Initially, the testing focused on establishing the appropriate parameters for receive and transmit gain. Specifically, it concentrated on how to appropriately set the gain levels for each to ensure both signals were audible. The challenge with voice transmissions is that while a spectrum analyzer measures signal strength in terms of dBm, a determination on signal quality depends upon someone listening to it. In other words, a person must determine the signal quality based upon what they hear. Unfortunately, this process is less than precise. However, if the same person conducts the series of tests, a general baseline is achieved. A baseline helps to judge the change in signal quality during bench tests in the lab. This process proved successful for testing SAVIOR-Cube in the lab.

For testing, the payload was initially assembled with all components, connected to the appropriate peripherals such as a monitor and a keyboard, and powered on. Next, a PRC152 radio was turned on and tuned to the appropriate frequencies to support the test within the 144–148 MHz range. For the lab tests, the receive frequency on the SDR was set to 145.5 MHz, and the transmit frequency was set to 147.0 MHz. With these parameters, both the receive and transmit gain were set to 0.00 dB as a baseline. The PRC152 then transmitted a simple voice transmission on 145.5 MHz, which the SDR received and retransmitted on 147.0 MHz. After iteratively adjusting the receive gain, the best range was determined to be between 10.0 and 20.0 dB. Below 10.0 dB, the received signal was too weak; above 20.0 dB, the received signal was over-amplified—it was inaudible. In terms of transmit gain, the required levels were much higher. Below 30.0 dB, the signal was too weak for the PRC152 to receive. The receive gain was increased, and eventually 70.0 dB was found to be best for audible voice transmissions. Below 60.0 dB, the signal was weak; above 75.0 dB the signal was over-amplified. Based upon this test, the optimal receive gain for lab testing is generally 15.0 dB and the optimal transmit gain is generally 70.0 dB.

With the receive and transmit gain set, the next parameters to test in the lab were bandwidth filters and power squelch. For the B205-Mini, the minimum receive bandwidth is 200 kHz, which is too large for simple voice transmissions.[95] A bandwidth that wide causes the SDR to retransmit much too sizable a signal. Generally, 5.00 kHz of bandwidth is sufficient for simple voice transmissions. A larger bandwidth includes too much noise, and a smaller bandwidth limits the quality of the voice transmissions. Due to these reasons, a low pass filter block within GNU Radio limited the received transmission to 5.00 kHz of bandwidth centered on the specified receive frequency with 2.50 kHz of bandwidth above and below that center frequency.

Beyond bandwidth filtering, power squelch also filters the signal appropriately. Specifically, it mutes received frequencies below a certain threshold. If the power threshold is too low, the payload will retransmit too much noise; too high, and it will not receive intended transmissions. With SAVIOR-Cube’s purpose in mind, the lower the receive threshold, the better. In other words, the payload is designed to receive weak transmissions over a distance, and thus a low margin is best. Generally, if the margin is too low it picks up unintended transmissions. After a number of tests, a range between -60.0 to -70.0 dBm worked best. Below -60.0 dBm, the payload failed to pick up intended transmission; above

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[95] Ettus Research: “USRP B200-Mini Series.”

-70.0 dBm and it rebroadcasted too much noise. Thus, the default power squelch for SAVIOR-Cube is -65.0 dBm. With a bandwidth filter of 5.00 kHz and a power squelch of -65.0 dBm, the appropriate filters support payload functionality.

After the filters and software were set, the payload required some basic power testing. Specifically, the testing included baseline power for the assembled payload, the maximum power limit, and the minimum power requirement. For baseline power, the payload was attached to a lab bench power supply via a power harness designed specifically for SAVIOR-Cube. The power supply provided 5.00 V since both the SDR and Raspberry Pi 3 require 5.00 V to function.[96] This lab set-up allowed for easy monitoring of the payload current draw, measured in amperes (A). With this configuration, the baseline power requirements for SAVIOR-Cube—the voltage and current necessary to power the payload, but not fully operate—is 5.00 V and 800 mA, which equates to 4.00 W. This value is derived from Equation 4, where power (P) in watts is equal to current (I) in amperes multiplied by voltage (V).

$$P = IV \qquad \text{(Equation 4)}$$

However, while receiving and transmitting signals, the payload power requirements fluctuated from the baseline. During a HAB flight specifically, peak power matters because it demonstrates the maximum power requirements of a system while operating. A test designed to monitor peak power thus provided clarity for understanding the payload's power requirements. For the test, the payload functioned while the voltage remained at 5.00 V, but the current fluctuated due to payload operations. Peak payload operations consisted of receiving transmissions, recording transmissions, and sending transmissions. During these modes, the current peaked at 1.50 A, resulting in a total of 7.50 W at peak operating modes. The last power test concerned minimum operating voltage. Minimum power requirements are important for real-time data and post-flight analysis because in the event that the voltage supplied to the payload drops below the normal value of 5.00 V, it is essential to know at what voltage the payload ceases to function. For this experiment, the

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[96] Ettus Research, "USRP B200-Mini Series,"; Raspberry Pi Learning Resources, "Raspberry Pi Hardware Guide."

set-up remained the same with the payload operating and the bench power supply set to 5.00 V. The voltage supplied to SAVIOR-Cube via the bench supply was slowly lowered in increments of 0.50 V. Interestingly, the payload functioned within the expected parameters—adequately receiving and transmitting signals—until the voltage supplied to the payload dropped below 4.00 V. In other words, as soon as the voltage fell below 4.00 V, the payload failed and no longer functioned. Table 13 break down these values as they relate to payload power.

Table 13. Payload Electrical Power System Requirements

Mode	Voltage	Current	Power
Baseline	5.00 V	0.80 A	4.00 W
Peak Power	5.00 V	1.50 A	7.50 W
Minimum Required	4.00 V	1.00 A	3.20 W

As Table 13 shows, the payload operated in a voltage range from 4.00-5.00 V, and the current ranged from 800 mA to 1.50 A for a total wattage range from 3.20-7.50 W. If power drops during a flight, the payload will still function until the voltage falls below 4.00 V—a promising power range. With these series of tests in the lab, SAVIOR-Cube finished its rounds on the lab bench. It was ready to graduate to the field and begin operational testing.

C. OPERATIONAL TESTING

Outside the lab, the SAVIOR-Cube payload was also tested across the Naval Postgraduate School (NPS) campus. The intent was to identify weaknesses in the payload design that escaped detection in the lab. First, a series of tests identified distance-related constraints and how they affect payload functionality. For the first test, PRC152 radios were separated from the payload by incremental distances ranging from 10 m to 250 m while the payload operated, sending and receiving transmissions. Figure 17 depicts on-campus operational testing, with the SAVIOR-Cube payload connected to a laptop for easy manipulation while testing, and two PRC152 radios nearby to send and receive transmissions via the payload.

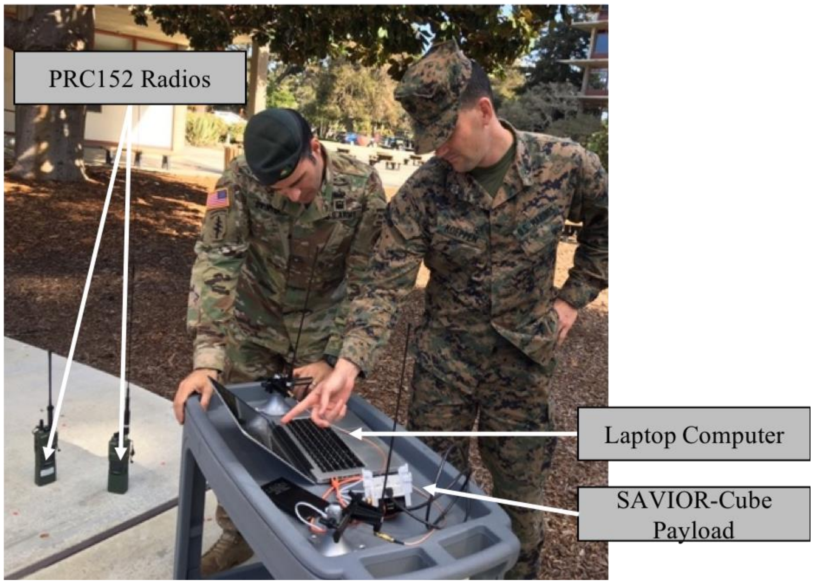

Figure 17. On-Campus Operational Testing

Though the payload functioned outside the lab, the on-campus test helped identify that the SDR was struggling to receive weaker signals, which would be a problem during flight. Specifically, when the PRC152s were more than 50 m from SAVIOR-Cube, the received transmissions were too weak for the payload to receive clearly. Additionally, the transmitted signal quality and strength were directionally proportional to the received signal quality and strength. In other words, if the received signal was weak in terms of dBm, then the transmitted signal was also weak. Based on this information, the payload needed a low noise amplifier to increase SAVIOR-Cube's ability to receive weak signals. Furthermore, it required a change to the software design within GNU Radio; it needed an additional block to ensure the transmitted signal was always near the same level regardless of the received signal strength.

In order to deal with the first problem, a low noise amplifier was installed to increase the received signal strength. Mini-Circuits Corporation's ZX60-P103LN+ low noise amplifier is ideally suited for solving this problem because it increases a received signal by 20.0 dB. Furthermore, its small form factor and mass, similar to the wideband amplifier installed for the transmit signal, ensured that it would fit within the allowable payload volume in the HAB bus, and it met the supplied voltage requirement of 5.00 V. Figure 18 depicts a rudimentary diagram of the final SAVIOR-Cube hardware design.

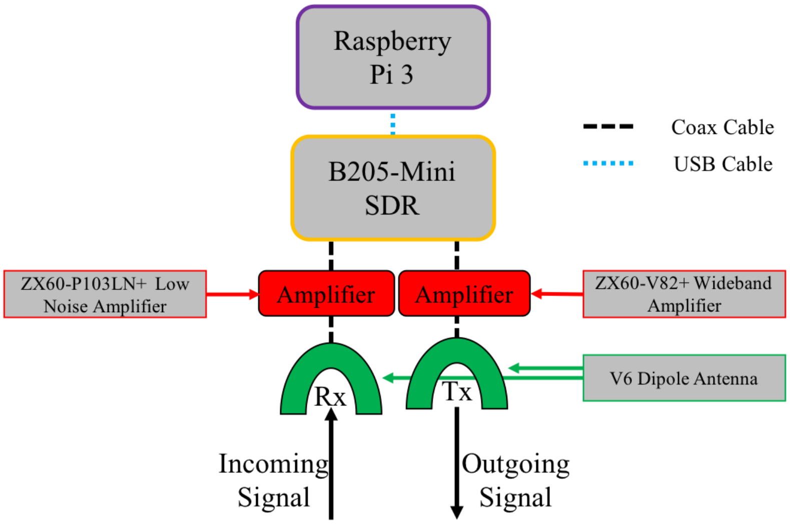

Figure 18. Final SAVIOR-Cube Design

For the second issue, equalizing the transmit signal strength, an Automatic Gain Control block installed in the GNU Radio flow diagram solved the problem. It is a simple block that increases all transmitted signals to the same level. In this case, it is programmed to increase all signals to approximately 0.00 dB. Regardless of the weakness of the signal received, the Automatic Gain Control block raises the signal strength to 0.00 dB prior to the reaching the SDR. However, with the low noise amplifier, the receive gain also required adjusting to ensure the signal was not over-amplified. Thus, the receive gain was adjusted to -10.0 dB, ensuring the signal was not too intense. With these changes, the on-campus test was repeated. Fortunately, the changes proved successful, and SAVIOR-Cube functioned well across the NPS campus with a final distance of up to 500 m.

With the success of the on-campus operational test, the payload was then tested over a longer distance, approximately 3.5 km. The payload was placed on the roof of Spanagel Hall on the NPS campus. A PRC152 radio, approximately 3.5 km away, was at Jack’s Peak County Park with a clear LOS of the NPS campus. Despite the distance between the SDR and the PRC152, the payload functioned as designed. Figure 19 depicts a map of this test, demonstrating the distance between the payload and the PRC152 radio.

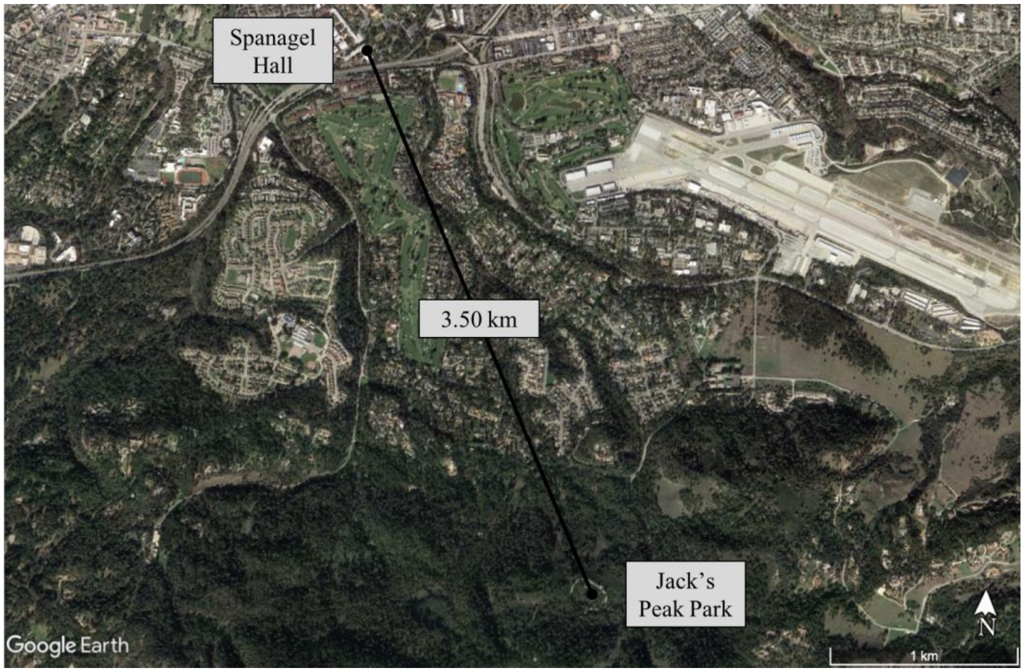

Figure 19. SAVIOR-Cube LOS Field Test

To simulate a greater distance between the SDR and the radio, 30.0 dB of manual attenuation were added to weaken the signal via physical attenuators. Due to free-space path loss and the added attenuation, that was a signal of approximately -96.6 dBm, equivalent to a distance of approximately 101 km (not counting receiver, transmitter, and miscellaneous losses or gains). Thus, the results of this specific test demonstrate that SAVIOR-Cube could function over a distance of 100 km away from a ground-based radio such as a PRC152.

Beyond the payload tests, operational testing was also conducted to ensure the radios used to communicate with the HAB would effectively close the communications link over a distance. Given that the PRC152 handheld radios are the primary form of communication with the payload, a LOS field test was performed to ensure they will suffice. Specifically, a PRC152 was located on the roof of Spanagel Hall on the NPS campus, and a second was 19.6 km northeast of the NPS campus on a ridgeline west of Mount Toro, CA. A LOS communication test between the radios to test the receive margin of the PRC152 demonstrated their strength, as the map in Figure 20 depicts.

Figure 20. PRC152 LOS Field Test

With a combination of free-space path loss and manually added signal attenuation, the test demonstrated that the PRC152 could effectively receive a signal of -106 dBm, well below the lowest signal expected during the HAB flight. This test helped establish confidence in the equipment used to test SAVIOR-Cube and proved that the PRC152s could communicate with a HAB overhead. With these iterative tests completed both in and out of the lab, the final hardware and software design for SAVIOR-Cube was complete, and it was ready for environmental testing.

D. FINAL SOFTWARE AND HARDWARE DESIGN

Prior to discussing the results of environmental testing or the HAB flight, a description of the final payload hardware and software design provides a final picture of SAVIOR-Cube’s physical and virtual configurations. In terms of hardware, the design is simple. The V6 dipole antenna receives the signal, which the low noise amplifier increases;

the signal then travels to the B205-Mini SDR where the software and Raspberry Pi 3 modulate the signal appropriately. Next, the signal travels from the SDR to the wideband amplifier, increasing signal strength, and it finally radiates from the payload via a second V6 dipole antenna. In terms of interfaces within the payload, antenna and amplifiers connect via coax cables. The SDR and Raspberry Pi 3 communicate using a customized universal serial bus (USB) 2.0 connection. Finally, the SDR, Raspberry Pi 3, and amplifiers all receive their own power from a common power harness. The power harness connects to a common source of power, whether from a satellite bus or a lab bench. As a single unit, the payload fits into a custom-designed 3D-printed plastic chassis that provides a compact structure appropriate for a CubeSat. This design supports SAVIOR-Cube functionality. Figure 21 depicts this final payload design.

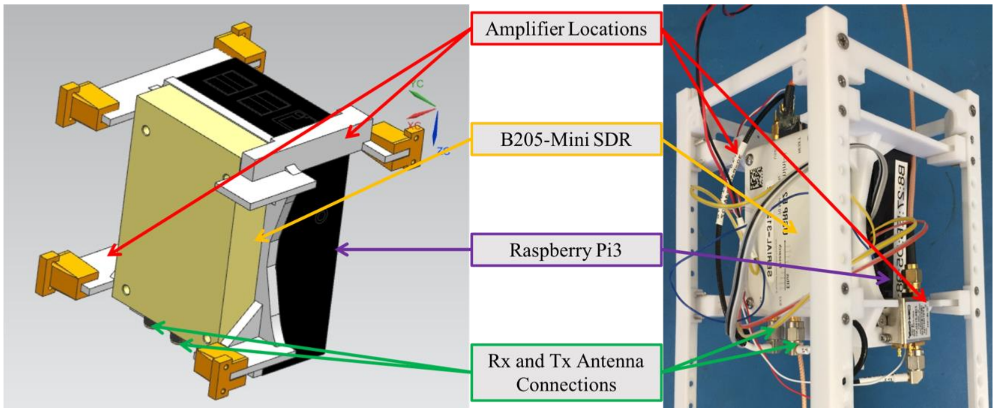

Figure 21. SAVIOR-Cube Assembly

In terms of the final software design, the GNU Radio flow graphs provide a starting point for building a Python source code.[97] In other words, they provide a GUI for manipulating the software in order to generate a Python source code to drive the payload. The software design also complements the desired test conditions. Specifically, the payload software is split into two segments that operate independently: receive and transmit. The receive segment consists of the USRP Source block, which sends the appropriate

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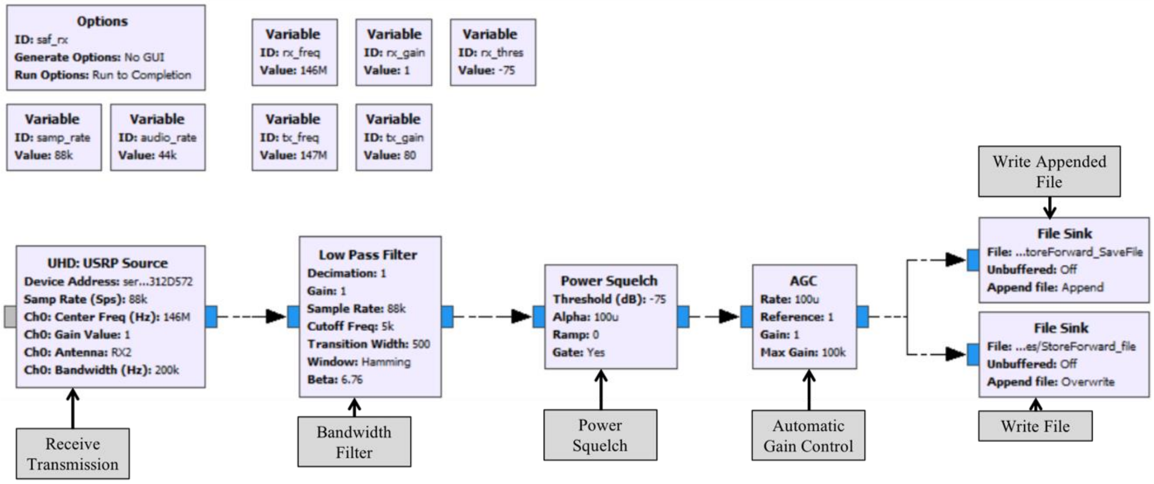
[97] Python is a user-friendly computer programming language used widely by many open-source programs such as GNU Radio.

parameters to the SDR; followed by the Low Pass Filter set at 5.00 kHz centered on 144.8 MHz; the Power Squelch set at -65.0 dB; the Automatic Gain Control, which raises the signal to 0.00 dB; and finally, two File Source blocks, which save the signal. The first block saves the signal to an appended binary file for post-flight analysis, supporting a complete review of all in-fight transmissions in the lab, while the second block sends the signal to an overwritten binary file for immediate retransmission. Figure 22 is this final receive flow graph, and Appendix A contains a breakdown of each of the final blocks in both the receive and transmit flow graphs.



Options
ID: saf_rx
Generate Options: No GUI
Run Options: Run to Completion

Variable
ID: rx_freq
Value: 146M

Variable
ID: rx_gain
Value: 1

Variable
ID: rx_thres
Value: -75

Variable
ID: samp_rate
Value: 88k

Variable
ID: audio_rate
Value: 44k

Variable
ID: tx_freq
Value: 147M

Variable
ID: tx_gain
Value: 80

UHD: USRP Source
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 146M
Ch0: Gain Value: 1
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 200k

Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 88k
Cutoff Freq: 5k
Transition Width: 500
Window: Hamming
Beta: 6.76

Power Squelch
Threshold (dB): -75
Alpha: 100u
Ramp: 0
Gate: Yes

AGC
Rate: 100u
Reference: 1
Gain: 1
Max Gain: 100k

File Sink
File: ...toreForward_SaveFile
Unbuffered: Off
Append file: Append

File Sink
File: ...es/StoreForward_file
Unbuffered: Off
Append file: Overwrite

Figure 22. Final GNU RADIO Receive Flow Graph

Additionally, to help provide a baseline transmission for the payload while the payload is in the receive mode, SAVIOR-Cube simultaneously broadcasts a baseline .wav file transmission pre-recorded in the lab.[98] The transmission essentially ensures there is a clearly recorded transmission emitting from the payload from which to judge the signal quality and ensure the payload functions, while also broadcasting required amateur radio call signs and information in accordance with U.S. regulations. It consists of the Wav File Source block from which the pre-recorded .wav file is opened, a Narrow Band Frequency Modulation (NBFM) block and a Rational Resampler block that translate the .wav file from

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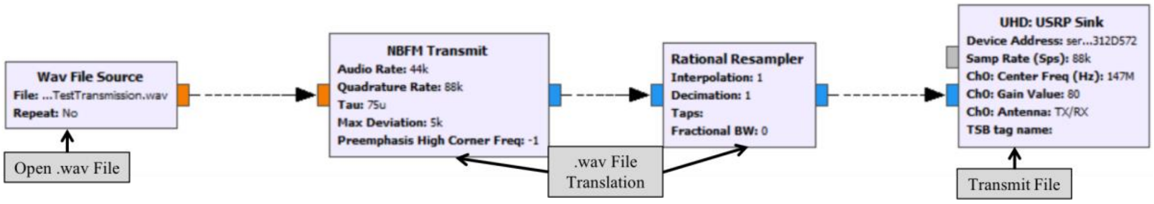
[98] A .wav file is a standard computer file type for storing audio files.

an audio file and into the appropriate configuration for SDR playback, and finally the USRP Source block, which instructs the SDR to transmit signals appropriately. Figure 23 is the final flow graph for transmitting the .wav file.



Wav File Source
File: ...TestTransmission.wav
Repeat: No

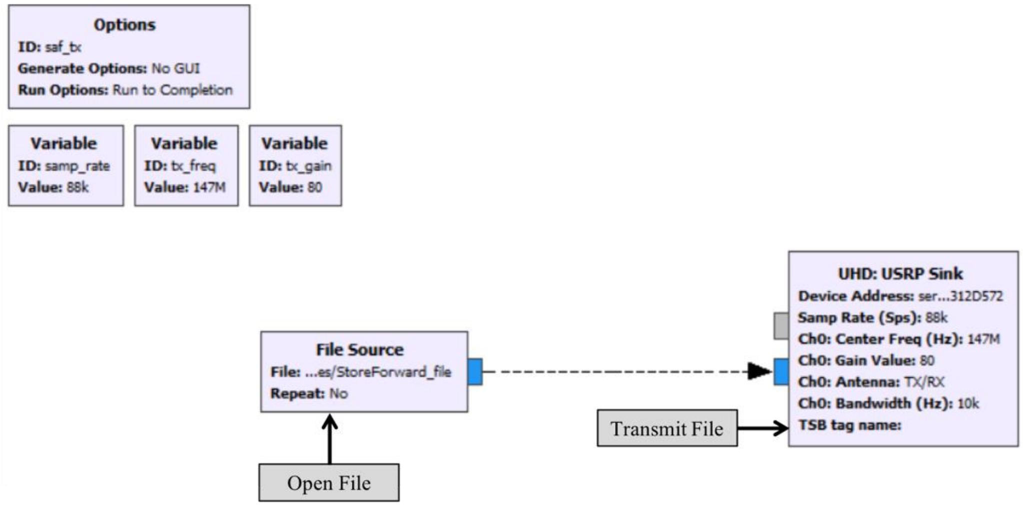
NBFM Transmit
Audio Rate: 44k
Quadrature Rate: 88k
Tau: 75u
Max Deviation: 5k
Preemphasis High Corner Freq: -1

Rational Resampler
Interpolation: 1
Decimation: 1
Taps:
Fractional BW: 0

UHD: USRP Sink
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 147M
Ch0: Gain Value: 80
Ch0: Antenna: TX/RX
TSB tag name:

Figure 23. Final GNU Radio .wav File Flow Graph

The second flow graph, the transmit flow graph, is much simpler. The first block is a File Source that opens the file recorded during the receive mode, followed by a USRP Sink that provides the parameters to the SDR for transmitting the signal. Figure 24 depicts the final transmit flow graph.



Options
ID: saf_tx
Generate Options: No GUI
Run Options: Run to Completion

Variable
ID: samp_rate
Value: 88k

Variable
ID: tx_freq
Value: 147M

Variable
ID: tx_gain
Value: 80

File Source
File: ...es/StoreForward_file
Repeat: No

UHD: USRP Sink
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 147M
Ch0: Gain Value: 80
Ch0: Antenna: TX/RX
Ch0: Bandwidth (Hz): 10k
TSB tag name:

Figure 24. Final GNU Radio Transmit Flow Graph

Both of these flow graphs help visualize the software programming of SAVIOR-Cube and help generate the Python source code from GNU Radio. However, the Python scripts only provide a basis for the customization required to facilitate on-demand parameter adjustments and a scripted receive-and-transmit cycle. The code generated by GNU Radio requires modification to support this specific payload and HAB flight. Custom Python programming merges these two flow graphs into a predictable cycle. Figure 25 breaks down the Python cycle, and Appendix B contains the raw Python scripts.

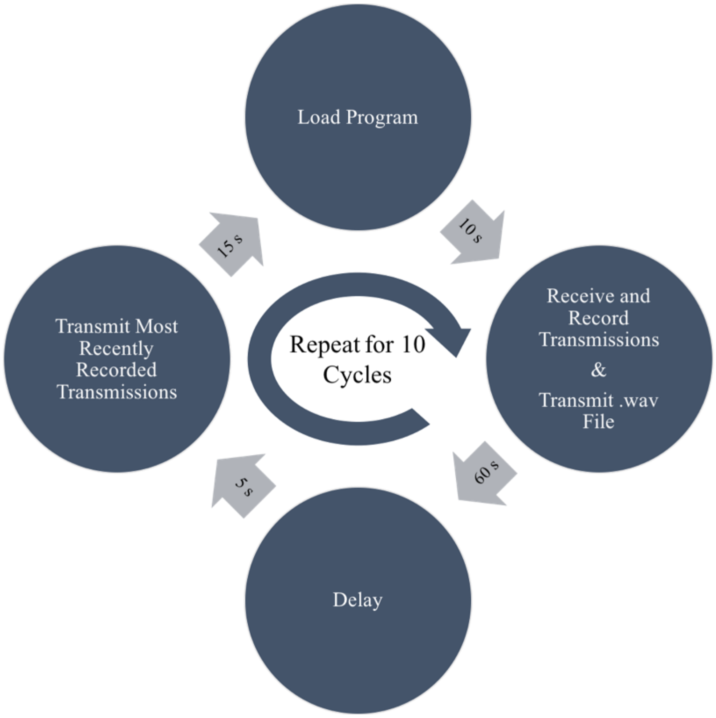


Figure 25. SAVIOR-Cube Python Script Flow

As Figure 25 depicts, the entire process first simultaneously activates the receive flow graph and the .wav file transmit flow graph, followed by the transmit flow graph. Upon activation, the payload loads the receive flow graph—or a Python source code of the graph—and transmits the prerecorded .wav file (approximately 10 seconds long) and simultaneously receives transmissions for 60 seconds. After 60 seconds, the receive mode ends, and the transmit mode opens after a brief but intentional delay and plays the most recent transmission, which takes approximately 15 seconds (based upon the length of the most recent transmission). This cycle lasts approximately 85–90 seconds and repeats 10 times before the payload computer reboots, after which the cycle starts anew. The reboot avoids or kills errors that might result during threading and connection within the payload, which occurred frequently enough during ground testing to warrant implementing this reboot feature to increase reliability during flight. Lastly, this Python code launches automatically on startup in case the payload loses power or suffers an unintentionally reboot. Both the final hardware and software design support easy testing and analysis for a HAB flight.

E. ENVIRONMENTAL TESTING

To ensure the finalized hardware and software designs were flight-ready, SAVIOR-Cube underwent environmental testing. In terms of environmental considerations during a HAB flight, the accelerations from winds at altitude and the jet stream as well as temperature fluctuations during the flight posed the biggest risks. Generally, for vibration constraints, winds at altitude can stress a HAB and have the potential to damage payload components. Throughout the flight, temperatures may fluctuate greatly from up to 35°C on the ground at launch to -40°C at target altitude. These extreme temperatures and dramatic changes over a short time can also damage payload components. As a result, these two potential stressors were the focus of environmental testing to ensure SAVIOR-Cube would survive its launch and flight.

1. Vibration Testing

For the vibration testing, the NPS Small Satellite Laboratory vibration table provided the necessary test bed. The payload was mounted in a metal 2U CubeSat structure (shown in Figure 26) and tested in the X, Y, and Z axes to General Environmental Verification Specification (GEVS) acceptance levels—a standard testing level defined by NASA for environmental testing.[99] Vibration testing included a baseline sine sweep to determine fundamental frequencies and corresponding damping, random vibration to simulate accelerations during high-wind conditions at altitude, and a post-test sine sweep

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[99] J. Scott Milne Jr. and Daniel S. Kaufman, “General Environmental Verification Specification,” Goddard Spaceflight Center, January 1, 2003, accessed April 3, 2018, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20030106019.pdf.

to see if the random vibration test caused any significant structural damage. Each random vibration test ran for one minute at 6.80 G_{rms} per the GEVS standard. Vibration sensors (accelerometers) were placed on both the SDR and Raspberry Pi 3 to individually monitor each component. Finally, before and after each test axis, the payload underwent a functional test to ensure it was still operable. The test configuration depicted in Figure 26 supported the individual monitoring of the key payload components and ensured survived the vibration tests.

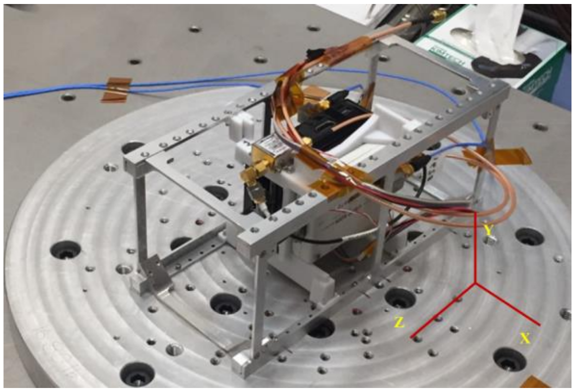

Figure 26. Vibration Testing

When comparing the baseline and post-sine sweeps of the Raspberry Pi 3 (Figure 27), the plots show that the fundamental frequencies for the Raspberry Pi 3 in the Z direction seemed to change slightly but less than the fundamental frequency changes in the X and Y directions, with the measured acceleration response on the Raspberry Pi 3 of 9.00 G_{rms}. The pretest and post-test signatures may have differed slightly for a number of reasons. Most likely, however, it was simply that the structure settled in place over the course of the tests. In other words, it was the first time the payload and structure were subjected to stress, and as they vibrated across each axis, the structure settled in place at the various joints and connections. Fortunately, despite any differences between the tests, a visual inspection of SAVIOR-Cube revealed that there were no loose screws, cracks, or fatigue in the payload structure. Furthermore, the post-test payload functional test—a baseline test to ensure the payload functions—succeeded. The Raspberry Pi 3 survived the vibration testing no worse for the wear.

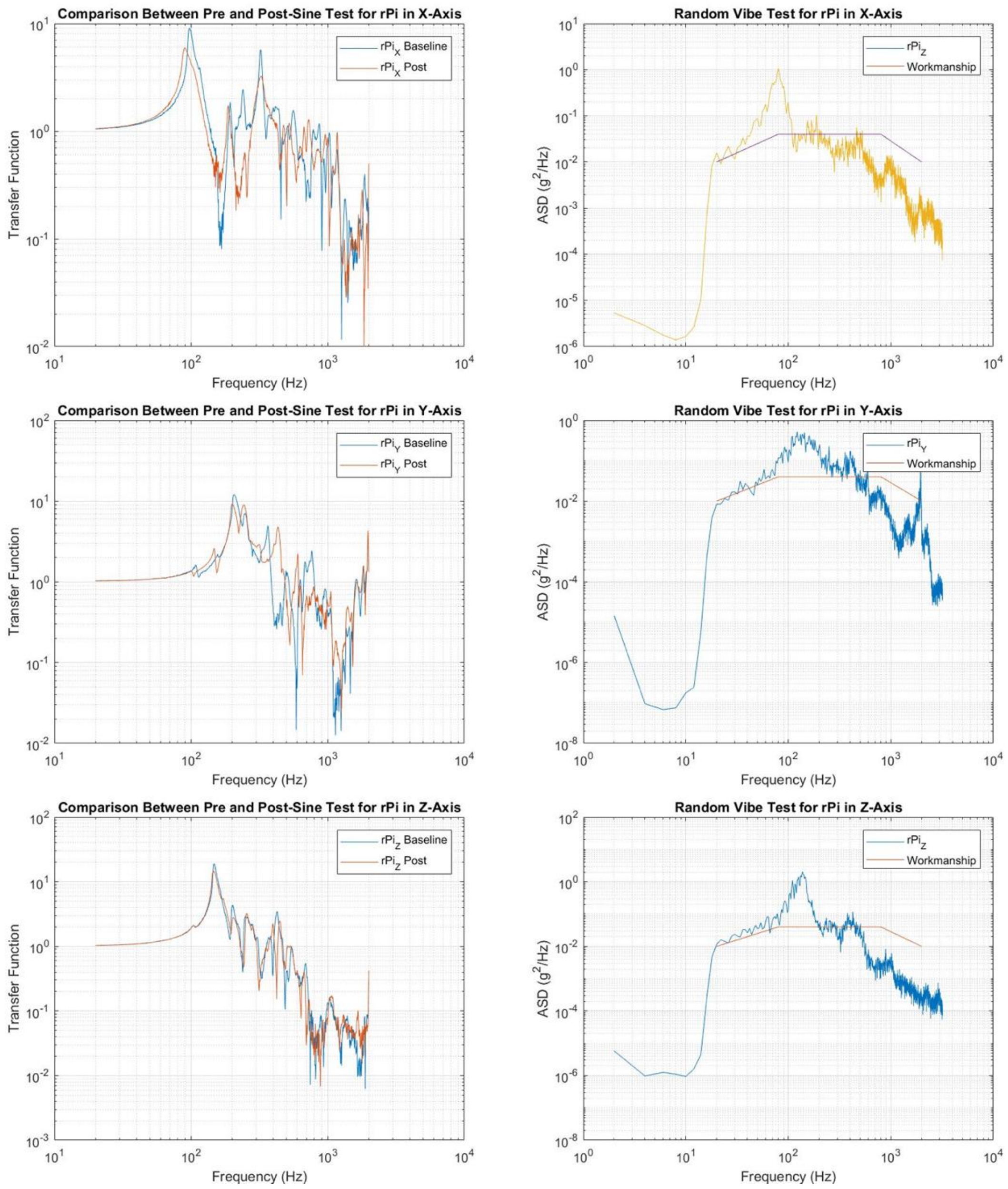

Figure 27. Raspberry Pi 3 Vibration Test Results[100]

For the SDR, the differences between the baseline sine sweep and post-test sine sweep were greater than those differences observed in the Raspberry Pi 3, as Figure 28 demonstrates.

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[100] Source: SS4861 Payload Design Course II: SAVIOR-Cube Final Report (Monterey, CA: Naval Postgraduate School Space Systems Academic Group, 2018), 24.

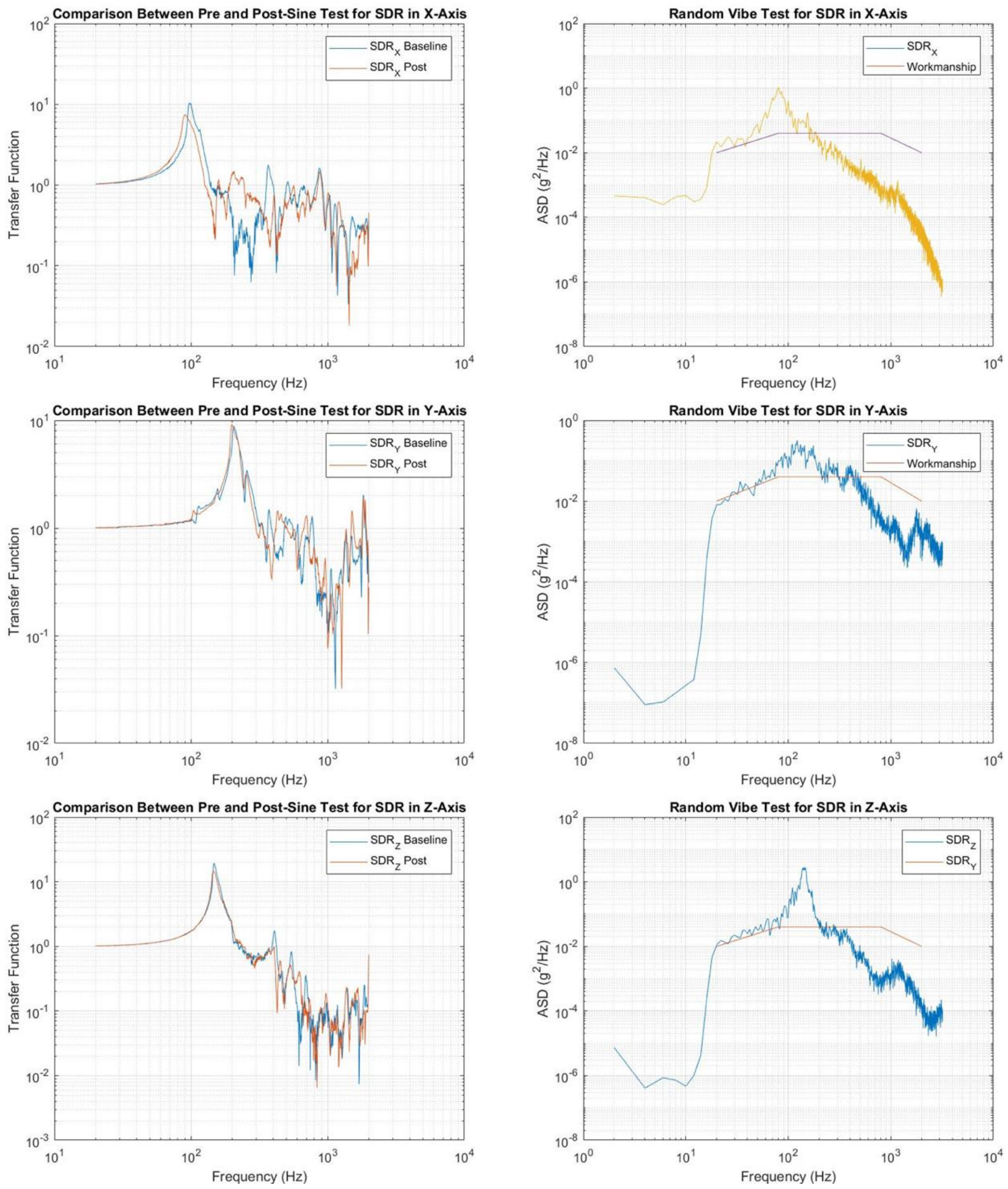

Figure 28. B205-Mini SDR Vibration Test Results[101]

Specifically for the SDR, there were greater anti-resonance frequencies in the post-test in the X and Y directions than the Z direction, with the measured response on the SDR of 9.20 G_{rms}. Once again, a visual inspection did not reveal any damage to the structure, and the payload operated as intended during the functional tests. The manner in which the

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[101] Source: SS4861 Payload Design Course II: SAVIOR-Cube Final Report, 25.

sensors were mounted to the case and the slight changes in the structure may have caused the differences between the test results. Regardless, the vibration tests did not damage the SDR.

As a whole, the vibration tests built confidence in SAVIOR-Cube's ability to survive a HAB flight, which the results in Figures 27 and 28 confirm. The functional tests and visual inspection proved that SAVIOR-Cube would still function after being subjected to accelerations up to 6.80 G_{rms}, with the measured responses reaching 9.00 G_{rms} for the Raspberry Pi 3 and 9.20 G_{rms} for the SDR. These series of tests demonstrated that the payload is designed properly.

2. Thermal-Vacuum (TVAC) Testing

The second and final environmental test SAVIOR-Cube underwent was a thermal-vacuum (TVAC) chamber test. TVAC testing ensured the payload would survive the extreme temperatures and corresponding temperatures it may be subjected to during a HAB flight. Testing consisted of a range of hot and cold temperatures in a near-vacuum environment, simulating the potential high temperatures at launch up to 35.0°C, the low temperatures at altitude up to -40.0°C, and the pressure at altitude. The payload was thus placed in the NPS Small Satellite Lab TVAC chamber with sensors to monitor payload temperature and using the appropriate connections to allow the payload to operate during the test. Thermocouples monitored the SDR case and Raspberry Pi 3 case temperatures, and the internal temperature of the Raspberry Pi 3 was monitored with its built-in temperature sensor. Figure 29 depicts the payload as it was set up in the TVAC chamber.

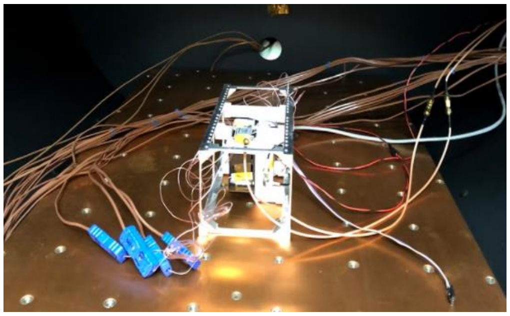

Figure 29. TVAC Testing

Within the chamber, the temperature was initially at 19.0° C—room, or ambient, temperature. To simulate potential conditions on the ground at launch, the temperature increased to 35.0°C, heat soaking the payload for thirty minutes. Next, the chamber temperature was lowered from 35.0°C to -40.0°C over the course of thirty minutes to simulate a dramatic temperature and pressure change from launch to altitude. The TVAC chamber maintained this minimum expected temperature for one hour to simulate the expected duration of the flight, subjecting SAVIOR-Cube to a cold soak. Finally, the chamber returned to ambient temperature and pressure to simulate landing. This profile simulated the various temperature ranges expected during a HAB flight. Figure 30 depicts the temperature profile for the TVAC test.

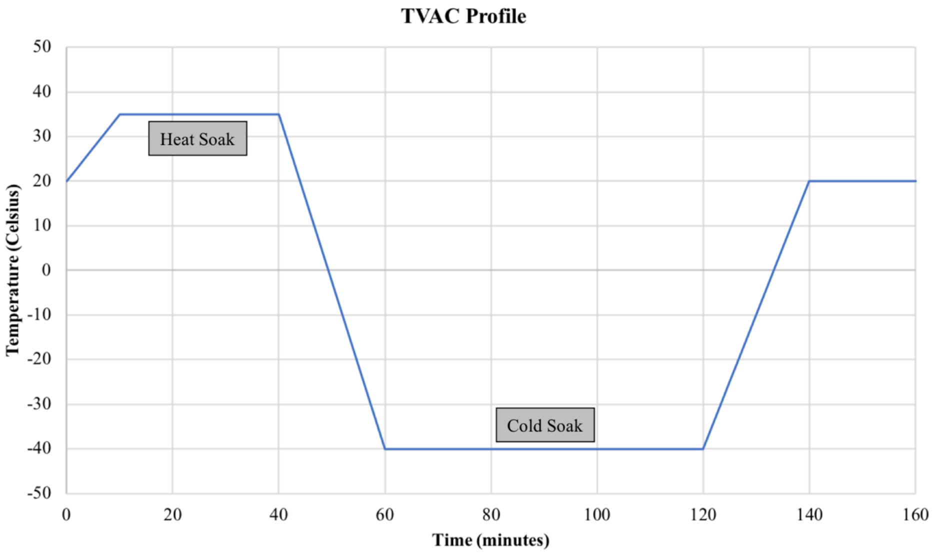

Figure 30. TVAC Test Temperature Profile

Interestingly, the temperature sensors for the various components follow a similar profile as one another, but the highs and lows of each vary significantly. Based on the manufacturing specifications, the operating temperature of the Raspberry Pi 3 should be maintained between -40.0 and 70.0°C, and the SDR temperature should stay between -40.0

and 75.0˚C.[102] During the TVAC test, however, the internal temperature of the Raspberry Pi 3 reached as high as 77.0˚C, and the SDR and Raspberry Pi 3 cases reached approximately 40.0˚C despite the maximum chamber temperature of 35˚C. In terms of minimum temperatures, the internal minimum temperature recorded for the Raspberry Pi 3 was 17.0˚C. Unfortunately, the TVAC chamber did not succeed in lowering the internal temperature of the Raspberry Pi 3 because its internal temperature remained too high from prior testing to adequately lower it during the remainder of the test. However, the external temperature of the Raspberry Pi 3 reached -24.6˚C, and the SDR case reached -6.07˚C. While the cases and internal components themselves did not reach -40.0˚ C, the cold soak subjected the payload to the minimum and maximum environmental temperatures expected for the planned duration of the flight. Figure 31 graphically depicts the results of the TVAC testing, with the red line at the highest recorded temperatures and the blue line at the lowest recorded temperatures.

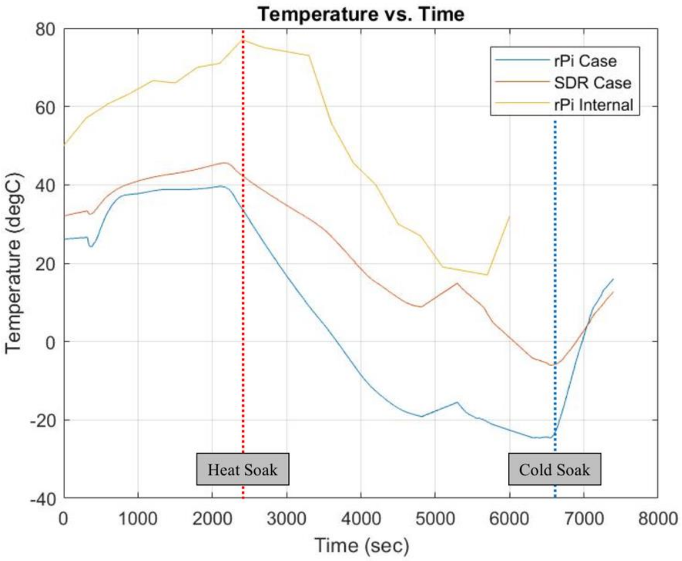

Figure 31. TVAC Testing Results[103]

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[102] "USRP B200-Mini Series," Ettus Research; "Raspberry Pi Hardware Guide," Raspberry Pi Learning Resources.

[103] Source: SS4861 Payload Design Course II: SAVIOR-Cube Final Report, 28.

Akin to the vibration tests, the payload underwent functional testing before and after the TVAC test. However, it also underwent functional tests throughout the TVAC test to simulate the HAB flight and better understand its behavior during its operational modes. SAVIOR-Cube functioned well throughout and after the TVAC test, proving it could survive extreme temperatures. Fortuitously, both the vibration and TVAC tests succeeded, and the payload design proved to be sound. SAVIOR-Cube was not only ready for a HAB flight, but it was vetted to survive the flight.

F. SAVIOR-CUBE IS A GO FOR LAUNCH!

With testing and design complete, flight operations were a go. To support a HAB flight, the SAVIOR-Cube payload was integrated into the 3U CubeSat HAB bus. The simple bus consisted of a bus computer and antenna, a global positioning system (GPS) tracker, a secondary GPS tracker called a SPOT Trace, and the electrical power system (EPS) consisting of both battery packs and two sets of solar panels (A and B), as the interface diagram in Figure 32 depicts.

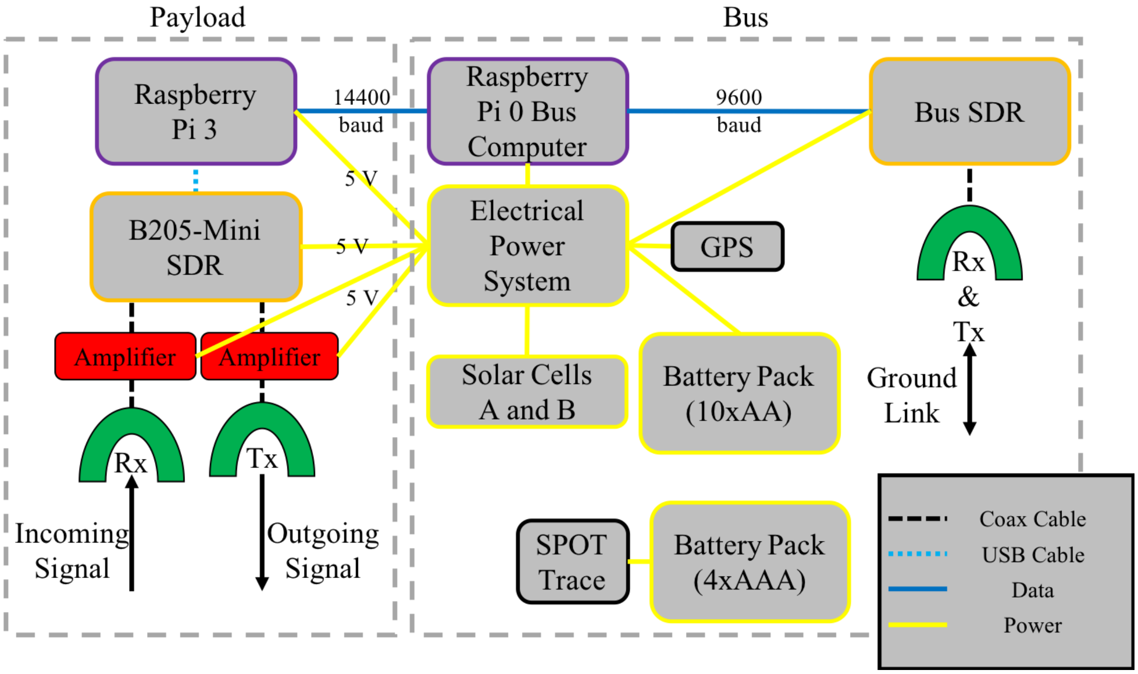

Figure 32. Payload and Bus Interface

In terms of interfaces, the bus provided the payload with power via a custom power harness and supported communication between the two on-board computers. SAVIOR-Cube's power harness simply connected to the EPS, receiving 5.00 V of power and up to 1.50 A of current. For communication, a universal asynchronous receiver transmitter (UART) exchanged data between the two computers (payload and bus) and allowed for payload commanding from a mobile ground station during the flight. While Figure 32 provides a schematic of the interfaces internal to the payload and from the payload to the bus, Appendix C depicts the formal interface schematic diagram. As a final pre-flight step, both the payload and bus were assembled in a 3D-printed 3U CubeSat structure seen in Figure 33—SAVIOR-Cube in its final pre-flight form.

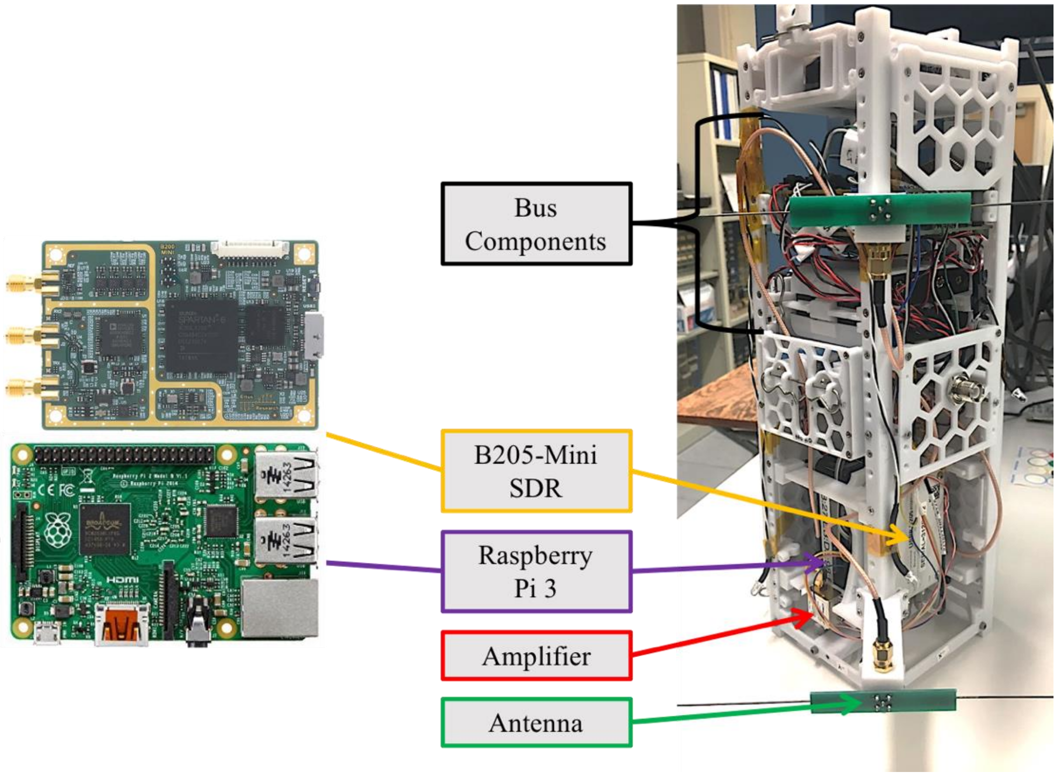

Figure 33. SAVIOR-Cube Pre-Flight

With SAVIOR-Cube assembled into the bus and ready for flight, a program called Habhub assisted in building a flight plan. Habhub is an open source website that calculates predicted flight paths, balloon burst altitude, and other important information for HAB flights based upon local wind and weather predictions. With this information, a plan to fly SAVIOR-Cube 83 km east across California's Central Valley provided a launch location, predicted landing location, and a flight time of approximately ninety minutes. At the launch location, a team of students and faculty attached the 3U CubeSat to a HAB filled with helium, as seen in Figure 34.

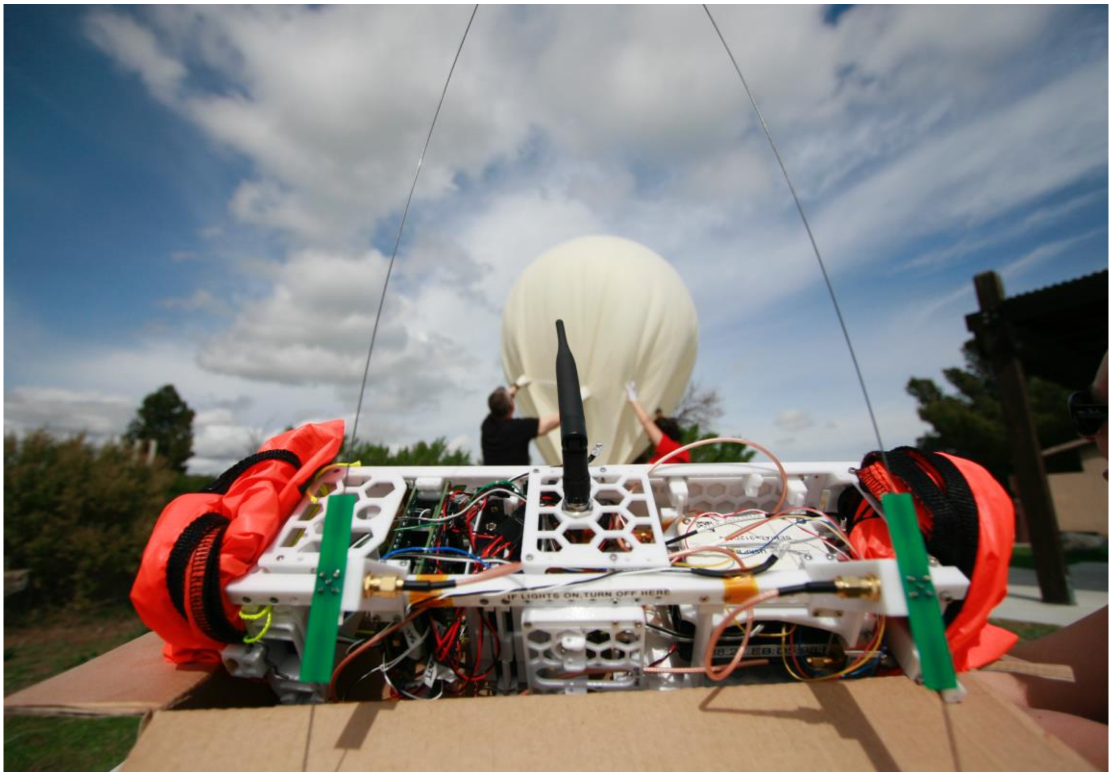

Figure 34. Filling the High-Altitude Balloon

Once the balloon was filled with helium, the team attached the CubeSat and powered the bus and payload on to ensure all systems were functioning. Multiple PRC152 radios were assembled and tuned to communicate with SAVIOR-Cube, which had a final receive frequency of 145.25 MHz and a transmit frequency of 147.425 MHz. Using the PRC152s, one final functional test of the payload proved it worked immediately prior to launch. With all systems a go, SAVIOR-Cube left the ground and began its journey into a near-space environment at approximately 1149 Pacific Standard Time (PST). Figure 35 is SAVIOR-Cube in-flight approximately five minutes after launch.

Figure 35. SAVIOR-Cube In-Flight

For the first thirty minutes of the flight, the payload functioned admirably despite a few minor issues. It received transmissions from the PRC152s, broadcasted the baseline transmission, and retransmitted recently recorded transmissions. Simply put, it successfully served as a VHF bent-pipe relay. The team began receiving and sending transmissions to SAVIOR-Cube approximately one minute prior to launch at 1148 PST. Approximately nine minutes after launch at 1158 PST, the payload malfunctioned and froze in a state of inoperability. It was manually rebooted via the mobile ground-station computer using a Python command (see Appendix B) and began working again at 1205 PST. After a successful reboot, the payload continued to function well, both sending and receiving transmissions. SAVIOR-Cube performed as expected for the first thirty minutes of the flight, receiving and sending a total of fourteen test transmissions. The flight was a success.

However, a failure between the payload and bus occurred at approximately 1219 PST, rendering the payload inoperable for the remainder of the flight. Based on the flight data, the power to the payload dropped below 4.00 V at 1219 PST, which is the absolute minimum amount of voltage the payload requires to function based upon the lab power tests. Figure 36 depicts payload voltage as a function of time, showing a voltage drop near 1219.

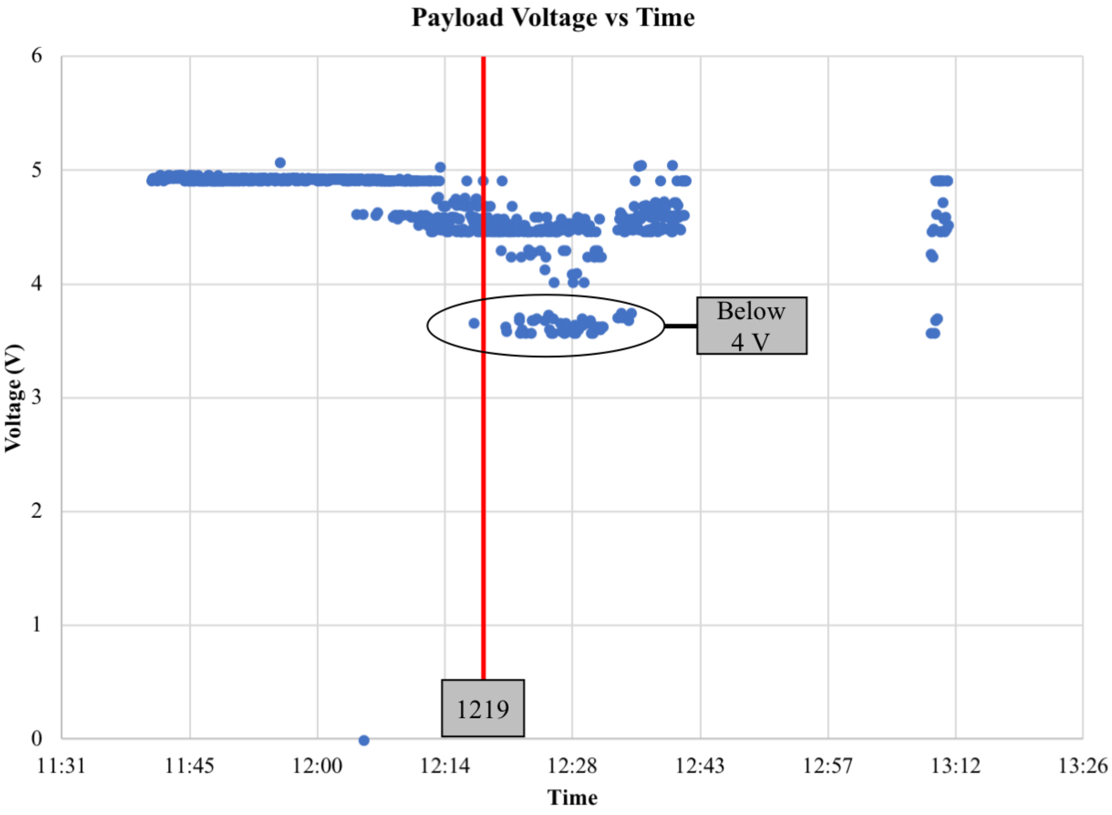

Figure 36. Payload Voltage Versus Time

Most likely, the low voltage caused critical failures within the payload, forcing a brownout. While it did reboot later in the flight, the team did not send or receive successful transmissions to SAVIOR-Cube for the remainder of the flight. The data recorded by the payload computer and bus computer, coupled with an analysis of the recorded audio transmissions and ground-based logs, indicate that the payload received its last successful transmission at that same approximate time—1219 PST. Correlating the last recorded latitude and longitude of the payload at 1218 PST (37.1283, -120.6146) with the latitude and longitude of the ground-based PRC152 radio at approximately 1219 PST (37.05676, -121.00082) gives a straight-line distance of 35.3 km between the two. Correlating this distance with the altitude of SAVIOR-Cube at that time of 9.67 km into account provides a slant range between the payload and radio of 36.6 km. Thus, SAVIOR-Cube functioned in-flight for approximately thirty minutes at a maximum distance of over 36 km, which

Figure 37 depicts. With this data, the initial proof of concept for an SDR VHF CubeSat relay succeeded.

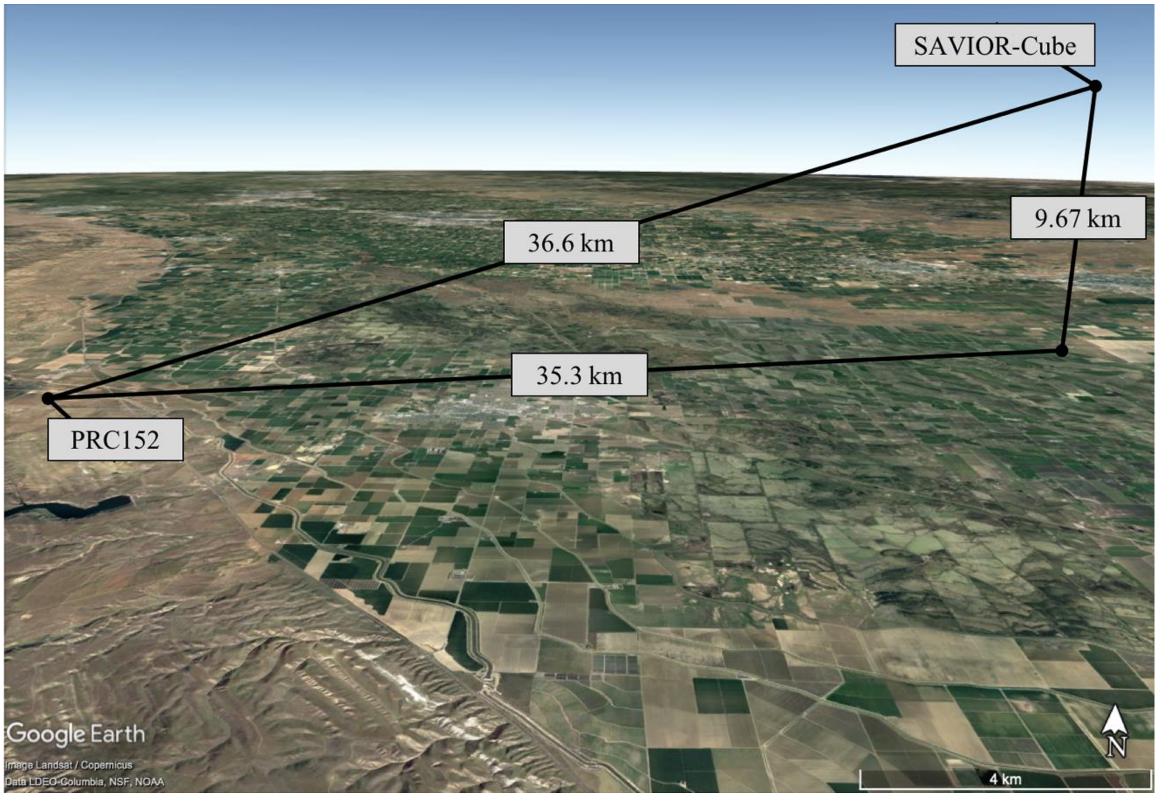

Figure 37. SAVIOR-Cube In-flight Slant Range

Unfortunately, the CubeSat structure did not survive the landing. Winds at altitude caused a parachute malfunction, forcing one of the parachutes to deploy early and significantly increasing the distance and time of the flight, reaching a maximum altitude of approximately 21 km. As a result, SAVIOR-Cube eventually landed 120 km to the west of the launch site. Figure 38 compares the predicted and actual flight paths.

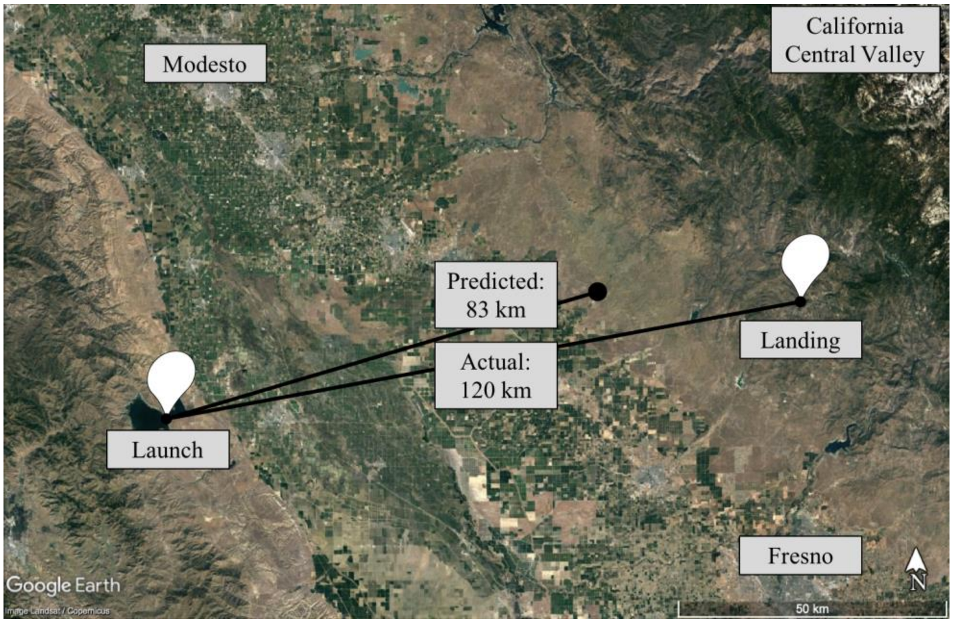

Figure 38. SAVIOR-Cube Flight Path

Due the winds at altitude and the premature parachute deployment, the antennas also became entangled in the parachute cord and only one of the parachutes opened as a result. This caused a rough landing that shattered the 3U CubeSat structure. However, the 3D-printed CubeSat structure and payload chassis were designed precisely for the purpose of absorbing the impact in the event of a rough landing to protect the bus and payload components. Figure 39 depicts SAVIOR-Cube as it was discovered post-flight.

Figure 39. SAVIOR-Cube Post-Flight

Despite the rough landing, a post-flight functional test conducted in the lab was successful. After an initial reboot, it performed as designed, sending and receiving transmissions in the lab. SAVIOR-Cube survived the HAB test and flight, which validated the structural design. Despite the temperature fluctuation during the flight, power outages, and a very rough landing, SAVIOR-Cube still endured. Not only did the HAB flight prove the viability of the concept, but it also validated the payload design.

G. CHAPTER CONCLUSION

To ensure the concept of a VHF nanosatellite relay was realistic, SAVIOR-Cube required thorough testing. First, extensive bench testing in the laboratory and iterative operational and functional testing identified flaws in the payload design and solidified the SAVIOR-Cube hardware and software designs. Robust environmental testing ensured the payload would survive the stresses of a HAB flight. Most importantly, the success of the HAB flight demonstrates that the payload is designed to support the intended purpose of SAVIOR-Cube. This testing proves that an SDR-based VHF relay flown in a nanosatellite is a realistic and feasible concept. It could provide resiliency and redundancy to the U.S. SATCOM infrastructure and support SOF across the globe. While this chapter focuses on the extent of the testing SAVIOR-Cube endured, the next chapter concludes this study and provides recommendations for future research.

V. SUMMARY AND CONCLUSION

As the body of this thesis demonstrates, the U.S. military is highly reliant upon space-based technology and special operations forces in particular (SOF) are nearly addicted to this advanced technology, conducting decentralized operations across the globe. Satellites support precision guided munitions, provide unparalleled overhead imagery, and enable global satellite communication (SATCOM). SATCOM especially supports U.S. SOF as they wage a far-reaching and decentralized conflict. However, as Chapter I explains, a high reliance upon the same technology that provides an edge to U.S. forces on the battlefield could also be a vulnerability. U.S. competitors undoubtedly possess the ability to disable U.S. satellites via kinetic or cyber means. Furthermore, the space domain is becoming ever more contested, and space-based technological resources are not infinite. While it would be unwise for the U.S. military and SOF in particular to divest from advanced technology due to the many advantages it provides, space-based resiliency and redundancy are required to help insulate against potential vulnerabilities.

Fortunately, emerging technology in nanosatellites provides potential methods for building required protections. Nanosatellites offer low-cost and expedient solutions that support innovation and experimentation across space-based technologies. Their small-price tag makes them ideal for developing custom payloads and testing new ideas. Furthermore, their small form factor leads to low satellite mass and supports large constellation size, potentially allowing operationally responsive launch and orbit customization. In other words, nanosatellites and Cube Satellites (CubeSats) allow for cheap innovation to augment the U.S. space infrastructure with custom solutions. With this idea in mind specifically for SATCOM and U.S. SOF, enormous potential exists for developing nanosatellite payloads that build resiliency and redundancy into traditional SATCOM architecture. Traditional SATCOM utilizes ultra high frequency (UHF) bands and most line of sight (LOS) communication relies upon very high frequencies (VHF), creating a potential for innovation between VHF and SATCOM. Specifically, as this thesis demonstrates, a nanosatellite that offers VHF communication from low Earth orbit (LEO) merits exploration. Hence, the impetus for the Software Assisted VHF Information

Overhead Relay-CubeSat (SAVIOR-Cube). SAVIOR-Cube utilizes existing software-defined radio (SDR) technology augmented to provide VHF communication via a nanosatellite relay—a nanosatellite alternative to traditional SATCOM.

The research, experimentation, and test results derived from this thesis illustrate that SAVIOR-Cube is a viable innovation. Chapter II demonstrates that SAVIOR-Cube is applicable to U.S. SOF today, feasible in terms of orbital mechanics, and realistic for implementation. More specifically, it shows how SOF across the globe today would benefit from a CubeSat that serves as a VHF relay overhead. Furthermore, example constellations demonstrate its feasibility, and a detailed communication budget from LEO validates that SAVIOR-Cube is realistic. In other words, a constellation of CubeSats programmed as a VHF relay will provide a redundant form of SATCOM to U.S. forces that could immediately support a myriad of operations from evasion plans to unconventional warfare campaigns. To further build upon this idea, a comprehensive trade space analysis in Chapter III results in the most favorable design for an initial engineering design unit (EDU) for a payload. The results of which were an EDU for SAVIOR-Cube that consists of a B205-Mini SDR, a Raspberry Pi 3 payload computer, a low noise amplifier for received signals, a wideband amplifier for transmitted signals, and two separate receive and transmit dipole antennas. This configuration, augmented by custom software programming via GNU Radio, allows SAVIOR-Cube to receive a VHF transmission, modulate the signal appropriately, amplify the signal, and retransmit it on a separate VHF frequency—a VHF bent-pipe relay.

While Chapter I and II articulate the depth of the problem and a potential solution, and Chapter III further designs the concept via a trade space analysis, if SAVIOR-Cube is intended to fly in orbit one day, it requires in-depth testing. Thus, the payload hardware and software were iteratively tested on the laboratory bench, via functional and operational tests, through environmentally testing, and finally onboard a high-altitude balloon (HAB). The operational testing in the lab and functional testing outside the lab assisted in software and hardware refinement, leading to the most optimal design. Environmental testing ensured the SAVIOR-Cube was properly designed and would survive the rigors of a near-space flight in a HAB. Finally, the HAB flight proved the viability of the payload and completed the regimen of iterative tests for SAVIOR-Cube.

From the results of these tests, SAVIOR-Cube demonstrated that it would function as designed. Functional testing validated its ability to retransmit signals over a simulated distance of over 100 km. Onboard a HAB, it reached an altitude of close to 21 km, transmitted over a distance of 36 km, and functioned for approximately 30 minutes inflight. Initial SAVIOR-Cube testing and experimentation was a success, which is key for proving the viability of this payload and its potential applications. This regime of iterative tests not only led to the best design for the SAVIOR-Cube payload, but it also validated the hypothesis of this thesis by demonstrating that nanosatellites are a viable alternative to augment existing space-based architectures.

A. POTENTIAL SAVIOR-CUBE APPLICATIONS

Though SAVIOR-Cube has clear applications for U.S. SOF, its applicability goes beyond special operations. Within the military, conventional U.S. and allied forces could also benefit from a VHF relay as an alternative form of SATCOM. Additionally, such a payload could assist in military search and rescue operations, providing a redundant form of VHF communications. In terms of employment, CubeSats and nanosatellites are only one mode of transportation for SAVIOR-Cube. Both manned and unmanned aerial platforms could fly simple payloads such as SAVIOR-Cube to support short-duration missions. Tethered dirigibles could support a VHF relay as well, flying high-above large bases to expand local VHF capabilities. Alternatively, versions of SAVIOR-Cube spread around a metropolitan area could provide a mesh network of military VHF communication across a city or specific area target. For the U.S. military and its allies, the applications for a VHF relay are numerous.

Beyond military applications, SAVIOR-Cube can support a number of civilian applications as well. First, it could serve as an emergency beacon during disaster and emergency events, broadcasting pre-recorded messages and instructions across a range of VHF frequencies. Next, the payload could also assist with civilian search and rescue operations, tying into maritime or emergency VHF frequencies and serving as a redundant form of communication for those in need of rescue, from stranded climbers to wayward vessels in the ocean. Finally, SAVIOR-Cube could serve as a messaging service to remote areas with little communication infrastructure. A one-way radio service of sorts, sending VHF transmissions that could communicate with existing FM radios and provide weather updates, news, and much needed information to those lacking connectivity to the modern world. With the ease of programming SDRs and building nanosatellites, numerous options for SAVIOR-Cube applications and methods of employment exist beyond those discussed in this thesis.

B. RECOMMENDATION FOR FUTURE WORK

From the success of the SAVIOR-Cube EDU and testing, the potential for future design changes and additional experimentation exists. First in terms of the design, stronger amplifiers for both the received and transmitted signals would increase the distance across which the payload would function. Simply put, a more sensitive low noise amplifier would increase the margin for received signals, lowering the threshold for weakly received signals. A stronger transmit amplifier would increase the distance a transmitted signal could successfully travel and still reach its intended target. These changes would require more power, but a more robust satellite bus could support such a change. Furthermore, if intended to fly in orbit, stronger signals via more robust amplifiers and more power would be a requirement to ensure VHF signals successfully penetrate the Earth’s atmosphere. Additionally, a more capable SDR and payload computer would help fine-tune some of the issues caused by the limitations of the current design. Future iterations of SAVIOR-Cube could include a custom SDR or computer, specifically designed with the payload’s purpose in mind.

Akin to the hardware design, the software would also benefit from additional fine-tuning and experimentation. While the current software design for the payload functioned well, room for improvement always exists. Specifically, the software design and testing could be improved to support not just voice communication but also basic data transmissions. VHF is not ideal for data, but SAVIOR-Cube could support a simple data exchange if programmed appropriately. Similarly, the software could also be programmed to support encrypted transmissions, shielding transmissions from intercept. It could also be designed to support multiple simultaneous transmissions, expanding the payload's capabilities beyond its current limitations. Finally, the system could provide cross-linked communication within a constellation. It would expand beyond a bent-pipe relay to a truly global system. A future SAVIOR-Cube constellation could also tie into existing SATCOM systems such as the Mobile User Objective System (MUOS), moving beyond just this payload's capabilities and tying into the U.S. SATCOM infrastructure writ large. These ideas are just a scratch on the surface of the numerous options for further SAVIOR-Cube development. Regardless, SAVIOR-Cube is a concept that merits further exploration and testing; it is a viable alternative to support U.S. military SATCOM needs.

C. FINAL THOUGHTS

As the research question of this study ponders, emerging technologies in nanosatellites are ripe for innovation aimed at protecting against space-based vulnerabilities. For example, a VHF relay flying overhead in orbit has numerous applications for U.S. SOF, the U.S. military and its allies, and even civilian populations. While the design, experimentation, and testing of SAVIOR-Cube support the utility of such a concept, the lessons of this thesis range beyond a simple SDR nanosatellite relay. With the potential vulnerabilities associated with the U.S. military's dependence upon space-based resources such as SATCOM, SAVIOR-Cube simply provides an example solution to this otherwise exposed liability. More succinctly, it demonstrations that emerging technology in nanosatellites offer a testbed for innovation to build resiliency and redundancy into existing U.S. space-based infrastructure, thus validating the hypothesis of this thesis. The U.S. military must come to terms with its high reliance on advanced technology and build much needed protection into existing systems across all domains. Fortunately, nanosatellites provide a method for doing just that. Nanosatellites, however, are not just a viable alternative to traditional space-based architectures; they also provide an example for how to use emerging technology successfully, building redundancy and resiliency into legacy technological systems—a solution for a critical vulnerability.

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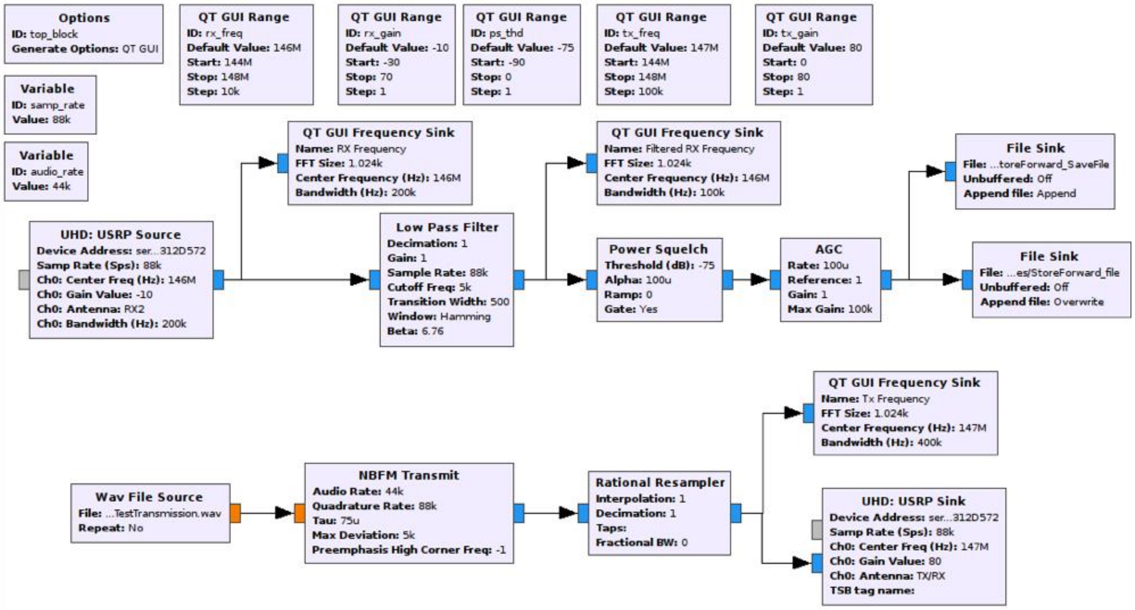
APPENDIX A. GNU RADIO FLOW CHARTS

A. RECEIVE FLOW CHARTS



Options
ID: top_block
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 88k

Variable
ID: audio_rate
Value: 44k

QT GUI Range
ID: rx_freq
Default Value: 146M
Start: 144M
Stop: 148M
Step: 10k

QT GUI Range
ID: rx_gain
Default Value: -10
Start: -30
Stop: 70
Step: 1

QT GUI Range
ID: ps_thd
Default Value: -75
Start: -90
Stop: 0
Step: 1

QT GUI Range
ID: tx_freq
Default Value: 147M
Start: 144M
Stop: 148M
Step: 100k

QT GUI Range
ID: tx_gain
Default Value: 80
Start: 0
Stop: 80
Step: 1

UHD: USRP Source
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 146M
Ch0: Gain Value: -10
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 200k

QT GUI Frequency Sink
Name: RX Frequency
FFT Size: 1.024k
Center Frequency (Hz): 146M
Bandwidth (Hz): 200k

Low Pass Filter
Decimation: 1
Gain: 1
Sample Rate: 88k
Cutoff Freq: 5k
Transition Width: 500
Window: Hamming
Beta: 6.76

QT GUI Frequency Sink
Name: Filtered RX Frequency
FFT Size: 1.024k
Center Frequency (Hz): 146M
Bandwidth (Hz): 100k

Power Squelch
Threshold (dB): -75
Alpha: 100u
Ramp: 0
Gate: Yes

AGC
Rate: 100u
Reference: 1
Gain: 1
Max Gain: 100k

File Sink
File: ...toreForward_SaveFile
Unbuffered: Off
Append file: Append

File Sink
File: ...es/StoreForward_file
Unbuffered: Off
Append file: Overwrite

Wav File Source
File: ...TestTransmission.wav
Repeat: No

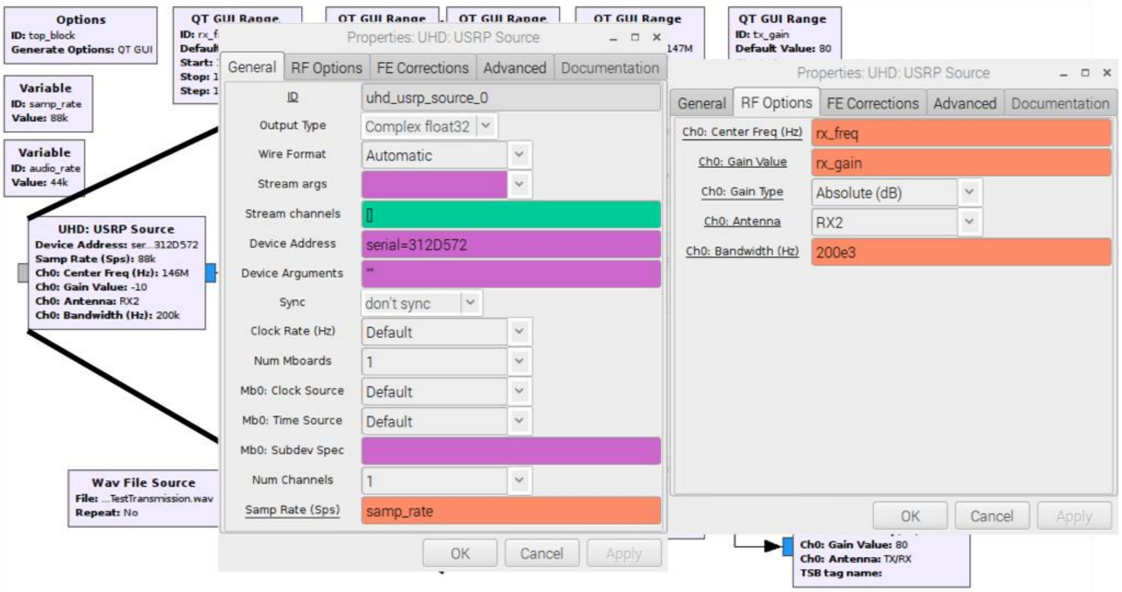
NBFM Transmit
Audio Rate: 44k
Quadrature Rate: 88k
Tau: 75u
Max Deviation: 5k
Preemphasis High Corner Freq: -1

Rational Resampler
Interpolation: 1
Decimation: 1
Taps:
Fractional BW: 0

QT GUI Frequency Sink
Name: Tx Frequency
FFT Size: 1.024k
Center Frequency (Hz): 147M
Bandwidth (Hz): 400k

UHD: USRP Sink
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 147M
Ch0: Gain Value: 80
Ch0: Antenna: TX/RX
TSB tag name:

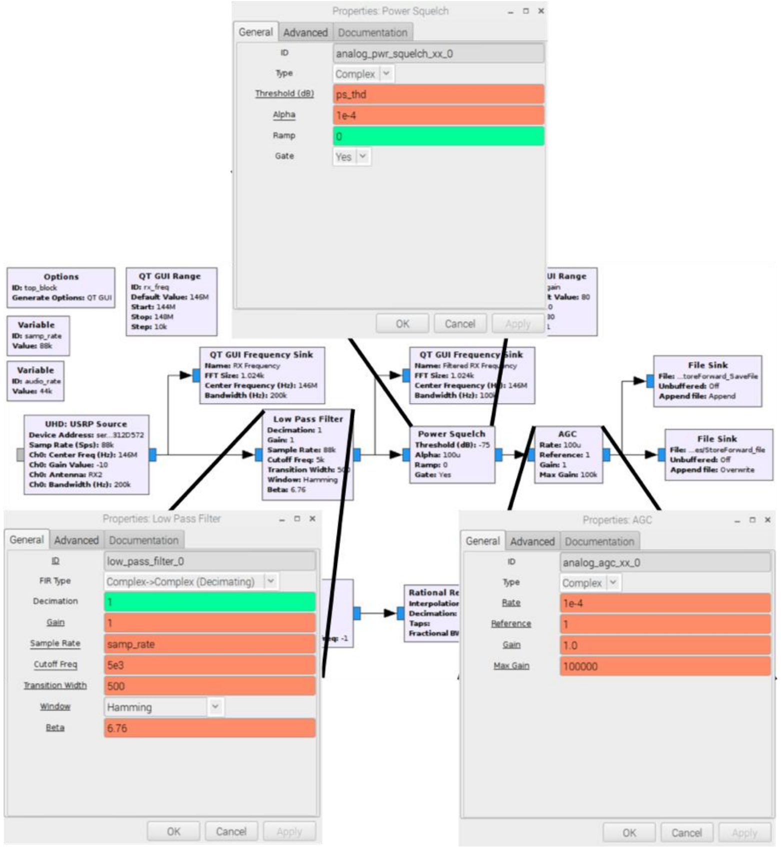
Figure 40. Complete Receive Flow Graph



ID: uhd_usrp_source_0
Output Type: Complex float32
Wire Format: Automatic
Stream args:
Stream channels: []
Device Address: serial=312D572
Device Arguments: ""
Sync: don't sync
Clock Rate (Hz): Default
Num Mboards: 1
Mb0: Clock Source: Default
Mb0: Time Source: Default
Mb0: Subdev Spec:
Num Channels: 1
Samp Rate (Sps): samp_rate

Ch0: Center Freq (Hz): rx_freq
Ch0: Gain Value: rx_gain
Ch0: Gain Type: Absolute (dB)
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 200e3

Figure 41. USRP Source Blocks



Properties: Power Squelch

ID: analog_pwr_squelch_xx_0
Type: Complex
Threshold (dB): ps_thd
Alpha: 1e-4
Ramp: 0
Gate: Yes

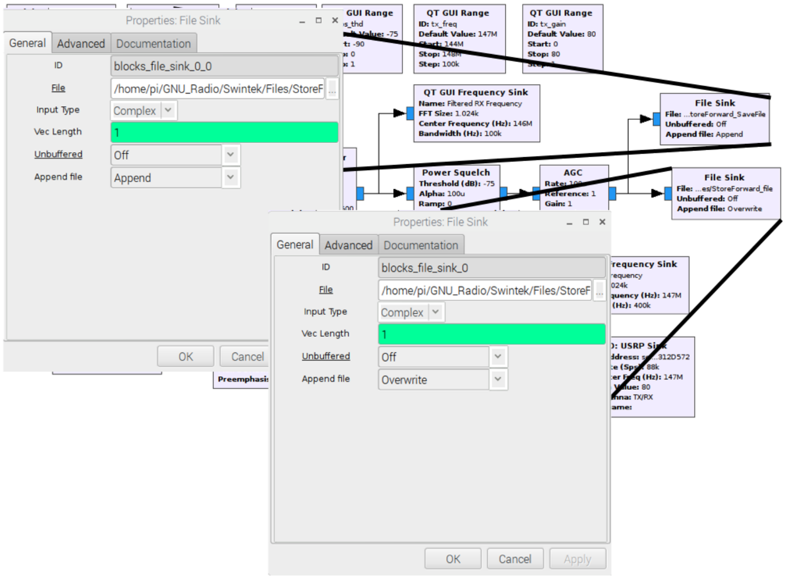
Properties: Low Pass Filter

ID: low_pass_filter_0
FIR Type: Complex->Complex (Decimating)
Decimation: 1
Gain: 1
Sample Rate: samp_rate
Cutoff Freq: 5e3
Transition Width: 500
Window: Hamming
Beta: 6.76

Properties: AGC

ID: analog_agc_xx_0
Type: Complex
Rate: 1e-4
Reference: 1
Gain: 1.0
Max Gain: 100000

Figure 42. Low Pass Filter, Power Squelch, and Automatic Gain Control Blocks



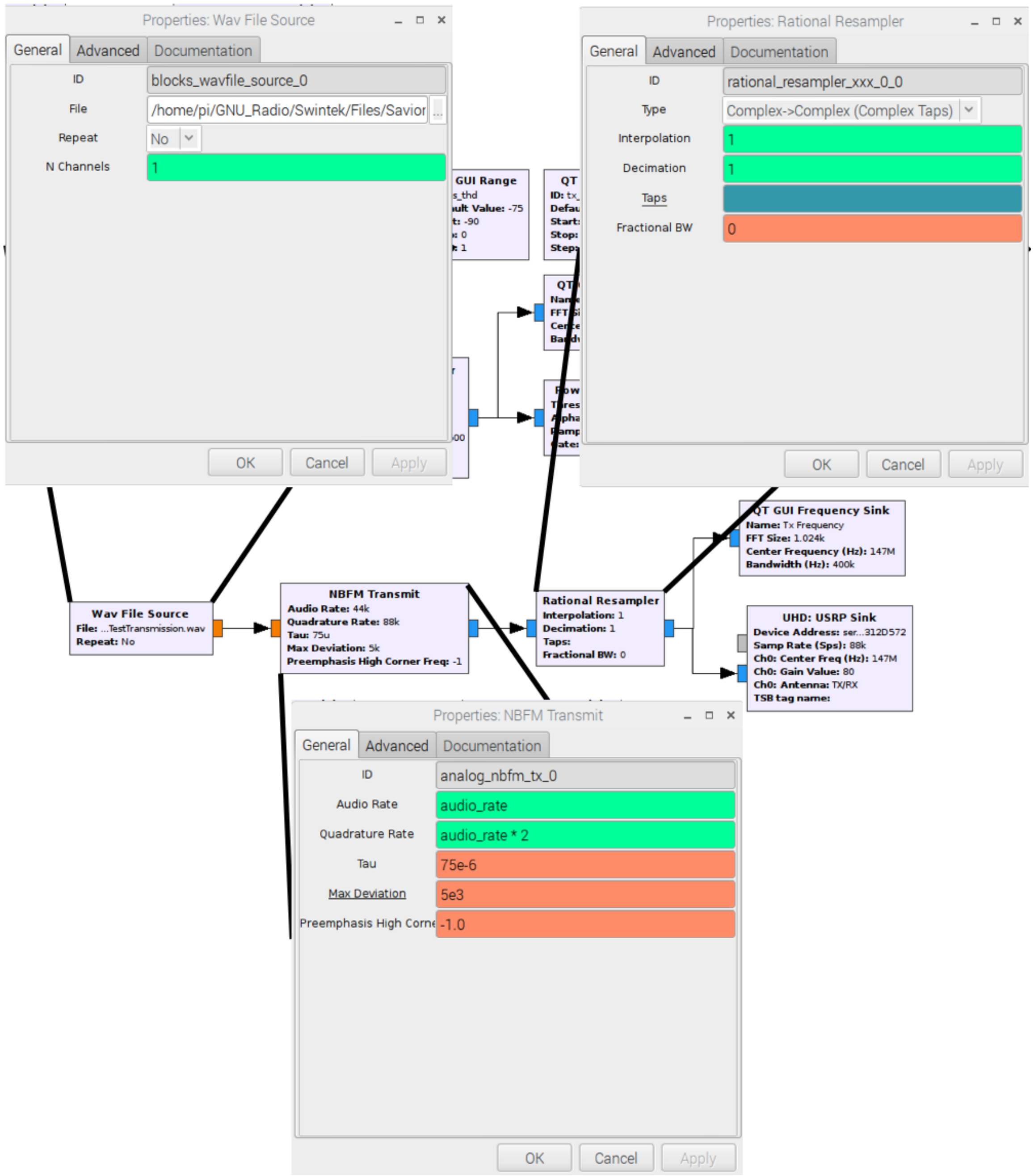
Properties: File Sink

ID: blocks_file_sink_0_0
File: /home/pi/GNU_Radio/Swintek/Files/StoreF
Input Type: Complex
Vec Length: 1
Unbuffered: Off
Append file: Append

Properties: File Sink

ID: blocks_file_sink_0
File: /home/pi/GNU_Radio/Swintek/Files/StoreF
Input Type: Complex
Vec Length: 1
Unbuffered: Off
Append file: Overwrite

Figure 43. File Sink Blocks



Properties: Wav File Source

General | Advanced | Documentation

ID: blocks_wavfile_source_0
File: /home/pi/GNU_Radio/Swintek/Files/Savior
Repeat: No
N Channels: 1

Properties: Rational Resampler

General | Advanced | Documentation

ID: rational_resampler_xxx_0_0
Type: Complex->Complex (Complex Taps)
Interpolation: 1
Decimation: 1
Taps:
Fractional BW: 0

Wav File Source
File: ...TestTransmission.wav
Repeat: No

NBFM Transmit
Audio Rate: 44k
Quadrature Rate: 88k
Tau: 75u
Max Deviation: 5k
Preemphasis High Corner Freq: -1

Rational Resampler
Interpolation: 1
Decimation: 1
Taps:
Fractional BW: 0

QT GUI Frequency Sink
Name: Tx Frequency
FFT Size: 1.024k
Center Frequency (Hz): 147M
Bandwidth (Hz): 400k

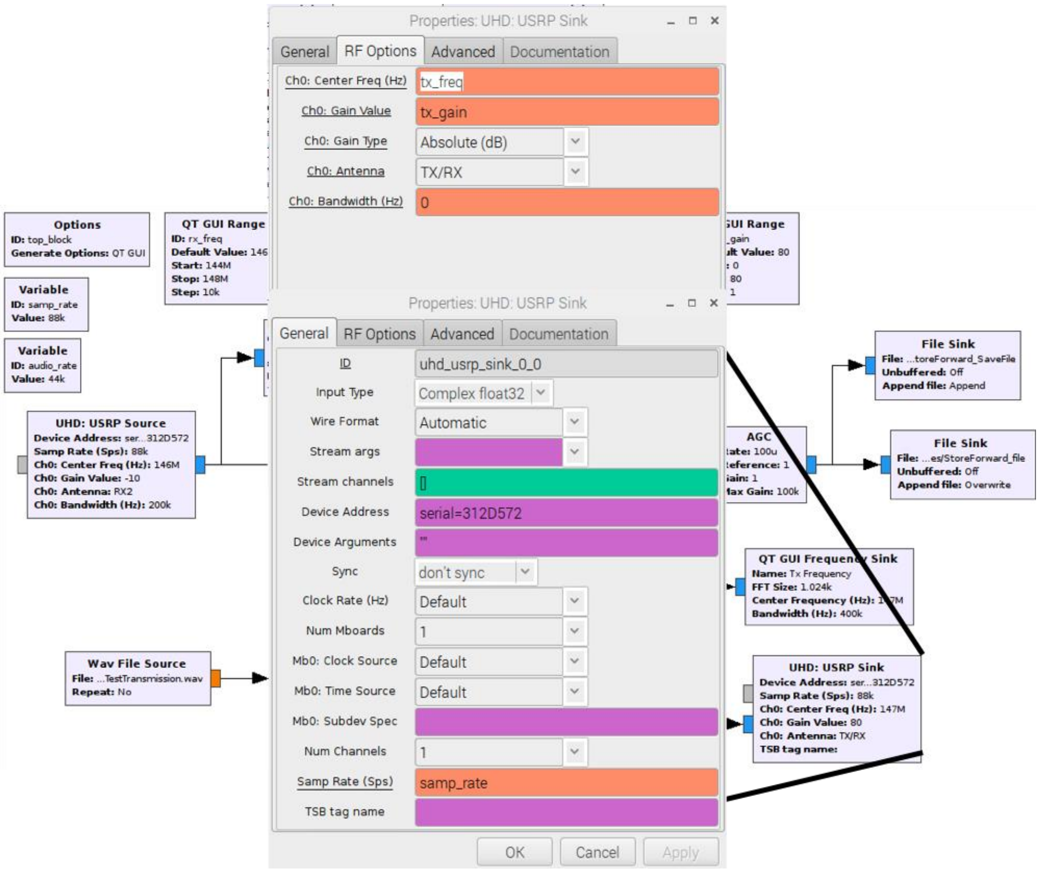
UHD: USRP Sink
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 147M
Ch0: Gain Value: 80
Ch0: Antenna: TX/RX
TSB tag name:

Properties: NBFM Transmit

General | Advanced | Documentation

ID: analog_nbfm_tx_0
Audio Rate: audio_rate
Quadrature Rate: audio_rate * 2
Tau: 75e-6
Max Deviation: 5e3
Preemphasis High Corne: -1.0

Figure 44. Wav File Source, NBFM Transmit, and Rational Resampler Blocks



Ch0: Center Freq (Hz): tx_freq
Ch0: Gain Value: tx_gain
Ch0: Gain Type: Absolute (dB)
Ch0: Antenna: TX/RX
Ch0: Bandwidth (Hz): 0

ID: uhd_usrp_sink_0_0
Input Type: Complex float32
Wire Format: Automatic
Stream args:
Stream channels: []
Device Address: serial=312D572
Device Arguments: ""
Sync: don't sync
Clock Rate (Hz): Default
Num Mboards: 1
Mb0: Clock Source: Default
Mb0: Time Source: Default
Mb0: Subdev Spec:
Num Channels: 1
Samp Rate (Sps): samp_rate
TSB tag name:

Figure 45. USRP Sink Block

B. TRANSMIT FLOW CHARTS

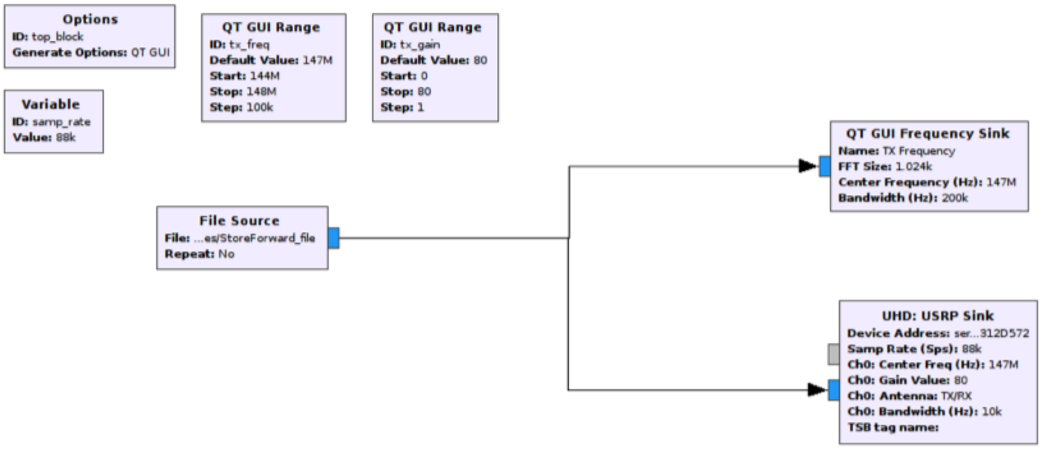
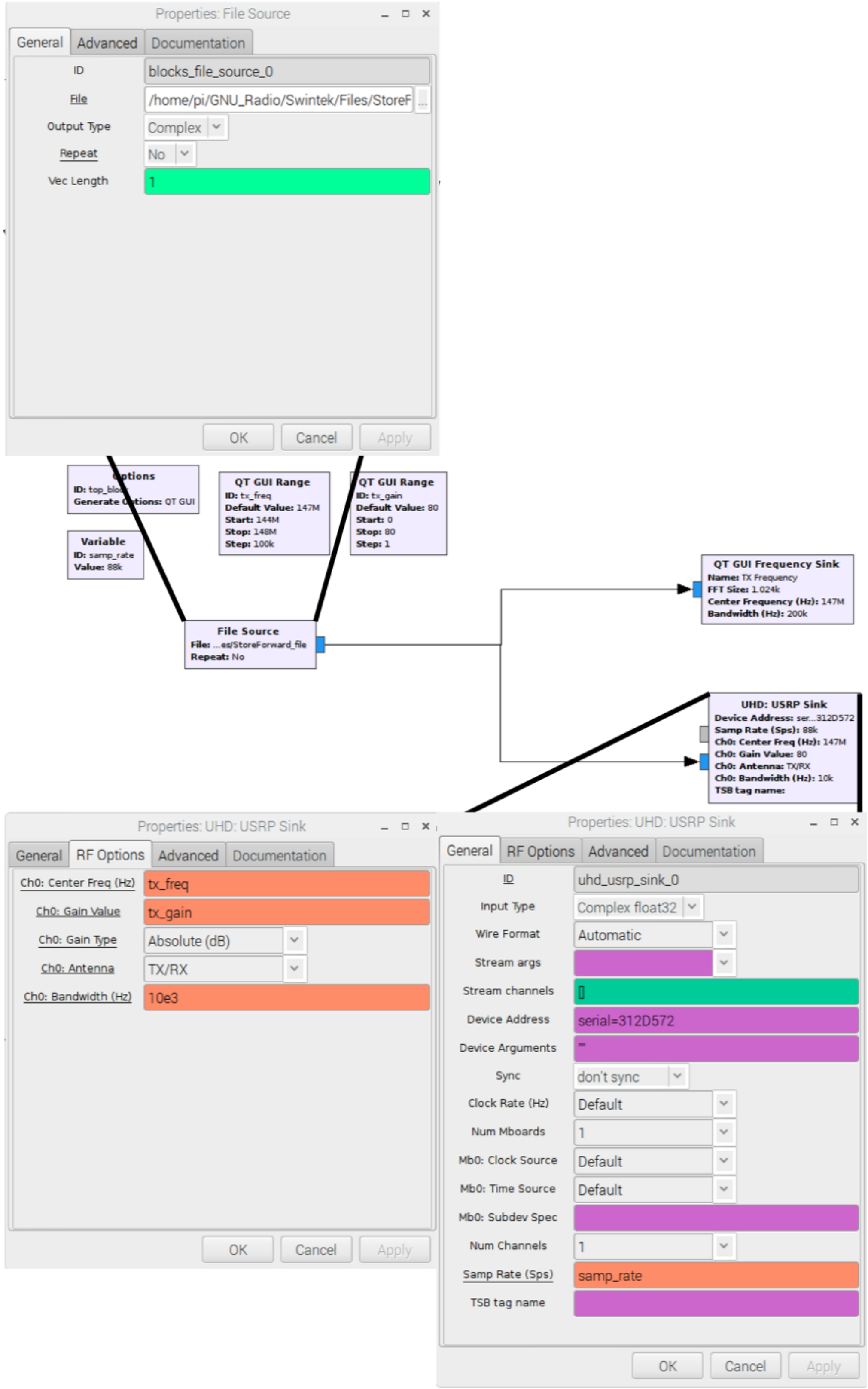


Figure 46. Complete Transmit Flow Graph



ID: blocks_file_source_0

File: /home/pi/GNU_Radio/Swintek/Files/StoreF

Output Type: Complex

Repeat: No

Vec Length: 1

Options
ID: top_block
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 88k

QT GUI Range
ID: tx_freq
Default Value: 147M
Start: 144M
Stop: 148M
Step: 100k

QT GUI Range
ID: tx_gain
Default Value: 80
Start: 0
Stop: 80
Step: 1

File Source
File: ...es/StoreForward_file
Repeat: No

QT GUI Frequency Sink
Name: TX Frequency
FFT Size: 1.024k
Center Frequency (Hz): 147M
Bandwidth (Hz): 200k

UHD: USRP Sink
Device Address: ser...312D572
Samp Rate (Sps): 88k
Ch0: Center Freq (Hz): 147M
Ch0: Gain Value: 80
Ch0: Antenna: TX/RX
Ch0: Bandwidth (Hz): 10k
TSB tag name:

Ch0: Center Freq (Hz): tx_freq

Ch0: Gain Value: tx_gain

Ch0: Gain Type: Absolute (dB)

Ch0: Antenna: TX/RX

Ch0: Bandwidth (Hz): 10e3

ID: uhd_usrp_sink_0

Input Type: Complex float32

Wire Format: Automatic

Stream args:

Stream channels: []

Device Address: serial=312D572

Device Arguments: ""

Sync: don't sync

Clock Rate (Hz): Default

Num Mboards: 1

Mb0: Clock Source: Default

Mb0: Time Source: Default

Mb0: Subdev Spec:

Num Channels: 1

Samp Rate (Sps): samp_rate

TSB tag name:

Figure 47. File Source and USRP Sink Blocks

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APPENDIX B. RAW PAYLOAD PYTHON SCRIPTS

A. MASTER PYTHON SCRIPT (MASTER.PY)[104]

```
from __future__ import print_function
import os
import shutil
import socket
import subprocess
import sys
#import cpu_temp
import threading
import time
import log
import serial
import UART

from store_and_forward import store_and_forward

STATUS_INTERVAL = 20

# C&DH serial connection variables
CDH_address = "/dev/ttyAMA0"
CDH_baud = 9600
CDH = UART.UART(CDH_address, CDH_baud)

STAT_STR = '20 {:>10d} {:>9d} {:>9d} {:>+3d} {:>2d} {:>+3d} {:>3d} {:>+5.1f} {:>6.1f}'
ACK_STR = '21 {:>10d} {:>2d} {:>1d} {:>1d}'
MSG_STR = '22 {:>100s}'

LOGGER = log.LOG()

# Payload variables
VERSION = "0.1"

def main():
  # RX_freq, TX_freq, RX_gain, TX_gain, RX_thres, TX_delay
  params = [145525000, 147550000, -10, 80, -75, 60]

  msg = '\n\n---------------------------------------------------------'
  LOGGER.log(msg)
  msg = '22 {:<100s}'.format('%d Payload Startup, version %s'%(time.time(), VERSION))
  LOGGER.log(msg)
  CDH.write(msg, True)

  current_script = 'store_and_forward'
  error_msg = ''
  try:
```

---

[104] Nicholas Koeppen, email message to author, April 5, 2018.

```
    current_object = store_and_forward(params,CDH)
    current_object.run()
except:
    error_msg = "ERROR: Radio connection failed."
if error_msg:
    msg = error_msg
else:
    msg = "SDR Ready to Receive"
    time.sleep(2)
print(msg)
LOGGER.log(msg)

time2get_status = 0
while True:
    now = time.time()

    cmd = CDH.get_line()
    if cmd != None:
        cmd_id = None
        cmd_status = 0
        cmd = cmd.strip()
        msg = 'command <%s> received.'%cmd
        LOGGER.log(msg)
        print(msg)

        cmd_parts = cmd.split(" ")
        cmd = cmd_parts[0]
        if cmd == "pstat":
            cmd_id = 20
            opt_id = 0
            status_str = update_status(params)
            time2get_status = time.time() + STATUS_INTERVAL
            if status_str is not None:
                cmd_status = 1
                print(status_str)
                CDH.write(status_str, True)
        elif cmd == "preboot":
            cmd_id = 21
            opt_id = 0
            # REBOOT: Reboot the entire payload
            msg = MSG_STR.format('%d system reboot.'%now)
            print(msg)
            LOGGER.log(msg)
            msg = ACK_STR.format(int(now), cmd_id, opt_id, 1)
            print(msg)
            LOGGER.log(msg)
            CDH.write(msg, True)
            p = subprocess.Popen(['sync'], stdout=subprocess.PIPE, stderr=subprocess.PIPE)
            results, err = p.communicate()
            p.wait()
            time.sleep(1)
            p = subprocess.Popen(['reboot'], stdout=subprocess.PIPE, stderr=subprocess.PIPE)
            results, err = p.communicate()
            p.wait()
```

```
    while True:
        time.sleep(1)
elif cmd == "preset":
    cmd_id = 22
    opt_id = 0
    # RESTART: Restart the current payload script
    if not current_script:
        print("no current script running")
    else:
        print("Attempt to restart script: " + current_script)
        failed = False
        try:
            current_object.stop()
            sleep(2)
            current_object = store_and_forward(params)
            current_object.run()
        except:
            failed = True
            msg = MSG_STR.format('Script failed to reset.')
            print(msg)
            LOGGER.log(msg)
            CDH.write(msg, True)

        if not failed:
            print("Restarted script <%s> successfully."%current_script)
            cmd_status = 1
elif cmd == "padj":
    cmd_id = 23
    try:
        opt_id = int(cmd_parts[1])
        adj_val = int(cmd_parts[2].rstrip('\0'))

        if len(cmd_parts) != 3 or opt_id < 1 or opt_id > 7:
            msg = MSG_STR.format('command <%s> is invalid.'%cmd)
            print(msg)
            LOGGER.log(msg)
            CDH.write(msg, True)
            continue

        if opt_id > 7:
            msg = 'command <%s> is invalid.'%cmd
            print(msg)
            LOGGER.log(msg)
        elif opt_id > 0 and opt_id < 7:
            opt_valid = False
            cmd_status = 1 # Assume successful now, unless exception

            params[opt_id-1] = adj_val #adjust to base zero
            if opt_id == 1:
                current_object.set_rx_freq(adj_val)
            elif opt_id == 2:
                current_object.set_tx_freq(adj_val)
            elif opt_id == 3:
                current_object.set_rx_gain(adj_val)
            elif opt_id == 4:
```

```
                        current_object.set_tx_gain(adj_val)
                    elif opt_id == 5:
                        current_object.set_rx_thres(adj_val)
                    elif opt_id == 6:
                        current_object.set_tx_delay(adj_val)
            except:
                msg = MSG_STR.format('command <%s> is invalid. Adjustment failed.'%cmd)
                print(msg)
                LOGGER.log(msg)
                CDH.write(msg, True)
                cmd_status = 0
        else:
            msg = MSG_STR.format('command <%s> is invalid. Unknown command type.'%cmd)
            print(msg)
            LOGGER.log(msg)
            CDH.write(msg, True)

        if cmd_id is not None:
            msg = ACK_STR.format(int(now), cmd_id, opt_id, cmd_status)
            print(msg)
            LOGGER.log(msg)
            CDH.write(msg, True)

    if now > time2get_status:
        status_str = update_status(params)
        time2get_status = time.time() + STATUS_INTERVAL
        if status_str is not None:
            print(status_str)
            CDH.write(status_str, True)

def update_status(params):
    #temps = cpu_temp.get_temps()
    #if temps != None:
    # LOGGER.log(temps)
    p = os.popen('vcgencmd measure_temp').readline() # temperature values are stored inside of this file
    values = [float(p.replace("temp=","").replace("'C\n",""))]  # remove 'C' => float
    cpu_temp = values[0]

    data = get_SD_capacity()
    now = time.time()
    if data != None:
        (fs, size, used, avail, cap, mount) = data
        data_avail = float(avail)/(1024)
        msg = '22 {:<100s}'.format('%d SD available %s Mbytes'%(now, avail))
        LOGGER.log(msg)

    # Return status string
    return STAT_STR.format(int(now), params[0], params[1], params[2], params[3], params[4],
params[5], cpu_temp, data_avail)

def get_SD_capacity():
  p = subprocess.Popen(['df'], stdout=subprocess.PIPE, stderr=subprocess.PIPE)
  results, err = p.communicate()
  p.wait()
```

```
    cap = None
    for line in results.split("\n"):
        if line.find('/dev/root') >= 0:
            try:
                (fs, size, used, avail, cap, mount) = line.split()
                return (fs, size, used, avail, cap, mount)
            except:
                return None
    return None

if __name__ == "__main__":
    os.nice(-19)
    main()
```

B. STORE FORWARD PYTHON SCRIPT (STORE_AND_FORWARD.PY)[105]

```
from __future__ import print_function
import log
import time
import threading
import subprocess
import UART
from saf_rx import saf_rx
from saf_tx import saf_tx

RX_STR = "RX Started. RX_Freq: {:>9d}. RX_Gain: {:>+3d}. RX_Thres: {:>+3d}. TX_Freq: {:>9d}.
TX_Gain: {:>2d}."
MSG_STR = '22 {:>100s}'
LOGGER = log.LOG()

class store_and_forward(object):

    def __init__(self,params,CDH):
        self.rx_freq = params[0]
        self.tx_freq = params[1]
        self.rx_gain = params[2]
        self.tx_gain = params[3]
        self.rx_thres = params[4]
        self.tx_delay = params[5]
        self.CDH = CDH

        self.rx_obj = None
        self.tx_obj = None
        self.thread = threading.Thread(target=self.run_thread, args=(self.rx_obj,self.tx_obj))
        self.thread.daemon = True

    def get_params(self):
        return [self.rx_freq, self.tx_freq, self.rx_gain, self.tx_gain, self.rx_thres, self.tx_delay]

    def get_rx_freq(self):
        return self.rx_freq
```

---

[105] Koeppen.

```
def set_rx_freq(self, rx_freq):
    self.rx_freq = rx_freq
    if self.rx_obj is not None:
        self.rx_obj.set_rx_freq(rx_freq)

def get_tx_freq(self):
    return self.tx_freq

def set_tx_freq(self, tx_freq):
    self.tx_freq = tx_freq
    if self.rx_obj is not None:
        self.rx_obj.set_tx_freq(tx_freq)
    if self.tx_obj is not None:
        self.tx_obj.set_tx_freq(tx_freq)

def get_rx_gain(self):
    return self.rx_gain

def set_rx_gain(self, rx_gain):
    self.rx_gain = rx_gain
    if self.rx_obj is not None:
        self.rx_obj.set_rx_gain(rx_gain)

def get_tx_gain(self):
    return self.tx_gain

def set_tx_gain(self, tx_gain):
    self.tx_gain = tx_gain
    if self.rx_obj is not None:
        self.rx_obj.set_tx_gain(tx_gain)
    if self.tx_obj is not None:
        self.tx_obj.set_tx_gain(tx_gain)

def get_rx_thres(self):
    return self.rx_thres

def set_rx_thres(self, rx_thres):
    self.rx_thres = rx_thres
    if self.rx_obj is not None:
        self.rx_obj.set_rx_thres(rx_thres)

def run(self):
            self.thread.start()

def stop(self):
    self.thread.terminate()
    if self.rx_obj is not None:
        self.rx_obj.stop()

def run_thread(self, rx_obj, tx_obj):
    cycles = 0
    while cycles < 10:
```

```
            cycles = cycles + 1
            # Wait to transmit until after tx_delay
            self.rx_obj = rx_obj = saf_rx(self.get_params())
            rx_obj.start()
            time.sleep(3)  # 3 seconds to initialize

            msg = RX_STR.format(self.rx_freq,self.rx_gain,self.rx_thres,self.tx_freq,self.tx_gain)
            print(msg)
            LOGGER.log(msg)
            time2tx = time.time() + self.tx_delay
            while time.time() < time2tx:
                # Send preface message and RX (STORE)
                time.sleep(1)
                print("RXing")
            rx_obj.stop()
            rx_obj.wait()
            msg = "RX Stopped"
            print(msg)
            LOGGER.log(msg)

            time.sleep(2)  # 2 seconds to cleanup

            # Start sending stored message (FORWARD)
            self.tx_obj = tx_obj = saf_tx(self.get_params())
            tx_obj.start()
            msg = "TX Started. Freq: %d. Gain: %d"%(tx_obj.tx_freq,tx_obj.tx_gain)
            tx_obj.wait()
            print(msg)
            LOGGER.log(msg)
            print("TX Stopped")
            time.sleep(2)  # 2 seconds to cleanup

        msg = MSG_STR.format('Automatic reboot started.')
        print(msg)
        LOGGER.log(msg)
        self.CDH.write(msg, True)
        p = subprocess.Popen(['sync'], stdout=subprocess.PIPE, stderr=subprocess.PIPE)
        results, err = p.communicate()
        p.wait()
        time.sleep(1)
        p = subprocess.Popen(['reboot'], stdout=subprocess.PIPE, stderr=subprocess.PIPE)
        results, err = p.communicate()
        p.wait()
        while True:
            time.sleep(1)
```

C. RECEIVE PYTHON SCRIPT (SAF_RX.PY)[106]

```
#!/usr/bin/env python2
# -*- coding: utf-8 -*-
##################################################
```

---

[106] Koeppen.

```
# GNU Radio Python Flow Graph
# Title: Saf Rx
# Generated: Wed Feb 28 14:10:36 2018
##################################################

from gnuradio import analog
from gnuradio import blocks
from gnuradio import eng_notation
from gnuradio import filter
from gnuradio import gr
from gnuradio import uhd
from gnuradio.eng_option import eng_option
from gnuradio.filter import firdes
from optparse import OptionParser
import time

DEFAULT_PARAMS = [145525000, 147550000, -10, 80, -75]

class saf_rx(gr.top_block):

    def __init__(self, params=DEFAULT_PARAMS):
        gr.top_block.__init__(self, "Store and Forward RX")

        ##################################################
        # Variables
        ##################################################
        self.rx_freq = rx_freq = params[0]
        self.tx_freq = tx_freq = params[1]
        self.rx_gain = rx_gain = params[2]
        self.tx_gain = tx_gain = params[3]
        self.rx_thres = rx_thres = params[4]

        self.samp_rate = samp_rate = 88000
        self.audio_rate = audio_rate = 44000

        ##################################################
        # Blocks
        ##################################################
        self.uhd_usrp_source_0 = uhd.usrp_source(
                ",".join(('serial=312D572', "")),
                uhd.stream_args(
                                cpu_format="fc32",
                                channels=range(1),
                ),
        )
        self.uhd_usrp_source_0.set_samp_rate(samp_rate)
        self.uhd_usrp_source_0.set_center_freq(rx_freq, 0)
        self.uhd_usrp_source_0.set_gain(rx_gain, 0)
        self.uhd_usrp_source_0.set_antenna('RX2', 0)
        self.uhd_usrp_source_0.set_bandwidth(200e3, 0)
        self.uhd_usrp_sink_0_0 = uhd.usrp_sink(
                ",".join(('serial=312D572', "")),
                uhd.stream_args(
```

```
                    cpu_format="fc32",
                    channels=range(1),
            ),
        )
        self.uhd_usrp_sink_0_0.set_samp_rate(samp_rate)
        self.uhd_usrp_sink_0_0.set_center_freq(tx_freq, 0)
        self.uhd_usrp_sink_0_0.set_gain(tx_gain, 0)
        self.uhd_usrp_sink_0_0.set_antenna('TX/RX', 0)
        self.rational_resampler_xxx_0_0 = filter.rational_resampler_ccc(
                interpolation=1,
                decimation=1,
                taps=None,
                fractional_bw=None,
        )
        self.low_pass_filter_0 = filter.fir_filter_ccf(1, firdes.low_pass(
            1, samp_rate, 5e3, 500, firdes.WIN_HAMMING, 6.76))
        self.blocks_wavfile_source_0 = blocks.wavfile_source('/home/pi/SDRcontrol/Files/SAVIOR-Cube.wav', False)
        self.blocks_file_sink_0_0 = blocks.file_sink(gr.sizeof_gr_complex*1, '/home/pi/SDRcontrol/Files/StoreForward_SaveFile', True)
        self.blocks_file_sink_0_0.set_unbuffered(False)
        self.blocks_file_sink_0 = blocks.file_sink(gr.sizeof_gr_complex*1, '/home/pi/SDRcontrol/Files/StoreForward_file', False)
        self.blocks_file_sink_0.set_unbuffered(False)
        self.analog_pwr_squelch_xx_0 = analog.pwr_squelch_cc(rx_thres, 1e-4, 0, True)
        self.analog_nbfm_tx_0 = analog.nbfm_tx(
            audio_rate=audio_rate,
            quad_rate=audio_rate * 2,
            tau=75e-6,
            max_dev=5e3,
            fh=-1.0,
            )
        self.analog_agc_xx_0 = analog.agc_cc(1e-4, 1, 1.0)
        self.analog_agc_xx_0.set_max_gain(100000)

        ##################################################
        # Connections
        ##################################################
        self.connect((self.analog_agc_xx_0, 0), (self.blocks_file_sink_0, 0))
        self.connect((self.analog_agc_xx_0, 0), (self.blocks_file_sink_0_0, 0))
        self.connect((self.analog_nbfm_tx_0, 0), (self.rational_resampler_xxx_0_0, 0))
        self.connect((self.analog_pwr_squelch_xx_0, 0), (self.analog_agc_xx_0, 0))
        self.connect((self.blocks_wavfile_source_0, 0), (self.analog_nbfm_tx_0, 0))
        self.connect((self.low_pass_filter_0, 0), (self.analog_pwr_squelch_xx_0, 0))
        self.connect((self.rational_resampler_xxx_0_0, 0), (self.uhd_usrp_sink_0_0, 0))
        self.connect((self.uhd_usrp_source_0, 0), (self.low_pass_filter_0, 0))

    def get_tx_gain(self):
        return self.tx_gain

    def set_tx_gain(self, tx_gain):
        self.tx_gain = tx_gain
        self.uhd_usrp_sink_0_0.set_gain(self.tx_gain, 0)
```

```
    def get_tx_freq(self):
        return self.tx_freq

    def set_tx_freq(self, tx_freq):
        self.tx_freq = tx_freq
        self.uhd_usrp_sink_0_0.set_center_freq(self.tx_freq, 0)

    def get_samp_rate(self):
        return self.samp_rate

    def set_samp_rate(self, samp_rate):
        self.samp_rate = samp_rate
        self.uhd_usrp_source_0.set_samp_rate(self.samp_rate)
        self.uhd_usrp_sink_0_0.set_samp_rate(self.samp_rate)
        self.low_pass_filter_0.set_taps(firdes.low_pass(1, self.samp_rate, 5e3, 500, firdes.WIN_HAMMING,
6.76))

    def get_rx_thres(self):
        return self.rx_thres

    def set_rx_thres(self, rx_thres):
        self.rx_thres = rx_thres
        self.analog_pwr_squelch_xx_0.set_threshold(self.rx_thres)

    def get_rx_gain(self):
        return self.rx_gain

    def set_rx_gain(self, rx_gain):
        self.rx_gain = rx_gain
        self.uhd_usrp_source_0.set_gain(self.rx_gain, 0)


    def get_rx_freq(self):
        return self.rx_freq

    def set_rx_freq(self, rx_freq):
        self.rx_freq = rx_freq
        self.uhd_usrp_source_0.set_center_freq(self.rx_freq, 0)

    def get_audio_rate(self):
        return self.audio_rate

    def set_audio_rate(self, audio_rate):
        self.audio_rate = audio_rate


def main(top_block_cls=saf_rx, options=None):

    tb = top_block_cls()
    tb.start()
    tb.wait()
```

```
if __name__ == '__main__':
   main()
```

D. TRANSMIT PYTHON SCRIPT (SAF_TX.PY)[107]

```
#!/usr/bin/env python2
# -*- coding: utf-8 -*-
##################################################
# GNU Radio Python Flow Graph
# Title: Saf Tx
# Generated: Wed Feb 28 14:10:41 2018
##################################################

from gnuradio import blocks
from gnuradio import eng_notation
from gnuradio import gr
from gnuradio import uhd
from gnuradio.eng_option import eng_option
from gnuradio.filter import firdes
from optparse import OptionParser
import time

DEFAULT_PARAMS = [145525000, 147550000, -10, 80, -75]

class saf_tx(gr.top_block):

   def __init__(self, params=DEFAULT_PARAMS):
      gr.top_block.__init__(self, "Store and Forward TX")

      ##################################################
      # Variables
      ##################################################
      self.tx_freq = tx_freq = params[1]
      self.tx_gain = tx_gain = params[3]

      self.samp_rate = samp_rate = 88000

      ##################################################
      # Blocks
      ##################################################
      self.uhd_usrp_sink_0 = uhd.usrp_sink(
            ",".join(('serial=312D572', "")),
            uhd.stream_args(
                        cpu_format="fc32",
                        channels=range(1),
            ),
      )
      self.uhd_usrp_sink_0.set_samp_rate(samp_rate)
      self.uhd_usrp_sink_0.set_center_freq(tx_freq, 0)
```

---

[107] Koeppen.

```
        self.uhd_usrp_sink_0.set_gain(tx_gain, 0)
        self.uhd_usrp_sink_0.set_antenna('TX/RX', 0)
        self.uhd_usrp_sink_0.set_bandwidth(10e3, 0)
        self.blocks_file_source_0 = blocks.file_source(gr.sizeof_gr_complex*1, '/home/pi/SDRcontrol/Files/
StoreForward_file', False)

        ##################################################
        # Connections
        ##################################################
        self.connect((self.blocks_file_source_0, 0), (self.uhd_usrp_sink_0, 0))

    def get_tx_gain(self):
        return self.tx_gain

    def set_tx_gain(self, tx_gain):
        self.tx_gain = tx_gain
        self.uhd_usrp_sink_0.set_gain(self.tx_gain, 0)

        self.uhd_usrp_sink_0.set_gain(self.tx_gain, 1)


    def get_tx_freq(self):
        return self.tx_freq

    def set_tx_freq(self, tx_freq):
        self.tx_freq = tx_freq
        self.uhd_usrp_sink_0.set_center_freq(self.tx_freq, 0)
        self.uhd_usrp_sink_0.set_center_freq(self.tx_freq, 1)

    def get_samp_rate(self):
        return self.samp_rate

    def set_samp_rate(self, samp_rate):
        self.samp_rate = samp_rate
        self.uhd_usrp_sink_0.set_samp_rate(self.samp_rate)


def main(top_block_cls=saf_tx, options=None):

    tb = top_block_cls()
    tb.start()
    tb.wait()

if __name__ == '__main__':
    main()
```

E. UART PYTHON SCRIPT (UART.PY)[108]

```
from __future__ import print_function
```

---

[108] Koeppen.

```
import threading
import time
import Queue
import serial
import sys
import time


class UART(object):
    def __init__(self, port, baudrate, eol='\x0A'):
        self.eol = eol
        self.buff = ""
        self.ser = serial.Serial(port=port, baudrate=baudrate, bytesize=8, parity='N', stopbits=1,
timeout=0, xonxoff=0, rtscts=0)
        self.ser.flushInput()
        self.ser.flushOutput()
        self.queue = Queue.Queue()
        self.thread = threading.Thread(target=self.enqueue_output, args=(self.queue,))
        self.thread.daemon = True
        self.thread.start()



    def enqueue_output(self, queue):
        # run forever, looking for a line and putting it in the queue
        while True:
            queue.put(self.build_line())                # this blocks!



    def build_line(self):
        while True:
            n = self.ser.inWaiting()
            if n == 0:
                time.sleep(0.05)
                continue
            data = self.ser.read(n)
            self.buff = self.buff + data
            i = self.buff.find(self.eol)
            if i >= 0:
                s = self.buff[:i]
                self.buff = self.buff[i+len(self.eol):]
                return s



    def get_line(self,  timeout=0.01):
        try:
            line = self.queue.get(timeout=timeout)
        except Queue.Empty:
            return None
        else:
            return line



    def write(self, data, send_eol=False):
        if send_eol:
```

```
            self.ser.write(data+self.eol)
        else:
            self.ser.write(data)



    def write_print(self, data, send_eol=False):
        print(data)
        self.write(data+'\r\n', send_eol)



if __name__ == "__main__":
    # this only happens when this module is NOT imported, but is run as 'sudo python radio.py'
    link = UART("/dev/ttyAMA0", 9600) #changed from tty## to ttyAMA0
#   radio = RADIO("COM6", 9600, eol='@@@')

    count = 0
    while True:
        no_msg = True

        msg = link.get_line()               # this is NOT blocking!
        if msg != None:
            no_msg = False
            tstr = time.strftime('%Y-%m-%d %H:%M:%S')
            t = time.time()
            print("%1.3f: %s" %(t, msg))
            link.write('%d'%count)
            count += 1

        if no_msg:
```

APPENDIX C. PAYLOAD AND BUS SCHEMATICS

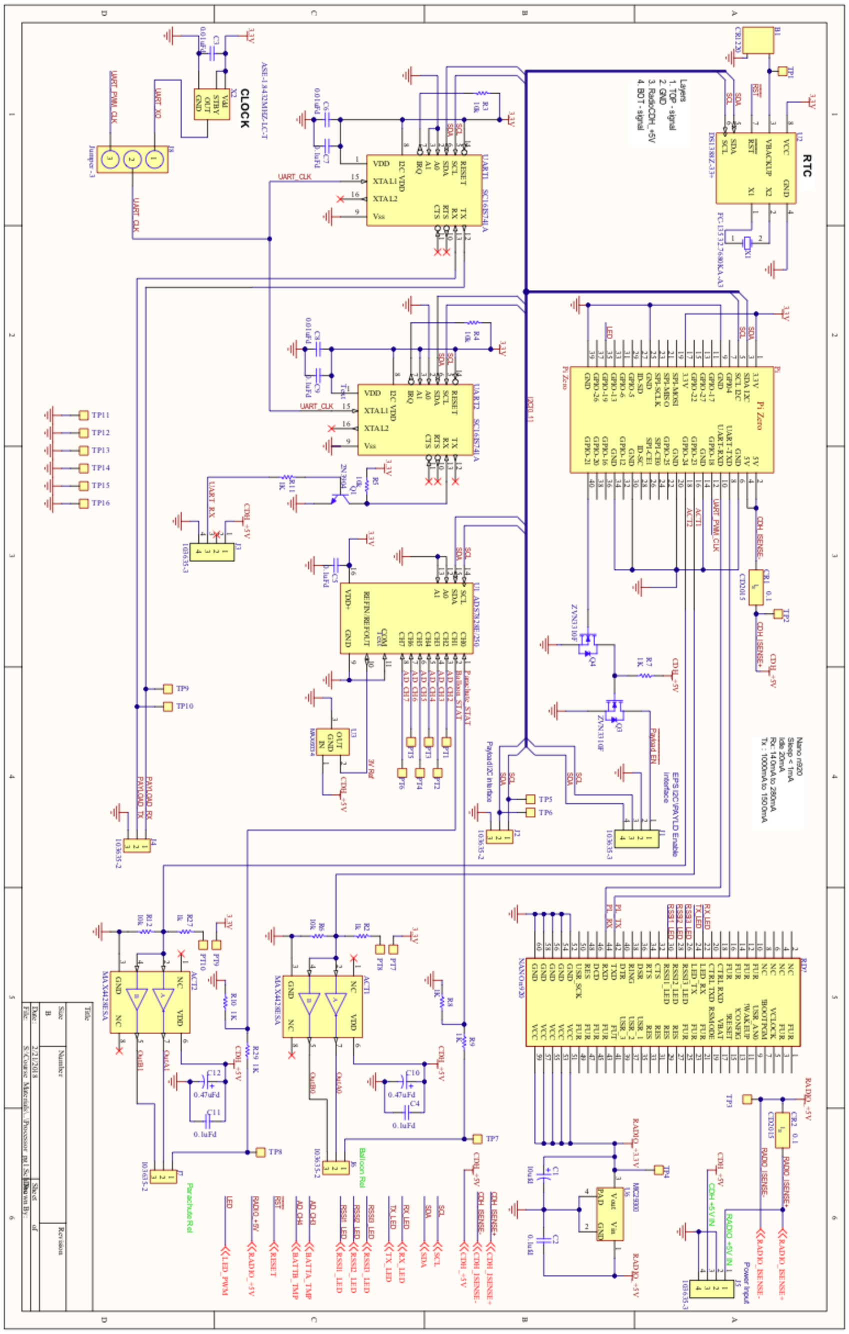

Figure 48. Payload and Bus Schematic Page 1[109]

---

[109] Source: Ronald Phelps, email message to author, February 21, 2018.

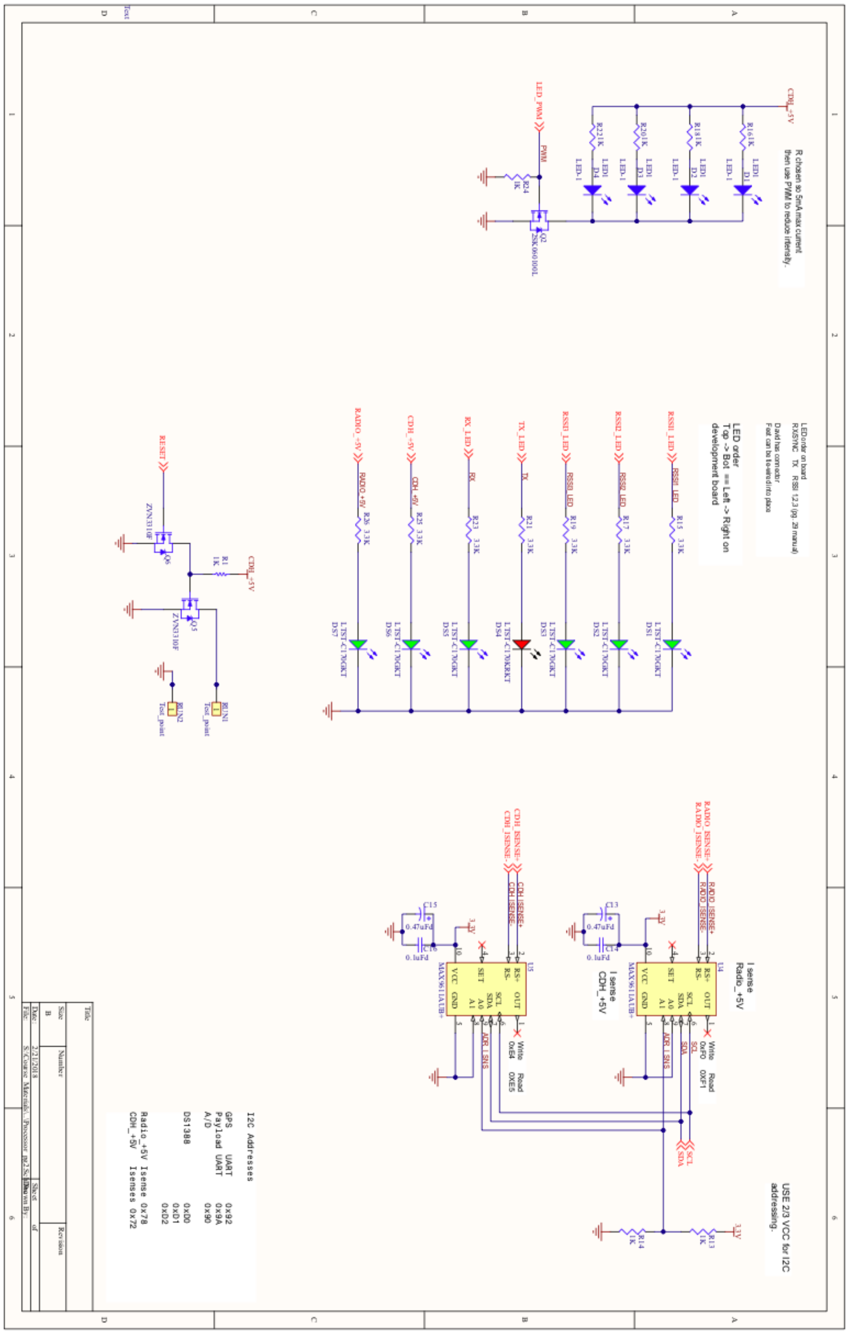

Figure 49. Payload and Bus Schematic Page 2[110]

---

[110] Source: Phelps.

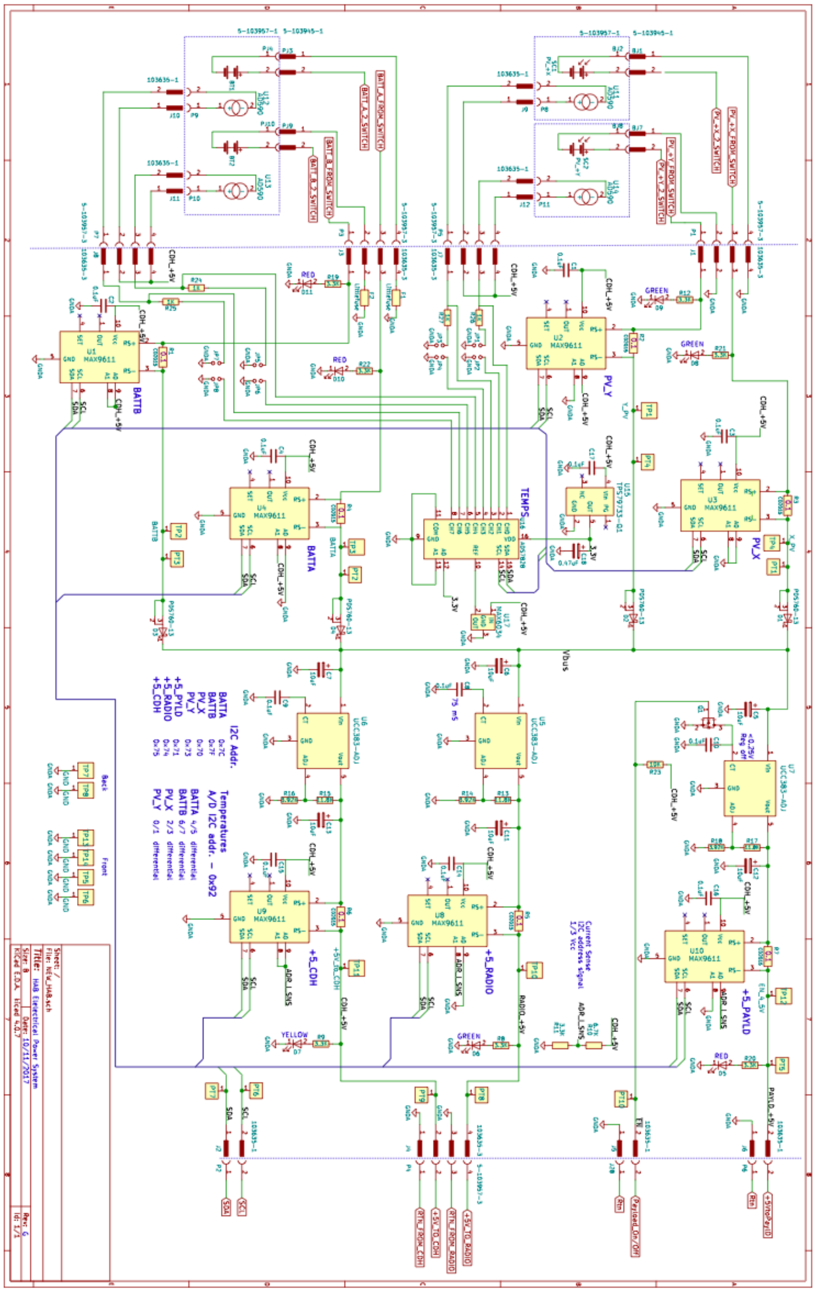

Figure 50. Bus Electrical Power System Schematic[111]

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[111] Source: Phelps.

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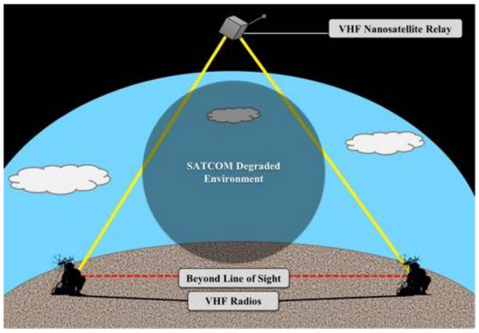
APPENDIX D. THESIS POSTER

Critical Vulnerabilities in the Space Domain: Using Nanosatellites as an Alternative to Traditional Satellite Architectures

Naval
Postgraduate
School

Today, the U.S. military relies upon space-based technology for a myriad of functions from precision navigation to satellite communication. However, the United States is highly reliant upon this technology and thus increasingly vulnerable with potential adversaries cultivating the ability to attack America's space-based infrastructure. As a safeguard against such vulnerabilities, nanosatellites, cube satellites (CubeSats), and other small satellites are a low-cost and expedient solution to build redundancy and resiliency, offering unique options as an alternative to traditional satellite systems. To support this hypothesis, this thesis provides such an alternative: A Software Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube). SAVIOR-Cube is a software-defined radio (SDR) payload operating as a very high frequency (VHF) relay via a nanosatellite in low Earth orbit. This thesis demonstrates the depth of the problem a payload such as SAVIOR-Cube could solve, the applicability of nanosatellite solutions to U.S. forces today, and the results of extensive testing, culminating with a proof of concept high-altitude balloon (HAB) flight.

The Software-Assisted VHF Information Overhead Relay-CubeSat (SAVIOR-Cube)



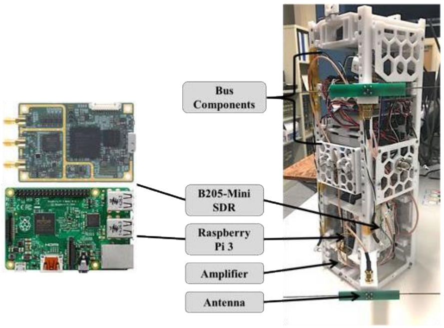
SAVIOR-Cube Concept of Operations

Method and Approach

- Illuminate the depth of the U.S. military's reliance on space-based technology.
- Understand the critical vulnerabilities this dependence creates.
- Research potential nanosatellite solutions.
- Build a model constellation and concept of operations for a VHF nanosatellite relay.
- Using Ettus Corporation's B205-Mini SDR, develop a prototype payload.
- Iteratively test the payload in and out of the laboratory environment.
- Integrate the payload into a CubeSat and launch it via a HAB to replicate a near-space environment.

Testing and Results

- Survived temperatures ranging from 70^{o}C to -45^{o}C during thermal-vacuum chamber testing.
- Endured vibration testing across all three axes via extensive vibration-table testing.
- Successfully communicated across a simulated distance of 100 km during line of sight field tests.
- Functioned for 30 minutes at altitude during HAB flight, sending and receiving 14 separate transmissions.
- Reached a maximum altitude of 21 km (70,000 ft).
- Communicated over a maximum slant-range of 36 km.
- A successful proof of concept test and design for a VHF nanosatellite relay.



SAVIOR-Cube

SAVIOR-Cube enables non-SATCOM capable VHF radios in a degraded space environment—a solution to a critical vulnerability

Thesis Author: Major Philip Swintek, Student, Defense Analysis / Space Systems Operations
Thesis Advisors: Dr. Leo Blanken, Associate Professor, Department of Defense Analysis;
Dr. Wenschel Lan, Senior Lecturer, Space Systems Academic Group
Lieutenant Colonel Scott Moore, Military Assistant Professor, Space Systems Academic Group
Thesis Sponsor: Space and Naval Warfare Systems Center-Pacific

Figure 51. Thesis Poster

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