DEVELOPMENT OF A DUAL-BAND RADIO REPEATER TO BE CARRIED BY A FIXED-WING SMALL UNMANNED AERIAL SYSTEMS

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ABSTRACT

Development of a Dual-Band Radio Repeater to be Carried by a Fixed-Wing Small Unmanned Aerial System

Carl Recine

With the continued rise in wildfires in California, and around the world, technological advancements are needed to improve the safety and effectiveness of wildland firefighters. One area that provides an opportunity for such development is the deployment of temporary communications networks. Currently, radio repeaters are set up on mountain tops in the response area; such repeaters do not provide flexibility once installed, still have blind spots, and require the time of valuable assets like helicopters to install.

This thesis will establish the feasibility of airborne radio repeaters for wildland firefighting. In order to successfully demonstrate the feasibility of such an airborne system, the resulting system should be rapidly deployable, improve communications range and reliability, and be compatible with existing regulations and guidelines. The design process for the repeater payload is described, as well as important troubleshooting steps. The resulting product is then compared to the initial requirements through testing and observation.

Although audio filtering provided by off-the-shelf handheld radios prevented the repeater from functioning as intended, the proposed 2m/70cm dual-band digital communications relay was capable of being carried by the Altavian Nova and was able to successfully demonstrate the feasibility of such a system. As such it will be an important contribution to communications needed for fighting future wildfires.

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NOMENCLATURE

AM – Amplitude Modulation

DMR – Digital Mobile Radio

FAA – Federal Aviation Administration

FCC – Federal Communications Commission

FM – Frequency Modulated

GCS – Ground Control Station

LiPo – Lithium Polymer

MCU – Microcontroller Unit

MMDVM – Multi-Mode Digital Voice Modem

NIFC – National Interagency Fire Center

NIRSC – National Incident Radio Support Cache

NWCG – National Wildfire Coordinating Group

PM – Phase Modulated

RaDAR – Rapidly Deployable Airborne Repeater

sUAS – Small Unmanned Aerial System

TFR – Temporary Flight Restriction

UAV – Unmanned Aerial Vehicle

UHF – Ultra High Frequency

VHF – Very High Frequency

1 INTRODUCTION

1.1 Motivation

In California, and around the world, the frequency and severity of wildfires has been on the rise in recent years. In fact, according to a joint effort between NASA, Idaho State University, and the Bureau of Land Management, over half of the fires that occurred on the West Coast between 1950 and 2017 have happened since 2000. [9]

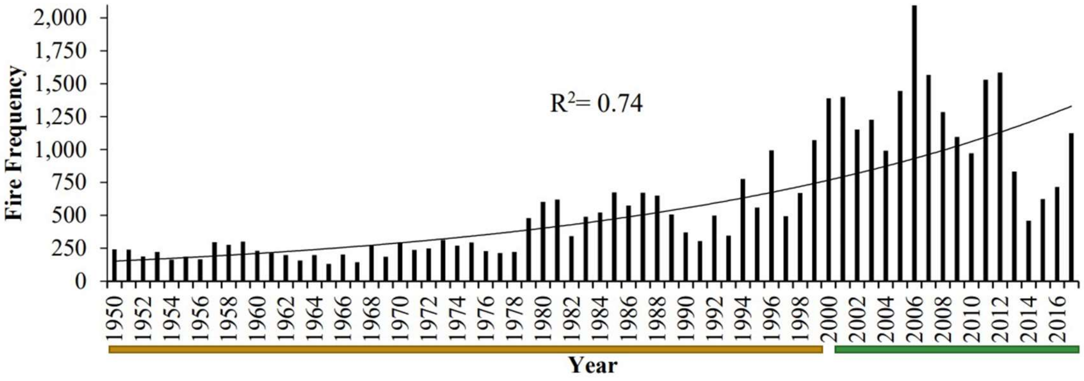


Figure 1. Fire frequency per year generated by counts of fire occurrence representing all documented fires from 1950 to 2017 across 11 western states. [9]

Not only are fires becoming more common, but they are also becoming more severe; in fact, 6 of the top 7 largest wildfires in California history (since they started being recorded in 1932, by acreage burned) have occurred since I finished my undergrad in June 2020. [5]

As fire departments, such as Cal Fire, seek to fight these fires, they need reliable communications networks. Fires often start in hard-to-reach places with inhospitable terrain. This means that cell service is often lacking, and radio reception may be inhibited by mountains or other obstructions. Currently, fire departments will set up temporary repeaters on mountain ridges in the response area to extend communications to both sides of the ridge. This is problematic as it requires a helicopter to fly in the components to be assembled on top of the mountain, and the equipment is staged at only fifteen National Interagency Support Caches across the nation.[23] In practice, the logistics required to get such a repeater in place, built, and operational means that the network will not be operational for several days after the initial request.[13] With the rapid rate of growth of recent fires, such as the August Complex Fire that grew an average of over 21,000 acres per day for the first month,[7] a few days’ delay in setting up a communications network can have a significant impact on firefighters' ability to contain the blaze quickly.

Table 1. Top 5 Most Destructive Fires in California History (By Structures Destroyed) [6]

FIRE NAME (CAUSE)	Date	County	Acres	Structures	Deaths
Camp Fire (Powerlines)	November 2018	Butte	153,336	18,804	85
Tubbs (Electrical)	October 2017	Napa & Sonoma	36,807	5,636	22
Tunnel – Oakland Hills (Rekindle)	October 1991	Alameda	1,600	2,900	25
Cedar (Human Related)	October 2003	San Diego	273,246	2,820	15
North Complex (Lightning)	August 2020	Butte, Plumas, & Yuba	318,935	2,352	15

In addition to pure wildland fires, fires that threaten the Wildland Urban Interface are becoming more prevalent. For example, the Camp Fire of November 2018 destroyed 18,804 structures and burned 153,336 acres, making it the most destructive fire in California's history.[6] Of the top 20 most destructive fires in California since 1932, 18 have occurred in the past 20 years.[5]

The wildland-urban interface offers a unique challenge for communications networks as homes, other structures, and electrical equipment can create obstructions and interference to first responders' radio equipment.

This can be a particularly difficult problem to address, as there may not be a nearby ridge that a temporary repeater can be set up on.

An effective and reliable communications network is valuable to fire departments not only for the utility benefit it provides in putting out fires, but it also serves as an essential component of their safety. A study titled "Firefighter Safety And Radio Communication" was presented in a 2003 edition of *Fire Engineering*; it focused on the connection between communications breakdown and firefighter fatalities. Although it mostly focused on structure fires, it did also discuss a few fatal wildfires and fires in the wildland-urban interface. Two of the fires it mentioned in the early 1990s specifically listed ineffective radio networks as a major contributing factor in the fatalities. In 1990, six firefighters died after becoming trapped in a canyon while fighting a wildfire in Arizona. Because they could not be reached over the radio, they were unaware of the evolving fire conditions. Similarly, a fire in Oakland in 1991 killed 25 people including an Oakland Fire Department Battalion Chief. Evidence discovered after the fact showed that the chief had been calling for help for approximately half an hour before he died. He was unable to contact the Operations Chief for help due to a breakdown in the radio network. [41]

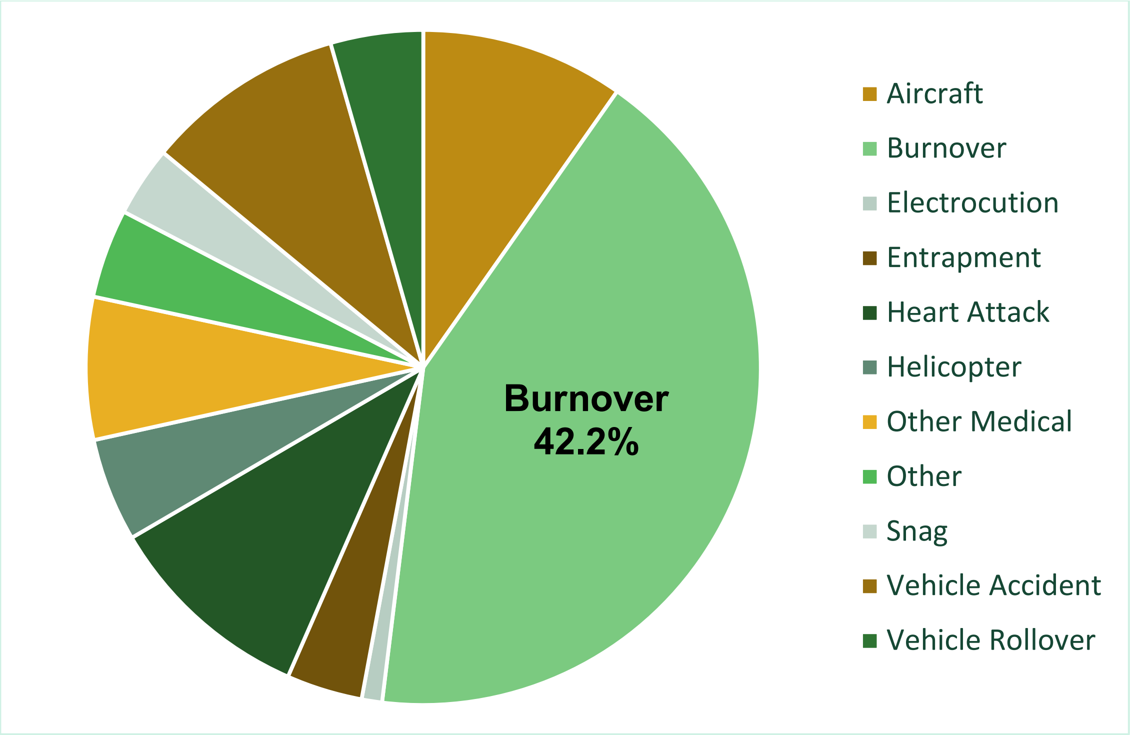


Figure 2. Cause of Firefighter Fatalities (1910-2016) [24]

Additionally, the National Interagency Fire Center (NIFC) has tracked the cause of death for all wildland firefighter fatalities from 1910-2016 [24] and has sorted them into various categories. Although radio communications are not listed as the actual cause of death in any of the cases, poor communications may have been a contributing factor for many of the deaths in the burn over, aircraft collision, or medical emergency categories.

One wildland firefighter that I consulted on this project said that it was very common to lose radio contact with incident commanders when working fires. One time in particular that he recalled involved his crew being caught in a box canyon when the fire came in over one of the ridges. They had been unable to communicate with other crews in the area while in the canyon and had to use runners to get information back to the command center. This led to them being surprised by the fire, because it was difficult to get information about the movement and status of the fire while in the radio dead-zone. When I described what the goal of my thesis was to him, he was incredibly excited about the possibility of a portable, rapidly deployable repeater. [33]

1.2 Previous Work

To explore an option to meet the need for better communication, NASA Ames, California State University Monterey Bay, and the US Forest Service collaborated on a project to deploy an airborne repeater on a NASA Ames' APV-3 UAV. The purpose of this project was to test a rapidly deployable radio repeater over controlled burns. They concluded that using unmanned aircraft offered significant benefits over temporary mountain-top units, but that further development was needed. [13] Their project has two notable areas for improvement: the radios chosen for the payload and the vehicle itself. First, the radio equipment carried by the APV-3 was analog, not digital. The NASA study took place in 2006 when analog radios were commonplace, but in February of 2020, the NIFC released guidelines seeking to phase out analog-only radios and begin replacing them with digital radios that use the P25 standard. [20]

Second, the APV-3 was a relatively large unmanned aerial vehicle with a gas engine. During flight tests, the vehicle was flown from the runway at Fort Hunter Liggett to a nearby controlled burn. Requiring additional facilities and infrastructure to operate a gas-powered UAV that takes off from a runway reduces the effectiveness and potentially increases the response time of the vehicle.

1.3 Why Now

Advances in technology since 2006 in the miniaturization of electronic flight controls, increased efficiency of electric motors, and increased energy density in batteries have enabled the development of electric aircraft that can perform a wide variety of missions. An example of one such sUAS is the Altavian Nova, a commercially available and fully autonomous aircraft built from durable composites that is intended to function in harsh environments, including water landings. [1]

The APV-3 aircraft that was used in the 2006 NASA study had an empty weight of 13.6 kg and a single segment wing with a span of 3.66 m.[8] The Nova, on the other hand, has an empty weight of only 4.4 kg and a wingspan of 2.77 m.[34] However, the Nova's wing is composed of 3 segments and most of the pre-flight procedures can be conducted with only the center section of the wing installed. With just the center section, the wingspan is only 1.45 m, making it manageable for a team of two to set up the aircraft; one to run the command-and-control software, and one to manipulate the vehicle.

Figure 3. Hand Launching the Nova [4]

A key feature of many electric aircraft, such as the Nova, is that they can be hand launched from nearly anywhere. Additionally, spare batteries can be recharged in a firetruck or other command vehicle while the UAV is in flight; reducing the time it takes to get the vehicle back in the air by quickly swapping the quick-release batteries. Electric aircraft are also less sensitive to smoke ingestion than combustion engines, making them more suitable for low altitude operations over wildfires.

Although temporary flight restrictions are typically enforced over wildfires for the safety of tanker pilots and hand crews, guidelines exist for exemptions to these TFRs. The Interagency Fire Unmanned Aircraft Systems Subcommittee of the National Wildfire Coordinating Group maintains the NWCG Standards for Fire

Unmanned Aircraft Systems Operations which standardize the processes and procedures for interagency use of UAVs at a federal level.[26] Agencies, such as Cal Fire, can operate unmanned aircraft over wildfires under FAA Part 107, Special Government Interest Waivers, or a Certificate of Authorization. Although unmanned aircraft are generally required to carry Mode C transponders to prevent conflict with manned aircraft, with the consent of the aerial supervisor, agency UAVs are not required to carry Mode C transponders while flying over the wildfire. [26] Together, these guidelines allow for, and even encourage the development of small, unmanned aircraft for the purpose of aiding wildland firefighters.

This is important, now more than ever, because with the recent rise - which is expected to continue - in the frequency and size of wildfires, wildland fire agencies are required to deploy more assets to contain these fires. This causes greater risk of injury and fatality because of the increased load on existing communications networks, the expanded range over which the networks must cover, and the close proximity of multiple aircraft, ground vehicles, and firefighters. Additionally, certain technological developments make the proposed airborne radio repeater more feasible and beneficial. Advancements in battery technology and autonomous vehicle autopilots have increased the flight time, decreased the size and weight, and allowed for more control of the vehicle during a mission. The recent requirement from the NIFC to begin the transition from analog-only radios to digital-capable systems contributes to the sense of urgency of taking this next step.

2 PROJECT DEFINITION

Current technology and standard practices for establishing communications networks at large wildfires are no longer adequate and need further development to promote the safety of first responders and increase their effectiveness. As the trend of increasing size and destructiveness of wildfires is expected to continue, and with the recent growth of communities in the wildland-urban interface, more and more assets are required to address wildfires. The increased load on existing communications networks and close proximity of so many ground units, air tankers, and bulldozers will lead to greater risks for first responders and may in turn increase the number of fatalities at each event. An overhaul of the communications infrastructure and operational procedures that takes advantage of modern technology and the latest rules and regulations would be beneficial for improving firefighter safety, provide more adaptability during rapidly-changing situations, and assist with containing wildfires more rapidly. Development and evaluation of the feasibility of the proposed 2m/70cm dual-band digital communications relay capable of being carried by hand-launched UAV, such as an Altavian Nova, will be an important contribution to communications needed for fighting future wildfires.

This thesis will seek to evaluate the feasibility of an airborne repeater small enough and light enough to be carried by a small, unmanned aircraft. RaDAR, the Rapidly Deployable Airborne Repeater, is intended to be a proof of concept for an airborne repeater. Using primarily off-the-shelf components, it demonstrates that a rapidly-deployable communications network based on a radio repeater could be carried by a small, unmanned aircraft while meeting FAA and FCC requirements. Such a system that cuts down on response time, improves the range and reliability of communications networks, and provides greater flexibility would increase the safety and effectiveness of wildland firefighters.

In order to successfully demonstrate the feasibility of such an airborne system, the resulting system should be able to fulfill the following requirements:

- Be rapidly deployable
  - Cutting down on response time could aid in containing fires before they grow out of control.
  - RaDAR must not require specialized tools or facilities.
- Be carried by a hand-launched electric UAV
  - Hand-launched vehicles can be flown from nearly anywhere.
  - RaDAR must have flexibility for launch and recovery sites.
- Improve communications range and reliability
  - Improved coverage reduces the risk of important messages not getting through in a timely manner.
  - RaDAR must not be detrimental to the communications network.
- Be compliant with FAA and FCC regulations

    - Operating within current legal boundaries enables immediate implementation.
    - RaDAR must be able to operate without requiring legislative changes.
- Be compatible with Cal Fire and other wildland fire agencies
    - Organizations are more likely to adopt small changes that do not significantly alter the way they operate.
    - RaDAR must not require significant modifications to standard practices.

If an airborne radio repeater is able to meet the preceding requirements, it should result in a reduced risk of fatalities and injuries for wildland firefighters.

Because RaDAR is a proof of concept intended to prove the feasibility of designing such a system, it should either be able to satisfy the performance requirements or must identify a path towards the resolution of any unsatisfied requirements.

3 METHODOLOGY

3.1 Design

The Altavian Nova was selected as the sUAS for this project because of its simple assembly and pre-flight checks, durable construction, easy controls, commercial availability, and relatively larger internal payload bay. These features make it a good candidate aircraft for use in wildland firefighting. Designing the repeater to fit in the Nova's payload bay ensures that it can be flown in the required situations.

The first step in the design process was to measure and model the volume available in the Nova payload bay to be sure the repeater could be carried by the sUAS. This, coupled with the payload weight limit of the Nova, limited the available components.

The first and most important components are the two radios for transmitting and receiving. To meet the stated objectives of the repeater as a whole, the radios must satisfy several requirements. The radios must be dual band and capable of UHF and VHF in order to maintain compatibility with current mountain-top units and handheld radios. 10 Watts of transmission power is needed to match the power output of current repeaters. [21] If testing shows that the size, weight, or power of a 10 W radio is impractical, the transmission power could be reduced to 5W. An important feature that would enable the radios to be easily reprogrammed in the field, without the need for a computer or special cable, is a keypad that enables front panel programming. In order to monitor both

UHF and VHF simultaneously, the radios should have dual watch functionality. The repeater must fit inside a 119 mm x 101 mm x 192 mm volume in order to fit inside the Nova’s payload insert. This means that each radio must take up less than half of the available space, and no single dimension may exceed the limitations.

After comparing many different options including both mobiles and handhelds, the handheld GA-510 was selected; most mobiles were too large and/or too heavy for the Nova and most handhelds were not capable of the standard 10W transmission of current mountaintop units. An analog radio was selected, because radio waves are analog, even if the data they are carrying is digital.

The next step was finding a repeater controller and duplexer that would fit in the payload bay. There are a variety of repeater controllers that would work, but the Repeater Builder STM32_DVM [43] was selected for several reasons. This repeater controller is based on a Raspberry Pi and is designed to convert two analog radios into a digital repeater. In addition to supporting P25, the repeater controller is also capable of running in analog FM and DMR (Digital Mobile Radio) modes as well. [43] This would provide flexibility for integrating with other agencies or organizations that are not using P25 currently. It also comes with a protective case and can power the Raspberry Pi, eliminating the need for additional power cables and voltage converters. Very few duplexers were small enough to fit in the payload bay, because they were intended to be used with fixed repeaters transmitting at a much higher power, up to 400 W. However, there are some that are designed for use with a 10 W, backpack-portable repeater, and that are small enough to fit in the Nova's payload bay. [42]

Because the radios run on 7.4 V batteries, and the repeater controller can convert anything from as high as 24 V down to the 5 V it needs, a two-cell battery was selected for the repeater controller so that it would also be capable of running the radios.

Table 2. Estimated Current Draw

	Estimated Current Draw
Transmit Radio:	1400 mA [32]
Receive Radio:	380 mA [32]
Repeater Controller:	520 mA [36]
Total:	2300 mA

Using published values for the current required to run each radio and double the current drawn by a Raspberry Pi 3B for the Pi/MMDVM combo, the approximate capacity of battery needed to operate the repeater was calculated. In order to run the repeater for 90 minutes, the battery must have a capacity of at least 3,450 mAh and be able to output 2.3 A continuously. LiPo batteries come in many shapes and sizes which meant that one could be chosen to maximize the capacity available in the remaining space. Additionally, a LiPo with a built-in case was chosen to improve the durability of the payload in the event of a crash.

Once all of the components were modeled in SolidWorks, they could be positioned inside the payload insert to confirm that everything would fit and to experiment with different configurations. This reduced the likelihood that multiple iterations of the payload insert would need to be 3D printed.

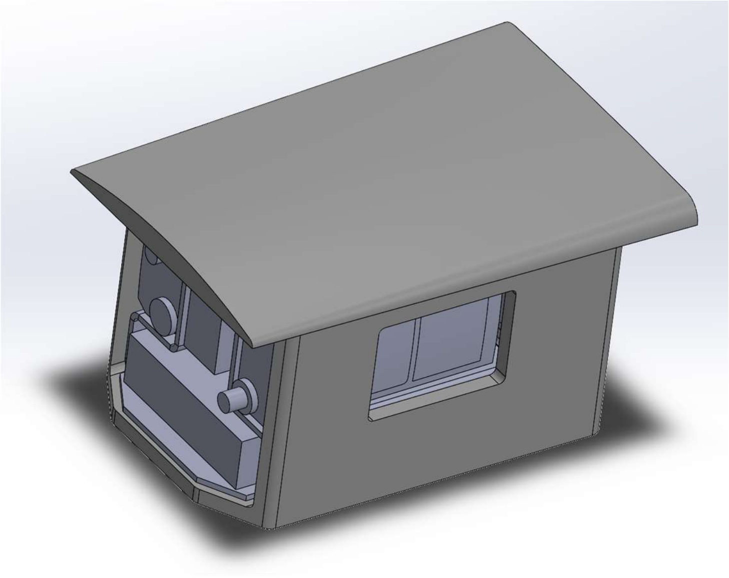


Figure 4. All controls of the payload are accessible while assembled [38]

While laying out the components, it was important that all of the controls of the payload be easily accessible in case changes needed to be made in the field. The full keypad and display of both radios are accessible when the payload is removed from the Nova but are protected once it is installed.

Another design decision was to try to balance the payload as symmetrically as possible to avoid detrimental impacts on the flight qualities of the vehicle. This ended up being straightforward once the radios were placed such that their keypads were accessible and the duplexer in the only place large enough to fit it.

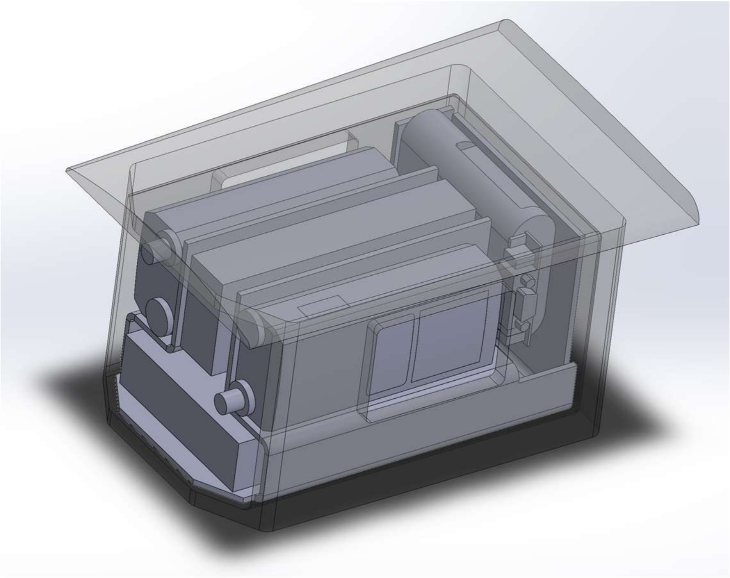


Figure 5. A cutaway showing the distribution of components in the payload [38]

The last component that needed to be designed was something to hold all of the components securely, without being too heavy. Several options were considered, such as 3D-printed plastic, folded sheet metal, and high-density foam. Foam was rejected because it would insulate the components, which could cause the transmitting radio to overheat. 3D printing a tray would have required lots of support material that would have been hard to remove. Thin Aluminum sheet metal is easy to cut and bend, lightweight, and thermally conductive; therefore, a folded sheet metal tray was designed to hold all of the components securely. Aspects of Design for Manufacturability, including the limitations of tools, such as the finger brake, influenced the sheet metal design. During this process, SolidWorks' sheet metal tool was routinely used to visualize the steps for bending the tray to make sure that it could actually be manufactured practically.

As with all electronics, heat dissipation was an important consideration. One advantage of using aluminum for the equipment tray is that it acts as a heatsink for all of the heat-generating components. With some modifications to the tray and payload insert, a heat sink could even be added that would interface with the airstream while still maintaining a sealed payload. Because the repeater will be flown over wildfires, there will likely be significant quantities of particulates in the air. To protect the payload from smoke ingestion, the payload was designed to be sealed once it is inserted into the payload bay of the Nova. A channel was added to the underside of the payload insert's lid that could be filled with a flexible rubber or silicone seal; this would interface with a mating feature that is included in the Nova's payload bay and protect the payload from particulates or water.

3.2 Initial Build

The first step of the building process was to 3D print the payload insert. The insert could then be tested in order to check that it would be sturdy enough and to provide a reference for measuring the lengths needed for various cables. The payload insert was too big to print as a single piece in the 3D printer, so it had to be divided in half. This also served to minimize the amount of support structure that would be needed, but required a temporary jig be used to ensure that the two pieces would be properly aligned while gluing, once both pieces had finished printing.

The next step was fabricating a cable to connect the radios, battery, and repeater controller together. This cable is essentially the backbone of the system; it passes the audio from the speaker of the receiving radio to the repeater controller, audio from the repeater controller to the mic of the transmitting radio, and power from the battery to the repeater controller. With modification, it could also be used to power both of the radios in order to eliminate their dedicated batteries.

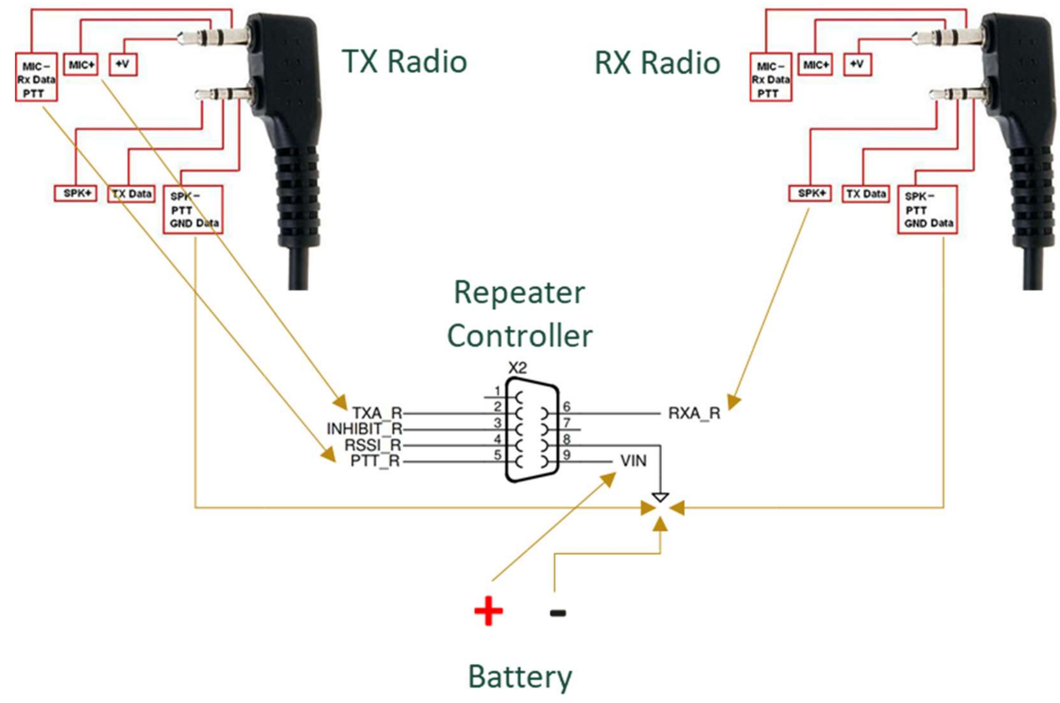


Figure 6. Wiring Diagram for Data Cable [28] [44]

The repeater controller was designed to be powered with a USB wall charger but had provisions for being powered through the DB-9 connector. This required disassembly of the controller and the addition of a small DC-DC converter to the MMDVM host board. The radios required minimal modifications initially, just the removal of the belt clip and converting the audio jack cover from permanently attached to quick release. All that was required for that was the disassembly of the radio and trimming the anchor of the cover. This enables the jacks to be protected when not in use but allows the cover to be removed when connecting the audio cables for ease of access.

Once the model of the sheet metal tray was completed, it was virtually unfolded and a vector file of the 2D shape was exported. Because the thinnest cutting tool available had a 3 mm diameter, a 1.5 mm offset was added to all of the external edges. This was then loaded into a 2.5 axis CNC router and cut. Lines were scored into the surface by the CNC machine to mark where the folds needed to be made. This allowed for a high degree of accuracy and eliminated the need to make difficult measurements on a partially folded workpiece.

3.3 Final Assembly

With all of the components in their final state, each piece was laid out in its position in the equipment tray and the locations for the needed mounting holes were marked. The holes were not included in the initial modeling and cutting of the equipment tray for two reasons: bending the sheet metal with the holes already cut can distort them or cause the metal to bend differently than intended, also it ensured that everything would fit together as expected and extra holes wouldn't need to be added later.

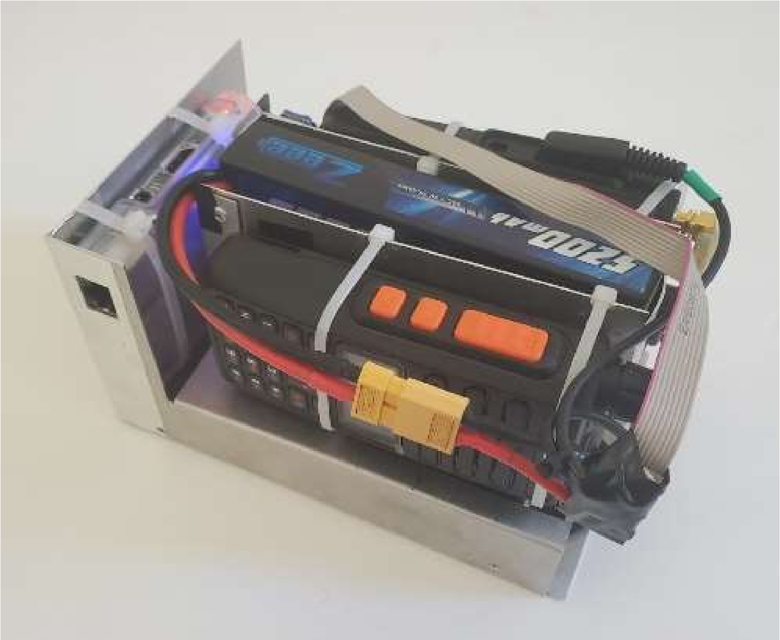


Figure 7. Fully Assembled Equipment Tray

The radios and repeated controller are held in place with zip-ties. These are able to securely hold the components in place and can easily be removed or replaced in the field if needed. The duplexer is screwed to the bottom of the equipment tray using its built-in feet and mounting holes. If the duplexer needs to be re-tuned for a different frequency pair, these screws can be removed with a pair of pliers and a screwdriver. The battery is held firmly in place with compressible foam to prevent movement and to protect the battery from being punctured by the sheet metal.

3.4 Antenna Design

Current mountain-top repeaters are dual band; they use a 440 MHz (UHF) link to connect to other repeaters and 150 MHz (VHF) to communicate with the handheld radios that firefighters carry. [21] In order to best integrate with current systems, the payload needed to be dual band. It was decided that although the repeater needed to be able to receive both 440 MHz and 150 MHz, it would be acceptable to only transmit on 150 MHz. Because the aircraft will be flying several hundred feet about any obstacles, it will likely be able to reach other mountain top units in a larger network with the VHF transmission. Each GA-510 can only transmit on one frequency at a time but is capable of monitoring two frequencies at once. This eliminates the need for a second radio which reduces the size and weight of the payload.

Figure 8. Receiving Radio Monitoring UHF and VHF

Another important aspect of the design phase was the design of a custom dual-band antenna. A semi-directional antenna would be preferable because there is no need to transmit any power upwards, as the UAV will be above all of the firefighters and mountain-top repeaters. However, most such antennas are quite large and heavy for 2-meter radios as they are typically used on vehicles or buildings where the size and weight are not an issue, this means a custom antenna would need to be designed. Fractal antennas address the size issue because the perimeter of the antenna can increase while the surface area it occupies remains constant. Using a code, written in MATLAB, the smallest area an antenna can fit in while satisfying requirements for side length and total perimeter could be found. [J]

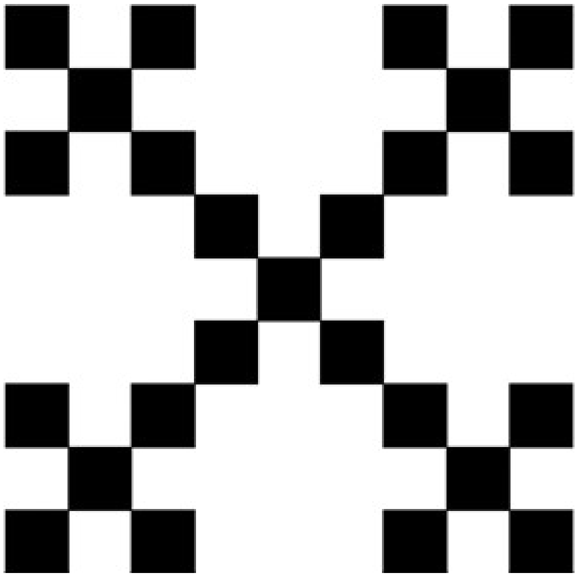


Figure 9. A Second Iteration Viscek Snowflake [19]

For a Viscek Snowflake, one of the most common fractal antennas used in cellphones, a second iteration with a side length of 2 cm could fit a square a little over 7 in wide, which is small enough to fit on the underside of the Nova's wing.

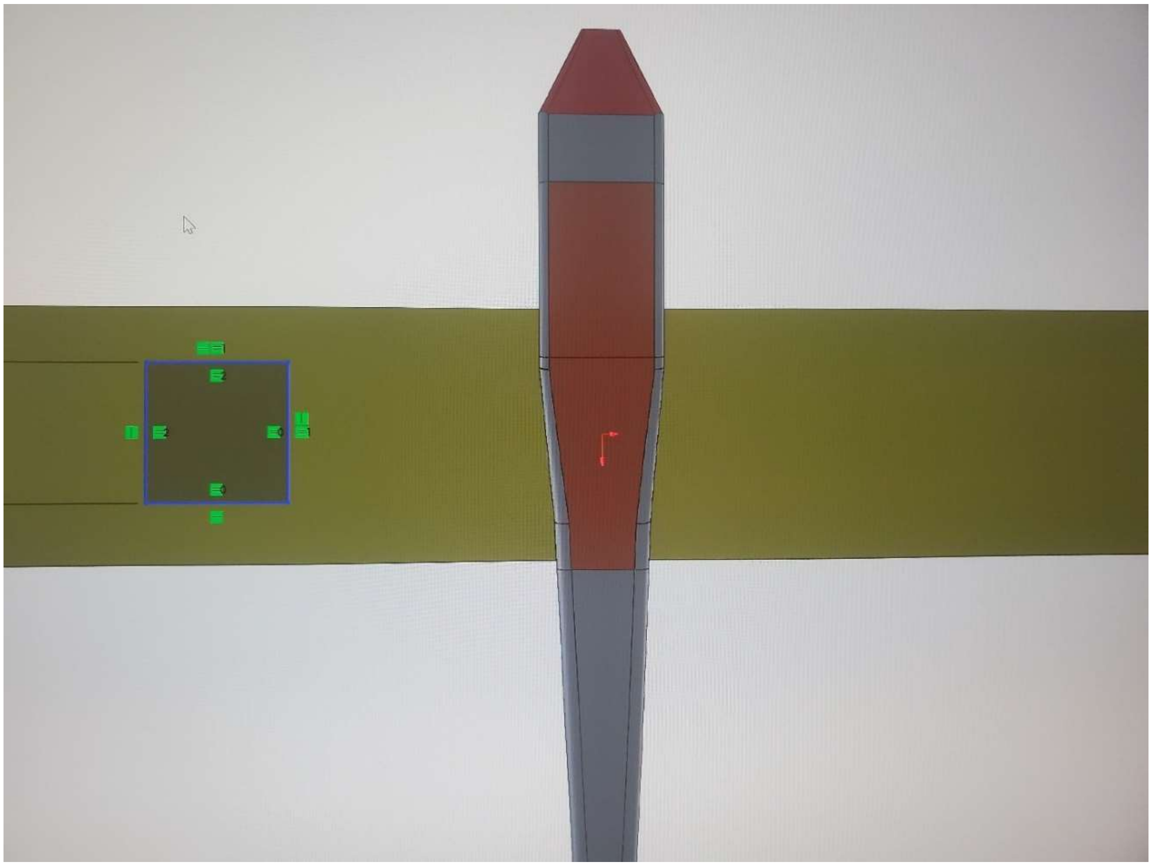


Figure 10. Size of Antenna Relative to Nova [38]

This provides a total perimeter of 2 meters and should also work for the 70-centimeter band as well.

3.5 Tuning the Duplexer

A duplexer is used in radio repeaters to isolate the transmitting and receiving radios. Transmitters emit power several orders of magnitude greater than the sensitivity of receivers. For example, the GA-510 is capable of transmitting 10 W or +40 dBm, while the receiver sensitivity is listed at 3.92×10^{-16} W or -124 dBm. [32] This means that the duplexer needs to provide 164 dB of isolation. Without the duplexer, the signal from the transmitting radio would desensitize or even permanently damage the receiver.

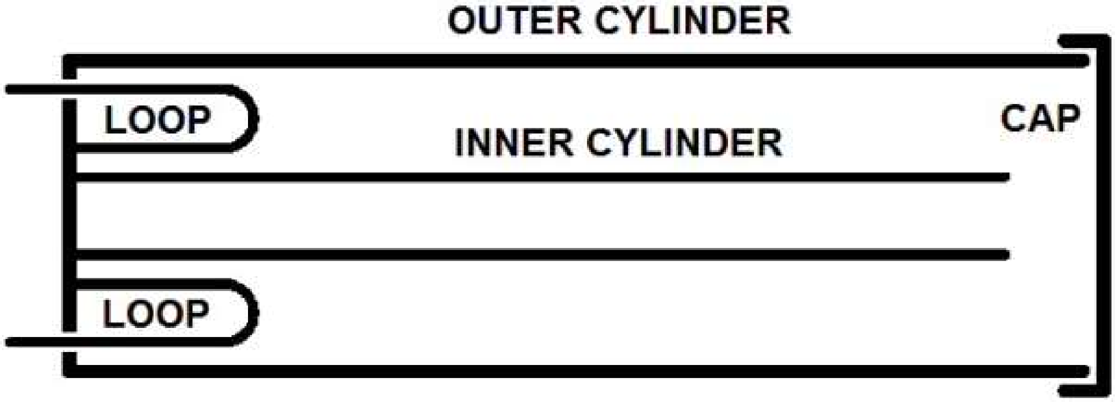


Figure 11. Cross-section of a Cavity Filter [30]

A duplexer is composed of several cavity filters connected together. Cavity filters can be configured as bandpass filters or band-reject filters. Bandpass filters block most frequencies while only letting a narrow band through. Band-reject, or notch, filters are the opposite; they block a narrow band of frequencies, while allowing all others to pass through. Before it can be used in a repeater, a duplexer must be tuned to the specific send and receive frequencies that will be used. This is achieved by lengthening or shortening the center conductors with adjustment screws. Changing the length of the center conductor changes the frequency at which the chamber resonates, which in turn, changes the center of the band that is either rejected or passed.

Repeaters operating in the 150 MHz band have a .6 MHz offset between their transmit and receive frequencies. The duplexer was tuned to operate for 147.3125 MHz with a positive offset.

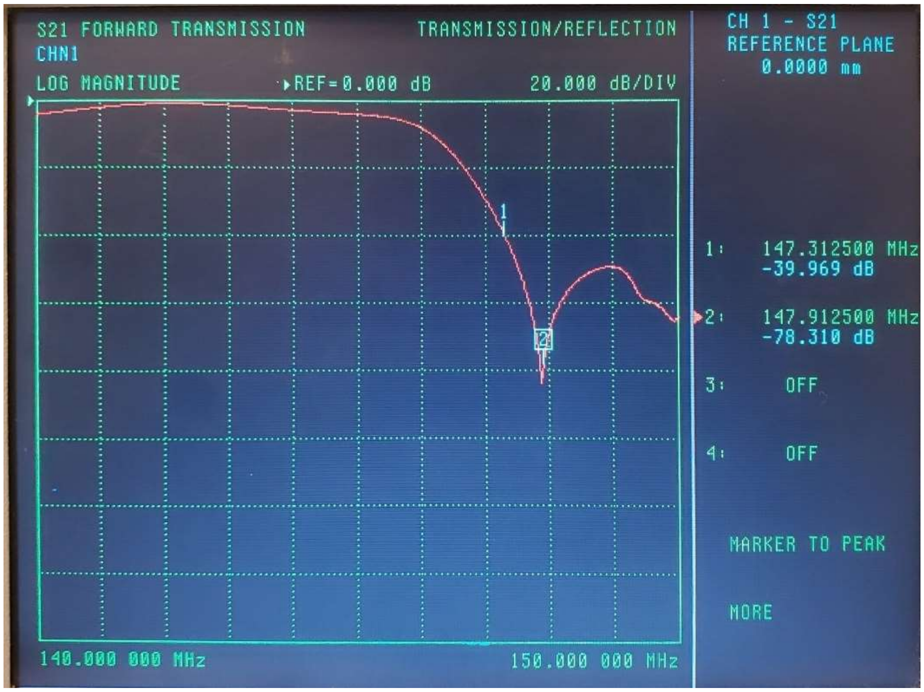


Figure 12. Tuned Duplexer [11]

Figure 12 shows the results of tuning the duplexer. The transmit and receive frequencies are 147.3125 MHz and 147.9125 MHz, respectively. This network analyzer was connected to the transmit side of the duplexer and shows that the duplexer offers far greater rejection of 147.9125 MHz than it does for the transmitting frequency, as desired.

4 TESTING AND VERIFICATION

4.1 Battery Life

In order to ensure that the payload would have sufficient battery to run continuously while the vehicle is in flight, the battery life of each component was tested under worst-case conditions. To ensure that the repeater would be running non-stop, it was set to transmit continuously for as long as the battery lasted - for the radios, this was until they shut themselves down, and for the main battery, it was once it reached 3.8v volts per cell. Measured times are recorded in Table 3.

This simulates the worst-case scenario in which the transmitting radio is running at a 100% duty cycle. Additionally, the times were rounded down nearest minute to calculate conservative results.

Table 3. Battery Life Test Durations

	Tx Radio (2200 mAh)	**Rx Radio (2200 mAh)**	**Repeater Controller (5200 mAh)**
Test 1: 1 W	126 minutes	1516 minutes	506 minutes
Test 2: 1 W	125 minutes	1521 minutes	495 minutes
Test 3: 5 W	72 minutes	1517 minutes	507 minutes
Test 4: 5 W	73 minutes	1522 minutes	502 minutes
Test 5: 10 W	50 minutes	1518 minutes	496 minutes
Test 6: 10 W	52 minutes	1519 minutes	502 minutes

By dividing the capacity of the battery by the battery life, the average current drawn by each component can be approximated. Because the radios and repeater controller are all run by two-cell batteries, they could all be run by the single main battery. This could reduce the weight of the payload and prevent the transmitting radio from running out of battery significantly before the rest of the payload.

Table 4. Estimation of Average Current Drawn

	Transmitting Radio	**Receiving Radio**	**Repeater Controller**	**Total**
Test 1: 1 W	1048 mA	87 mA	617 mA	1752 mA
Test 2: 1 W	1056 mA	87 mA	630 mA	1773 mA
Test 3: 5 W	1833 mA	87 mA	615 mA	2535 mA
Test 4: 5 W	1808 mA	87 mA	622 mA	2517 mA
Test 5: 10 W	2640 mA	87 mA	629 mA	3356 mA
Test 6: 10 W	2538 mA	87 mA	622 mA	3247 mA

Using the estimation of the total current drawn by all components of the payload, and the capacity of the main payload battery, how long the battery could run the payload under those conditions could then be calculated.

Table 5. Estimated Battery Life with Single Shared Battery

	Total Current	**Estimated Battery Life**
Test 1: 1 W	1752 mA	178 minutes
Test 2: 1 W	1773 mA	176 minutes
Test 3: 5 W	2535 mA	123 minutes
Test 4: 5 W	2517 mA	124 minutes
Test 5: 10 W	3356 mA	93 minutes
Test 6: 10 W	3247 mA	96 minutes

Since all of these exceed the 90-minute published flight time of the Nova, they do not need to be actively monitored during flight. [25]

The radios are capable of transmitting at low, medium, or high power, which are 1 watt, 5 watts, and 10 watts, respectively.[32] When set to the high-power setting, the payload would match the specifications of current mountain-top repeaters; however, because it would be operating from a higher altitude with fewer obstructions, it likely wouldn't need as much power to achieve similar range.

At all power settings, the payload would be able to be run from just the main payload battery for the duration of the flight. Even though the radio's published duty cycle was only 5%, [32] with the additional heatsinking provided by the aluminum tray, the radio was able to transmit continuously until it ran out of battery.

4.2 Antenna Simulation

To predict the performance and radiation pattern of the antenna, the antenna was modeled as three separate bodies in SolidWorks: the FR-4 substrate, the copper reflector, and the copper traces for the actual elements. This model was then imported into ANSYS HFSS, excitations were connected to the feed elements of the antenna, and its performance was simulated.

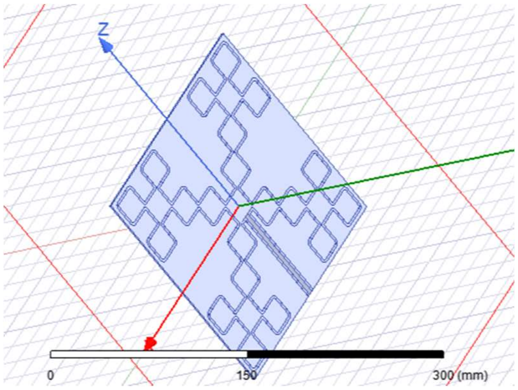


Figure 13. First Iteration of Fractal Antenna [1]

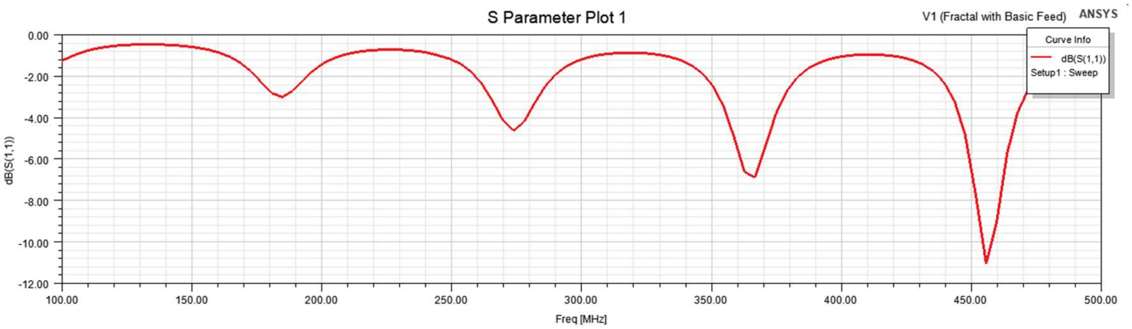


Figure 14. S Parameter of Original Design [1]

The S Parameter is known as the reflection coefficient and is a measure of how much power is reflected versus how much was delivered to the antenna. An S Parameter of 0 dB indicates that no power was accepted by the antenna, and all was reflected, -10 dB means that only 10% of the power is reflected. Generally, -6 dB is needed for an antenna to transmit a good signal, meaning that the antenna shown above would work for UHF, but not for VHF.

Because the first iteration of the design did not provide satisfactory performance in the150 MHz band, the implementation of the fractal was iterated upon. The length of the feed line, the thickness of the traces, and the radii of the corners were varied, and the resulting antennas were re-simulated.

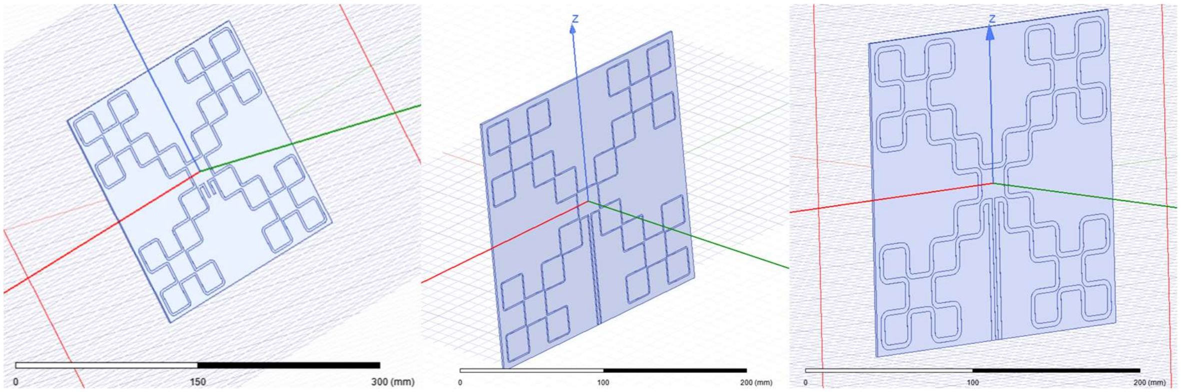


Figure 15. The Three Versions of the Second Iteration [1]

Of the three versions of the second iteration of the antenna design, the one with the thin traces and sharp corners performed the best.

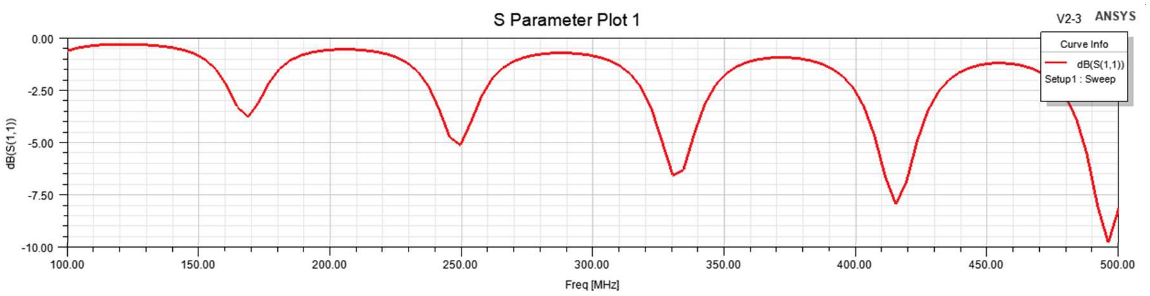


Figure 16. S Parameter of the Version with Thin Traces [1]

Unfortunately, this did not perform any better than the original version in either of the bands of interest. Someone with more expertise in antenna design would likely be able to create an antenna that could be manufactured on a PCB, would be small enough to fit under the wing of the Nova, and would work for both UHF and VHF transmissions. If such an antenna could not be designed, the original dual-band rubber duck antenna could be used, though more care would need to be taken not to cause interference due to its omnidirectionality.

4.3 Repeater Functionality

During initial testing, the stock antenna was used on the receiving radio and a dummy load on the transmitting radio. A dummy load takes the place of an antenna but instead of transmitting the energy from the radio, dissipates it as heat. This is important while testing in order to prevent accidental interference or other disruptive transmissions before confirmation that the system is working as expected. Radios that transmit without an antenna or dummy load can be damaged because too much power will be reflected back into the circuitry if it has nowhere else to go.

Figure 17. Initial Bench Testing Setup

Through the course of this testing, it was discovered that although the receiving radio was indicating that it was receiving signals, the repeater controller was not recording the callsign of the user radio. Additional research revealed that there were likely two features of the chosen off-the-shelf radio that were causing this. The first was a bandpass filter that is applied to the audio after it has been demodulated. This filter removes frequencies that are above or below audible frequencies in order to improve the audio quality. Because human speech varies between approximately 85 Hz and 255 Hz, [15] digital data that is transmitted at 9600 Hz would be blocked by this filter. [14]

The second feature that was problematic was a pre/de-emphasis filter. Emphasis is important for compatibility between analog FM radio and PM radio.

Early radios were crystal-based and phase-modulated; an inherent characteristic of Phase Modulation is that as the audio frequency doubles, the deviation doubles as well. In order to restore the original audio, a “de-emphasis” circuit is required in the receiver to reduce the deviation for higher frequencies.

When diode-based Frequency Modulated radios were developed, their deviation did not depend on the frequency of the audio. In order to maintain compatibility with existing PM systems, FM radios included a “pre-emphasis” circuit to intentionally increase the deviation before transmitting. [22]

While FM voice communications use a pre-emphasizer on the audio, digital communications do not. This means that when an analog radio receives a digital signal, it will de-emphasize the non-emphasized audio and will not recover the original audio. The repeater controller is expecting “flat audio”, so the audio stream must be accessed after it is de-modulated, but before it is filtered. This audio is extracted before it is filtered using a discriminator tap. This typically involves adding a connector to the radio chassis and a hook-up wire between the board and the connector, allowing some signal to bypass the filter.

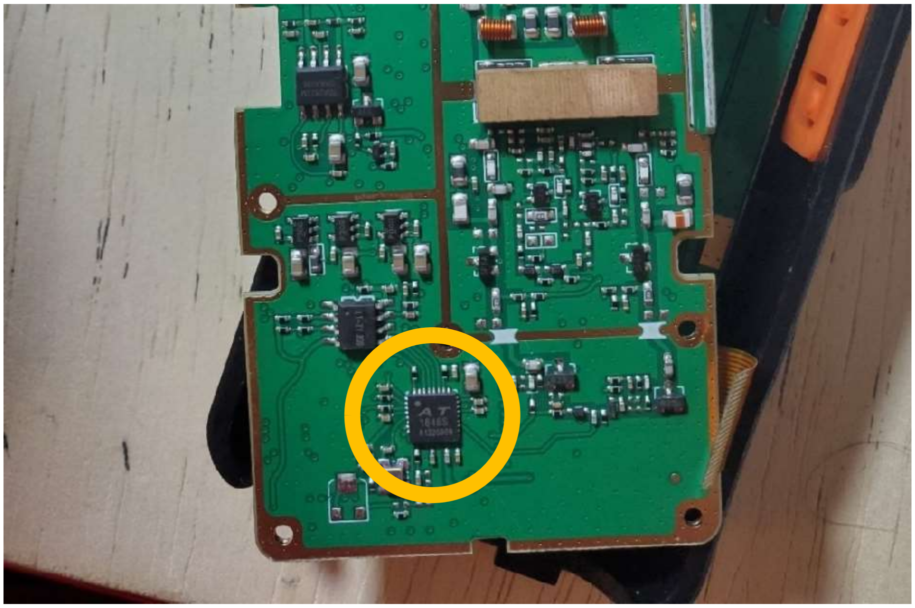


Figure 18. GA-510 with AT1846S Marked

In order to add a discriminator tap, the GA-510 was disassembled and the audio path was traced from the antenna. The GA-510 uses an AT1846S single-chip transceiver that converts between RF carrier and voice. Because all of the audio processing is done inside the AT1846, instead of a physical circuit, a discriminator tap can't be installed in this radio.

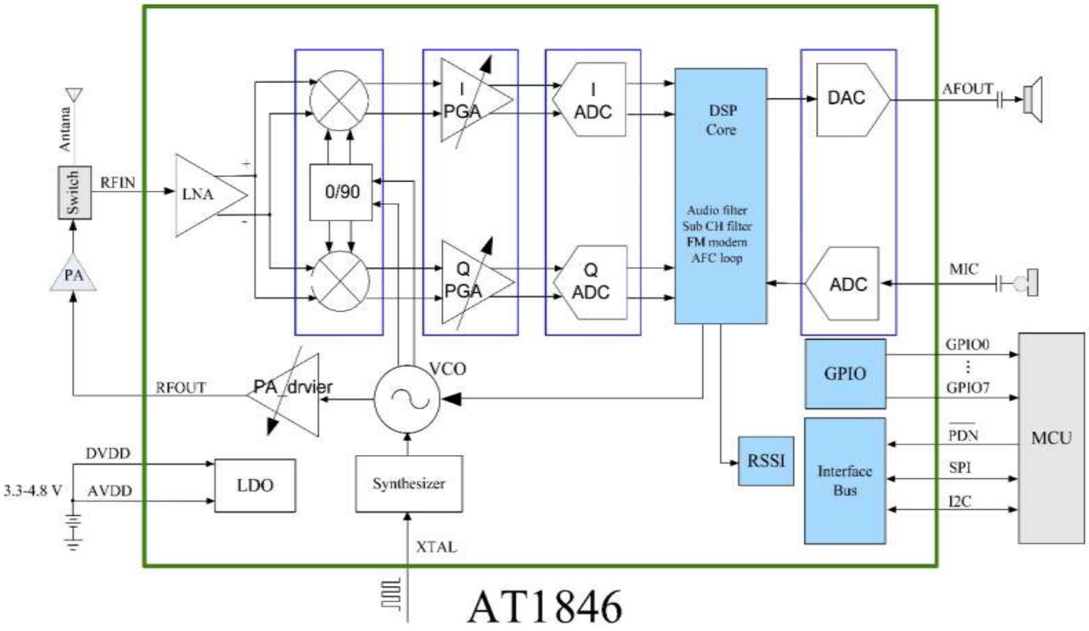


Figure 19. Block Diagram for AT1846 [35]

4.4 Reprogramming the Radios

Since the filtering is done in the software instead of a physical circuit, although a physical discriminator tap couldn't be added, it should be possible to bypass certain parts of the code. In order to access the unprocessed audio, the bandpass filter and the pre/de-emphasis filter needed to be disabled. The datasheet for the AT1846S includes a section about reading and writing certain settings to the chip as binary over an I^2C connection, one group of which was for various kinds of filtering.

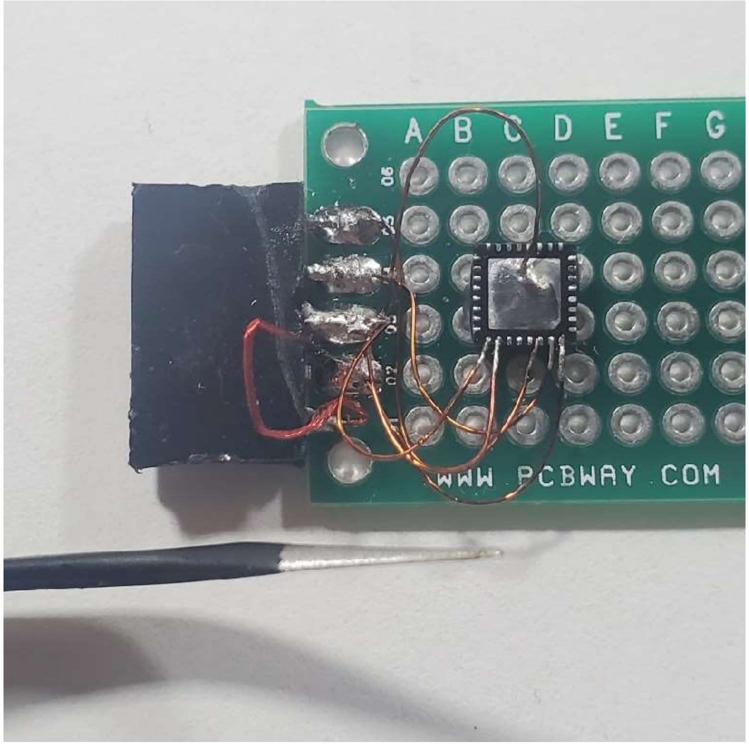


Figure 20. AT1846S Attached to Programming Board

Because the PCB did not have an easy way to access the chip for programming, the AT1846 needed to be removed with a hot-air rework station. It was then secured to a spare PCB and bond-wires were soldered between the necessary pins and a connector.

Using a short script in C++; an Arduino scanned through all available I^{2}C slave addresses and attempted to start a connection with each of them. If it was successful, it would report the addresses with devices connected.[A] A second script was then uploaded which was able to read the registers on the chip; this was used to verify that the Arduino could properly communicate with the AT1846 by reading registers with known values, such as the one that held the chip ID.

This was important to do before attempting to write anything to it, because storing the wrong value in certain registers can permanently damage devices. Once the ability to correctly read the chip ID was confirmed, it was safe to proceed with the register that stored filter information. The script included a section that could be toggled on and off; when enabled, it would write a modified two-byte sequence to the desired register and then request that the chip read back the new contents of that register. [D]

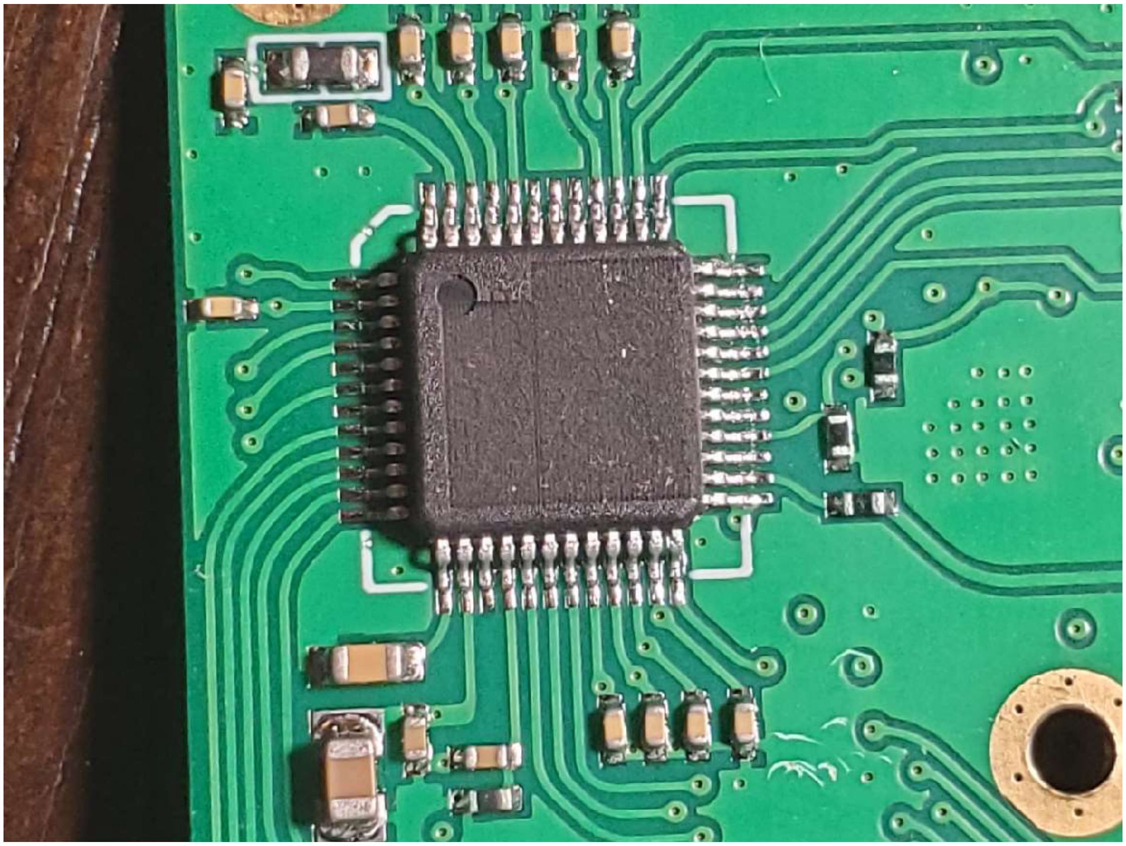


Figure 21. MCU with Identifying Information Removed

Unfortunately, the proprietary microcontroller re-writes this register during bootup, so the changes were not able to persist. It most likely would have been possible to develop a PCB that could have held the AT1846 and a microcontroller in order to disconnect the AT1846 from the radio’s microcontroller after bootup and reflash the filter’s register. However, based on time constraints, it was deemed that this was not necessary for establishing a proof of concept as a non-off-the-shelf radio would not have the same problem.

4.5 Communications Range

The initial plan to test the functionality of the repeater was to take two handheld radios and find the maximum range over which they could effectively communicate both with and without obstacles. The Nova would then be launched with the RaDAR payload to verify that communications could be restored when the radios were beyond that range. However, because of the issue with the filtering, the payload was unable to successfully repeat signals from any distance.

5 RESULTS

5.1 Weight

It was important that all components of the payload not exceed the sUAS carrying capacity, which is published as 1.7kg. Table 6 lists the weight of all the components and their total.

Table 6. Weight Build-up

Published Nova Payload Capacity:	**1.7 kg**
Transmit Radio:	.232 kg
Receive Radio:	.232 kg
Duplexer:	.502 kg
Battery:	.272 kg
Repeater Controller:	.110 kg
Subtotal:	**1.348 kg**
Housing:	.488 kg
Equipment Tray:	.144 kg
Cables/Hardware/etc.:	.032 kg
Total	**2.012 kg**

Although the original weight goal of 1.7 kg was not met with the off-the-shelf components, there are several areas for possible weight reduction that would enable the payload to meet the requirements for use in the Nova.

Table 7. Potential Weight Savings

Radios - Batteries Removed:	-.166 kg
Total	**1.846 kg**

Because one radio will be used exclusively for receiving, its power consumption will be significantly lower than that of the transmitting radio. This means that the receiving radio's battery will be quite a bit larger than it needs to be. Eliminating the radios' internal batteries in order to switch over to a single central battery would save approximately .166 kg, bringing the payload weight down to 1.846 kg.

Table 8. Potential Weight Savings

Radios – Board Only:	-.234 kg
Total	**1.612 kg**

A significant disadvantage to limiting this project to off-the-shelf radios instead of designing a radio specifically for RaDAR, is that various features or design choices are included in off-the-shelf radios that are beneficial to general handheld radios, but that just add weight and complexity that are not needed for repeaters. Removing the cases from the radios, and only using the main circuit board would save an additional .234 kg. This would also allow the heat generating components to be attached directly to the aluminum equipment tray for thermal management.

Incorporating all these weight-saving changes would get the total weight down to 1.612 kg, less than the published NOVA payload capacity, without impacting the functionality of the repeater.

5.2 Balance

Because the payload bay of the Nova is ahead of the aircraft's center of gravity, a ballast and aerodynamic fairing are needed even when no payload is installed. The payload capacity listed in the Nova's specifications is 1.7 kg, [25] but the included ballast and fairing weigh 1.976 kg, meaning that as built, the repeater payload is only .046 kg heavier than the original payload insert.

Figure 22. CG Balance

The payload's effect on the center of gravity was measured using a CG balance; the Nova, with its original payload installed, was slid forward and backward until the fuselage was level with the ground and a picture was taken. The original payload was then replaced with RaDAR, the aircraft was rebalanced, and another picture taken. The two pictures could then be overlayed and the change in CG location compared. The original center of gravity is marked in gold, and the new center of gravity in green. The difference in 46 grams between the ballast and RaDAR shifted the center of gravity forward approximately two millimeters and caused no noticeable shift in the lateral location of the center of gravity.

6 CONCLUSIONS

Although the first iteration of RaDAR was unable to successfully repeat P25 signals, because of the issues discussed in section 4.4, I believe that it was able to successfully demonstrate the feasibility of designing a dual band digital radio repeater to aid in the deployment of communications networks during wildland firefighting in mountainous terrain.

6.1 Rapidly Deployable

The Nova is stored and transported in a case that contains all necessary components. The wing and tail sections are all assembled using interlocking hooks with integrated electrical connectors; no tools are necessary, components only fit in their correct location, and there is only one step to connect each component. This allows the Nova to be assembled and ready for pre-flight checks in a matter of minutes.

Figure 23. Nova Stored and Assembled [25]

While the Nova is being assembled, RaDAR can be activated by connecting the main battery to the wiring harness and turning on the two radios. Additionally, if the radios were modified to share the main payload battery, the only step required would be plugging in that battery. It can then be returned to the payload bay and secured. The payload is secured with four quarter-turn thumbscrews that require no tools to operate. The repeater controller hosts its own local Wi-Fi network, allowing nearby phones and computers to access the settings for the repeater. Changing these settings requires logging in with an administrative username and password, protecting against unauthorized changes. [29]

RaDAR can be serviced and modified in the field with few to no tools. The radios can be programmed using their built-in keypads and displays, without being removed from the payload. All connectors are either press-fit or secured with thumbscrews to allow users to disconnect and replace components if needed.

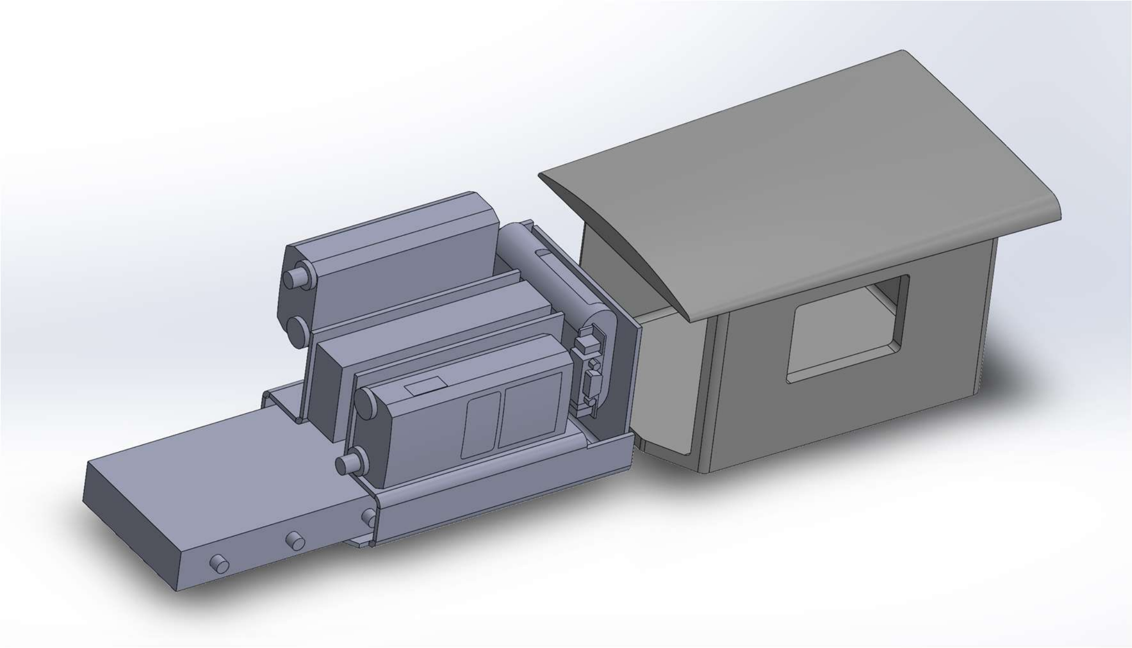


Figure 24. An exploded view of the payload components [38]

For more in-depth work on the radios or controller settings, the equipment tray can be slid out of the payload as a single unit, offering access to an ethernet port for connecting to the repeater controller as well as the audio jacks for reprogramming the radios.

6.2 Flexible Launch and Recovery

The Altavian Nova is hand-launched and designed for belly landings in unimproved conditions; this means it does not require runways or any special equipment other than its portable ground control station. In fact, according to manufacturer specifications, it can be launched and recovered from an area as small as 10 meters by 30 meters. [1]

Figure 25. Nova Landing Zone Compared to Dexter Lawn [17]

Requiring such a small area for launch and landing allows the Nova to be flown from nearly any field or mountain top and even many small clearings.

6.3 Improved Communications Range and Reliability

Although the prototype repeater was unable to verify the improvement in communications range, the ease with which the Nova can be temporarily re-tasked demonstrates a benefit to the reliability of communications networks. A mountain-top repeater will have a relatively-fixed coverage area. This means that any blind spots in valleys or behind obstacles are also fixed. Because the Nova can be ordered to orbit a new position with only a few clicks of the mouse, if a message needs to get to a crew in an area it can’t reach, it can simply fly to a new location for long enough to get the message through. It can then return to its original loiter area or move to a new one if needed. For a mountain-top repeater to achieve a similar result, a crew would have to fly out by helicopter, disassemble the current repeater, pack it into the helicopter, fly it to a new location, and reassemble it.

6.4 Compliant with FAA and FCC Regulations

As a commercially-available unmanned aircraft, the Nova can be flown in unrestricted airspace and within line-of-sight by properly trained and certified pilots under Part 107. Additionally, agencies, such as Cal Fire, can operate unmanned aircraft in the temporary flight restrictions that are enforced over wildfires and beyond line of sight with Special Government Interest Waivers or a Certificate of Authorization.

The radio-repeater aspect of RaDAR is intended to match the capabilities and characteristics of current mountain-top repeaters as closely as possible in terms of total output power, interference, and operational responsibility. This would ensure that it is compliant with any relevant FCC regulations.

6.5 Compatible with Cal Fire and other Wildland Firefighting Agencies

In order to be compatible with Cal Fire and other wildland firefighting agencies that work with the NWCG, RaDAR is intended to integrate with current communications networks by matching the frequencies, communications protocols, and transmission power of currently operated radio systems.

REFERENCES

1. “Altavian Nova F7200,” Unmanned Systems Source Available: https://www.unmannedsystemssource.com/shop/unmanned-vehicles/fixed-wing-uav/altavian-nova-f7200/.
2. “Ansys Electronics Desktop Student,” Ansys.
3. Bevelacqua, P., “Fractal Antenna,” Fractal antenna Available: https://antenna-theory.com/antennas/fractal.php.
4. Bodkin, L., NOVA_launch, 2019.
5. CAL FIRE, “Top 20 Largest California Wildfires,” Nov. 2021.
6. CAL FIRE, “Top 20 Most Destructive California Wildfires,” Nov. 2021.
7. California Department of Forestry and Fire Protection (CAL FIRE), “August Complex (includes Doe Fire),” Organization Image Available: https://www.fire.ca.gov/incidents/2020/8/16/august-complex-includes-doe-fire/.
8. Clark, J. B., and Jacques, D. R., “Flight test results for uavs using BOID guidance algorithms,” Procedia Computer Science, vol. 8, Mar. 2012, pp. 232–238.
9. Davis, J., and Weber, K. T., “Spatio-Temporal Relationships of Historic Wildfires: Using the NASA RECOVER Historic Fires Geodatabase to Perform Long-term Analysis of Wildfire Occurrences in the Western United States,” 2018.
10. de Oñate, J. J., “Fractal Antenna Project,” Fractal antenna experiment Available: https://www.m0wwa.co.uk/page/M0WWA_fractal_antenna.html.

11. Display of an Anritsu Vector Network Measurement System, 2021.
12. “DIY flexible fractal window HDTV antenna,” HTPC DIY Available: https://www.htpc-diy.com/2012/04/diy-flexible-fractal-window-hdtv.html.
13. Dunagan, S., Eilers, J., Lobitz, B., and Zajkowski, T., “UAS Enabled Communications for Tactical Firefighting,” AIAA Infotech@Aerospace 2007 Conference and Exhibit, 2007.
14. Elazary, L., “TX/RX Digital Data using the UV5R,” TX/RX digital data using the UV5R Available: https://web.archive.org/web/20210223160659/http://www.elazary.com/index.php?option=com_content&view=article&id=50%3Atxrx-digital-data-using-the-uv5r&catid=14%3Abaofeng-uv5r&Itemid=17.
15. Fitch, J. L., and Holbrook, A., “Modal vocal fundamental frequency of young adults,” Archives of Otolaryngology - Head and Neck Surgery, vol. 92, 1970, pp. 379–382.
16. Ge, L., and yy, L., “AT1846S/AT1846SD Programming Guide,” Jul. 2015.
17. “Google Earth Pro,” Mar. 2022.
18. Interagency Fire Unmanned Aircraft Systems Subcommittee, NWCG, 2019.
19. “Matlab Student Suite,” MathWorks, 2020.
20. McCutchan, K., “Approved_Radios_2020-02-28,” Feb. 2020.
21. McCutchan, K., *National Incident Radio Support Cache User's Guide*, Boise, ID: National Interagency Fire Center, 2020.

22. Morris, M. R., DePolo, J., Custer, K. K., and Schmid, B., “An Explanation of ‘Flat Audio’, ‘Pre-Emphasis’ and ‘De-Emphasis,’” Repeater Builder, Feb. 1999.

23. “National Fire Equipment System Subcommittee,” *NFES National Interagency Support Caches* Available: https://www.nwcg.gov/committees/national-fire-equipment-system-subcommittee/nisc.

24. NIFC, “Wildland Fire Fatalities by Type of Accident.”

25. “Nova series - industrial UAV by Altavian Inc.: AeroExpo,” The B2B marketplace for aeronautical equipment Available: https://www.aeroexpo.online/prod/altavian-inc/product-176230-26479.html.

26. “NWCG Standards for Fire Unmanned Aircraft Systems Operations,” Interagency Fire Unmanned Aircraft Systems Subcommittee, NWCG, Feb. 2019.

27. “Phase modulation: Theory, Time Domain, frequency domain: Radio Frequency Modulation: Electronics Textbook,” All About Circuits Available: https://www.allaboutcircuits.com/textbook/radio-frequency-analysis-design/radio-frequency-modulation/phase-modulation-theory-time-domain-frequency-domain/.

28. Pinout Diagram for Kenwood 2.5mm TRS/3.5 mm TRS connector, 2014.

29. “Playing with pi-star,” Amateur Radio Notes Available: https://amateurradionotes.com/pi-star.htm.

30. Portune, J., Understanding the Cavity Duplexer, Santa Maria, CA.
31. Press, “Altavian raises the bar with new commercial drones at unprecedented prices,” sUAS News - The Business of Drones Available: https://www.suasnews.com/2016/05/43456/.
32. “Radioddity ga-510: 10W: Dual band: Tri-power: Support chirp: 2 batteries,” Radioddity Available: https://www.radioddity.com/collections/consumer-radios-amateur-radios/products/radioddity-ga-510.
33. Recine, C., and Wiseman, M., “Interview with a Wildland Firefighter,” Sep. 2021.
34. Schaefer, J., “NOVA F7200 Aircraft Flight Manual,” Feb. 2016.
35. Shi, H., and Liu, G., “RDA1846 Datasheet,” Dec. 2009.
36. Shovon, S., “Raspberry Pi 3 Power Requirements,” linuxhint Available: https://linuxhint.com/raspberry_pi_3_power_requirements.
37. “Soaring toward a $100B industry,” Powering the New Engineer Available: https://www.eng.ufl.edu/newengineer/alumni-spotlight/soaring-toward-a-100b-industry/.
38. “SolidWorks,” SolidWorks, 2020.
39. SP5WWP, “RDA1846,” RadioReference.com Forums Available: https://forums.radioreference.com/threads/rda1846.378501/.

40. U, V. F., and Li, Z. J., “Modulation Techniques,” Modulation techniques Available: https://www-ee.eng.hawaii.edu/~sasaki/Undergrad/WaveCalc/ZeLi/modulation.html.

41. Varone, C., “FIREFIGHTER SAFETY AND RADIO COMMUNICATION,” *Fire Engineering*, vol. 156, Mar. 2003.

42. yee-cssl, “1PCS 10w VHF 136-174mhz Duplexer for hytera RD960/RD962/RD965 repeater SMA,” eBay Available: https://www.ebay.com/itm/274439988370.

43. Zimmerman, S., “STM32_DVM,” Repeater builder Available: http://www.repeater-builder.com/products/stm32-dvm.html.

44. Zimmerman, S., “STM32_DVM_v4,” Dec. 2020.

APPENDICES

A. Future Work

This proof of concept could be further improved by additional design work on the radios, duplexer, and antenna. Designing radios specifically for this purpose would allow them to be smaller, lighter, and more energy efficient by excluding unnecessary features. Currently, both radios are transceivers, which means that one radio has an unused receiver, and the other has an unused transmitter.

A single keypad and display that can be shared between the two radios would contribute a little towards the weight and power savings but would also allow for simplification of the payload insert and equipment tray by increasing the flexibility of component placement.

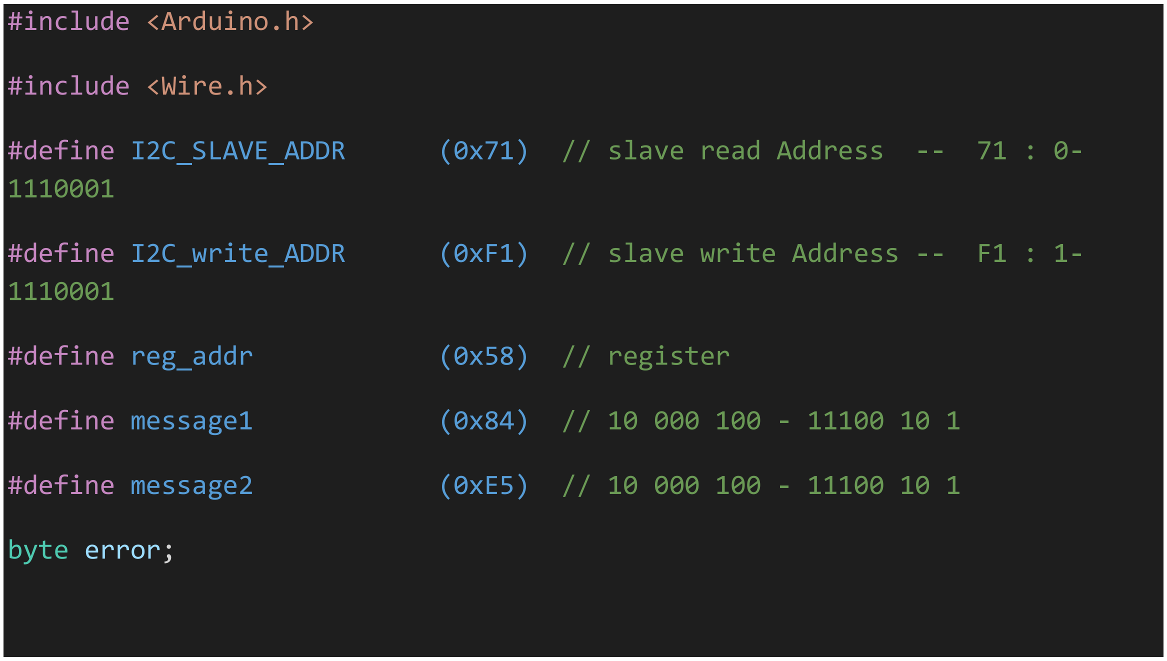
Duplexers are almost always used in fixed installations, making their size and weight unimportant. The duplexer I was able to find was significantly smaller and lighter than most but designing an even lighter one could enable the repeater to be carried by an even smaller vehicle. The chassis of the duplexer is machined from a block of aluminum and is rated for 100 watts. Since the repeater will only be transmitting 10 watts at the most, the duplexer doesn’t need to dissipate as much heat. A lightweight duplexer could be investigated that would use a metallic coating on the inside of the resonance chambers but could use a non-metallic structure to save weight.

Two other possible improvements to the system would be the addition of telemetry data and holes in the equipment tray to access the adjustment screws on the duplexer. Telemetry data such as aircraft battery and location, payload temperature and battery, or even air quality could be encoded by the Raspberry Pi and sent to the repeater controller for transmission. This would allow users on the ground to access potentially useful information while the vehicle is still in flight. Additionally, adding holes to the equipment tray to access the duplexer's adjustment screws would allow it to be retuned without removing it completely. I had initially excluded this as specialized equipment is needed to retune a duplexer, and it would almost certainly not be done in the field during a wildfire. However, it could be useful for those responsible for maintaining the repeaters after incidents and it likely wouldn't impact the integrity of the tray.

B. Logo for RaDAR Technologies

Figure 26. RaDAR – The Rapidly Deployable Airborne Repeater

C. reg_reader.cpp



```
#include <Arduino.h>

#include <Wire.h>

#define I2C_SLAVE_ADDR      (0x71)  // slave read Address   --   71 : 0-1110001

#define I2C_write_ADDR      (0xF1)  // slave write Address --   F1 : 1-1110001

#define reg_addr            (0x58)  // register

#define message1            (0x84)  // 10 000 100 - 11100 10 1

#define message2            (0xE5)  // 10 000 100 - 11100 10 1

byte error;
```

```
void setup() {
  digitalWrite(SDA, LOW);
  digitalWrite(SCL, LOW);
  Wire.begin();         // join i2c bus (address optional for master)
  Serial.begin(9600);   // start serial for output
  while (!Serial);      // wait for serial monitor
  Serial.println("\nI2C Reader");


  if (true) {
    Serial.println("Writing");
    Wire.beginTransmission(I2C_write_ADDR); // Get the slave's attention, tell it we're sending a command byte
    Wire.write(reg_addr);                   // The command byte, sets pointer to the register of interest
    Wire.write(message1);                   // The high byte
    Wire.write(message2);                   // The low byte
    error = Wire.endTransmission();         // "Hang up the line" so others can use it
    if (error == 0) {
      Serial.print("\nWrite Successful");
      }
    else if (error == 4) {
      Serial.print("\nUnknown error");
      }
    Serial.println("Writing Complete");
  }


}
```

```
void loop() {
  Serial.print("\nReading:");
  Wire.beginTransmission(I2C_SLAVE_ADDR);     // Get the slave's
attention, tell it we're sending a command byte
  Wire.write(reg_addr);                       // The command byte, sets
pointer to the register of interest

  Wire.requestFrom(I2C_SLAVE_ADDR,2);         // Tell slave we need to
read 2 bytes from the current register
  byte LSB = Wire.read();
  byte MSB = Wire.read();
  uint16_t values = ((LSB << 8) | MSB);       // 16bits that make up the
register contents

  error = Wire.endTransmission();             // "Hang up the line" so
others can use it

  if (error == 0) {
    Serial.print("\nBin: ");
    Serial.print(values,BIN);
    Serial.print(" Hex: ");
    Serial.print(values,HEX);
    }
    else if (error == 4) {
      Serial.print("\nUnknown error");
    }
  delay(2000);
}
```

D. i2c_scanner.cpp

```
#include <Arduino.h>
#include <Wire.h>
int dt;
int nDevices;
byte error, address;
byte reg_addr;

void setup() {
  dt = 10;
  digitalWrite(SDA, LOW);
  digitalWrite(SCL, LOW);
  delay(dt);
  Wire.begin();
  delay(dt);

  Serial.begin(9600);
  while (!Serial); // wait for serial monitor
  delay(dt);
  Serial.println("\nI2C Scanner");
  delay(dt);
}

void loop() {
  nDevices = 0;
```

```
  reg_addr = 0;
  Serial.println("Scanning...");

  for ( address = 1; address < 127; ++address) {
    // The i2c_scanner uses the return value of
    // the Write.endTransmisstion to see which addresses
    // had a device acknowledge the transmission.
    Serial.print(address);
    Wire.beginTransmission(address);
    Serial.print("begin");

    Wire.write(reg_addr);                           //  The command byte, sets
pointer to register with address of 0x32
    Serial.print("reg");
    Wire.requestFrom(address,2);           // Tell slave we need to read 2
bytes from the current register
    Serial.print("request");
    byte LSB = Wire.read();
    byte MSB = Wire.read();
    Serial.print("read");
    uint16_t values = ((MSB << 8) | LSB);       //16bits that make up the
register contents

    error = Wire.endTransmission();
    Serial.print("scanned\n");
    delay(dt);

    if (error == 0) {
```

```
    Serial.print("I2C device found at address 0x");
    if (address < 16) {
      Serial.print("0");
    }
    Serial.print(address, HEX);
    Serial.println("  !");
    Serial.print(values);

    ++nDevices;
  } else if (error == 4) {
    Serial.print("Unknown error at address 0x");
    if (address < 16) {
      Serial.print("0");
    }
    Serial.println(address, HEX);
  }
}
if (nDevices == 0) {
  Serial.println("No I2C devices found\n");
} else {
  Serial.println("done\n");
}
delay(500); // Wait .5 seconds for next scan
    }
```

E. Alternative Antenna Designs

Other compact antennas I have seen commonly used are the Fractal Bowtie and the Squared Dipole. These both offer promise for being manufactured on a PCB, working for multiple bands, and fitting on the Nova.

Figure 27. Two Types of Fractal Bowties [12][3]

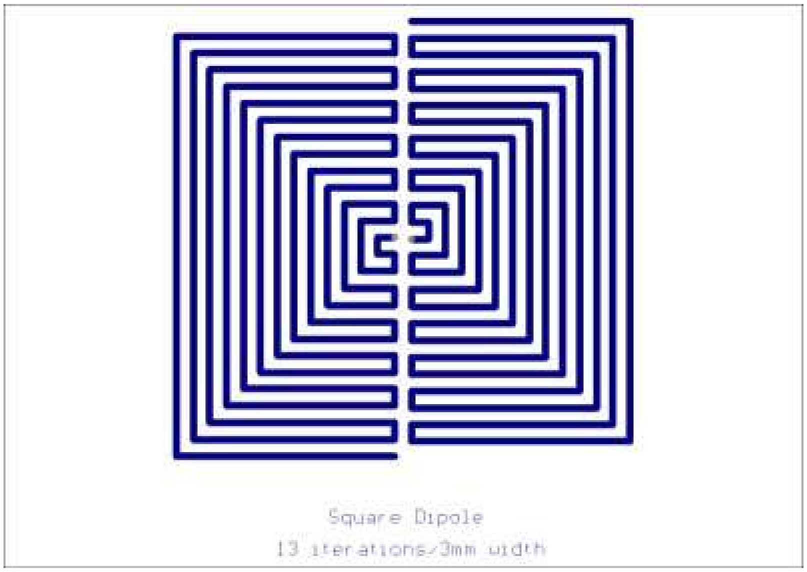


Figure 28. Square Dipole [10]

F. Phase Modulation

In PM radio, the amplitude of the message is used as an offset to the phase angle of the carrier wave. The carrier, referred to as $c(t)$, can be expressed as follows:

Equation 1 [27]

$$c(t) = A_c * \sin(\omega_c t + \phi_c)$$

If we represent the message to be transmitted as $m(t)$ and, for simplicity, assume that the phase angle of the carrier at time t=0 is 0, i.e. $\phi_c = 0$, the phase modulated signal becomes:

$$y(t) = A_c * \sin(\omega_c t + m(t))$$

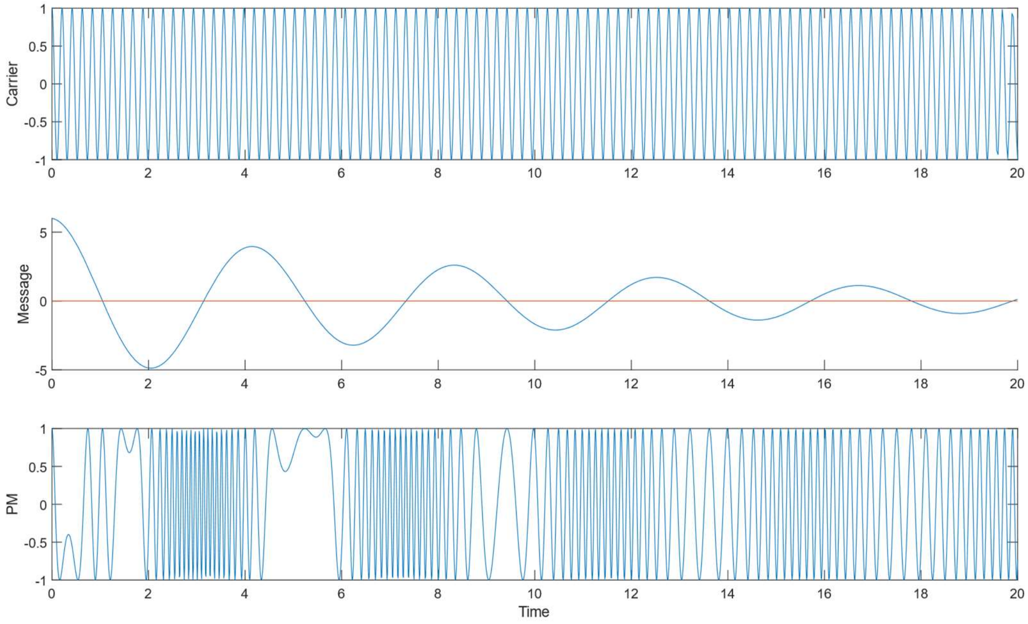


Figure 29. Phase Modulation Example [19]

G. FM Radio Modulation Example

$$y(t) = A_c * \sin\left(\omega_c t + I * 2\pi * \int_0^t m(\tau)\, d\tau\right)$$

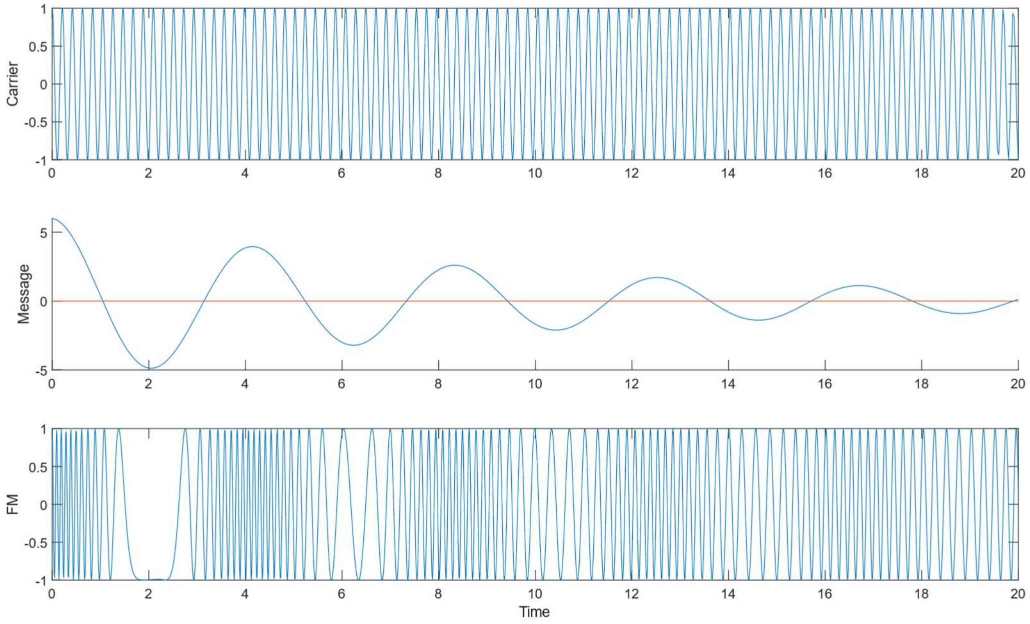


Figure 30. Frequency Modulation Example [19]

H. AM Radio Modulation Example

$$y(t) = (A_c + k * m(t)) * \sin(\omega_c t)$$

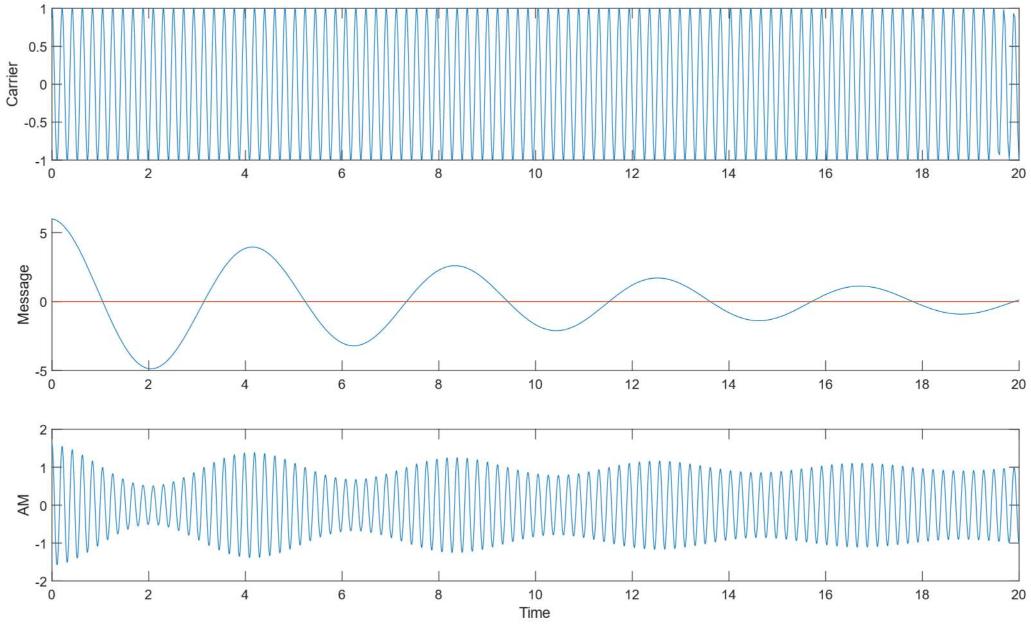


Figure 31. Amplitude Modulation Example [40]

I. Comparison of Different Radio Modulation Techniques

Figure

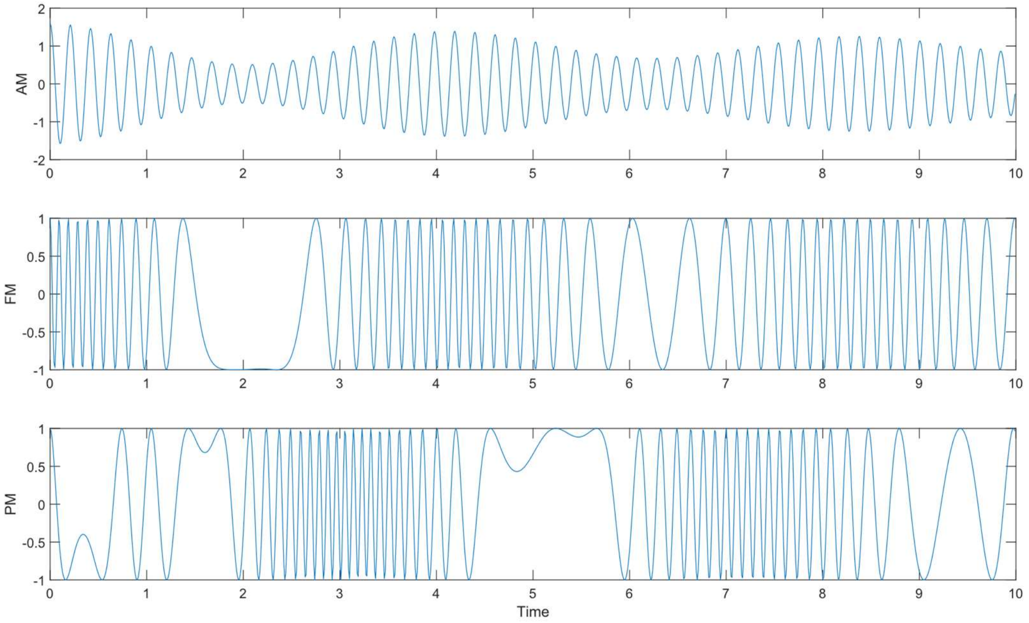


Figure 32. Modulation Comparison [27]

J. MATLAB Fractal Optimization

```
close all

s = 2;

pmin = 200;

n=0;


fractal(n,s,pmin);


%% optimize
```

```
sides = linspace(.1,25,100);

for ii=1:length(sides)

    w(ii) = fractal(0,sides(ii),pmin);

end

[min_width,I] = min(w);


disp(['The minimum width is
',num2str(min_width),' cm when each segment is
',num2str(sides(I)),' cm.'])

disp(' ')

fractal(0,sides(I),pmin,true);

disp(' ')

fractal(0,2,pmin,true);

figure

plot(sides,w)



function w = fractal(n,s,pmin,print)

    if nargin<4

      print=false;

    end

    M = [1,0,1;0,1,0;1,0,1];


    if not(n)

        P =s*4*5^n;
```

```
        while P<pmin
            n=n+1;
            P =s*4*5^n;
        end
    end
    segments_per_side = 5^n;
    positions = 3^n;

    for ii=1:n-1
        Z = zeros(3^ii);
        M = [M,Z,M;Z,M,Z;M,Z,M];
    end

    w = s*positions;
    if print
        figure
        for ii=1:positions
            for jj=1:positions
                if M(ii,jj)

rectangle('Position',[s*(ii-1), s*(jj-1), s,
s],'FaceColor',[0,0,0])
                end
            end
        end
```

```
        axis equal
        disp(['Each side is ',num2str(s),' cm
long.'])
        disp(['The perimeter is
',num2str(segments_per_side*4*s),' cm long.'])
        disp(['The antenna is ',num2str(w),' cm
(',num2str(round(w/2.54,2)),' in) wide.'])
    end
end
```

K. MATLAB for Modulation Examples

```
close all; clear all; clc
global carrier message t_vec
Tmax = 20;
t_vec=linspace(0,Tmax,4001);

%% set 1
Ac = 1; Fc = 20; Am = 10;
carrier =@(t) Ac*cos(Fc*t*2*pi);
message =@(t) Am*(.5*cos(.1*t*2*pi)-
.7*sin(.4*t*2*pi));

ka = .1;
am =@(t) (1+ka*message(t)) .* carrier(t);
I = 1;
fm =@(t) Ac*cos(Fc*t*2*pi +
I*2*pi.*integral(message,0,t));
I = 1;
pm =@(t) Ac*cos(Fc*t*2*pi + I.*message(t));

plot_(1,am,'AM')
plot_(2,fm,'FM')
plot_(3,pm,'PM')
```

```
%% set 2
Ac = 1; Fc=30/(2*pi); Am = 6; Fm = 1.5;
carrier =@(t) Ac*cos(Fc*t*2*pi);
message =@(t) (Am*exp(-.1*t)).*cos(Fm*t);
ka = 1;
am2 =@(t) (1+ka*message(t)) .* carrier(t);
I = 1;
fm2 =@(t) Ac*cos(Fc*t*2*pi +
I*2*pi.*integral(message,0,t));
I = pi*2;
pm2 =@(t) Ac*cos(Fc*t*2*pi + I.*message(t));

plot_(1,am2,'AM')
plot_(2,fm2,'FM')
plot_(3,pm2,'PM')

%%
plot_comp(4,am2,fm2,pm2)

%% emphasis
t_vec=linspace(0,5,4001);
Ac = 1; Fc=10; Am = 2; Fm = 1.5;
decay = -.2;
carrier =@(t) Ac*cos(Fc*t*2*pi);
message =@(t)
(Am*exp(decay*t)).*cos(Fm*t*2*pi);

I = pi*2;
pm1 =@(t) Ac*cos(Fc*t*2*pi + I.*message(t));
plot_(1,pm1,'PM1')

Fm = 3;
message =@(t)
(Am*exp(decay*t)).*cos(Fm*t*2*pi);
pm2 =@(t) Ac*cos(Fc*t*2*pi + I.*message(t));
plot_(3,pm2,'PM2')

%%
```

```
freq =@(t) (Fc*2*pi + I.*message(t))./(2*pi);
plot(t_vec,arrayfun(freq,t_vec))

%%
function plot_comp(fig,am,fm,pm)
    global t_vec
    t_vec2 = t_vec(1:floor(end/2));
    figure(fig)
    clf
    subplot(3,1,1)
    plot(t_vec2,arrayfun(am,t_vec2))
    ylabel('AM')
%     set(gca,'xtick',[])
    subplot(3,1,2)
    plot(t_vec2,arrayfun(fm,t_vec2))
    ylabel('FM')
%     set(gca,'xtick',[])
    subplot(3,1,3)
    plot(t_vec2,arrayfun(pm,t_vec2))
    ylabel('PM')
    xlabel('Time')
    pos = get(gcf, 'Position');
    pos(2) = pos(2)/2;
    pos(3) = pos(3)*2;
    pos(4) = pos(4)*1.5;
    set(gcf, 'position',pos)
end

function plot_(fig,fun,ylab)
    global carrier message t_vec
    Tmin = t_vec(1); Tmax = t_vec(end);
    close(figure(fig))
    figure(fig)
    subplot(3,1,1)
    fplot(carrier,[Tmin,Tmax])
    ylabel('Carrier')
    subplot(3,1,2)
    hold on
```

```
    fplot(message,[Tmin,Tmax])
    plot([Tmin,Tmax],[0,0])
    hold off
    ylabel('Message')

    y = arrayfun(fun,t_vec);
    subplot(3,1,3)
    plot(t_vec,y)
    ylabel(ylab)
    xlabel('Time')
    pos = get(gcf, 'Position');
    pos(2) = pos(2)/2;
    pos(3) = pos(3)*2;
    pos(4) = pos(4)*1.5;
    set(gcf, 'position',pos)
end
```