THE IMPLEMENTATION OF OPPORTUNISTIC MULTIPLE SPACECRAFT PER ANTENNA CONCEPTS ON THE MSU-STA DEEP SPACE STATION 17

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A new technique called the Opportunistic Multiple Spacecraft Per Antenna (OMSPA) is being developed by scientists at the Deep Space Network (DSN), and at the Jet Propulsion Laboratory (JPL). This technique is key to allow communication with many spacecrafts from a single antenna simultaneously. Currently, this is not possible with the existing JPL-DSN infrastructure. In a historic alliance, Morehead State has been invited to be part of the DSN as the first ever external organization outside of NASA to do so. As part of this, the MSU 21 Meter Space Tracking Antenna will be used as a communications asset and to allow experimentation with new techniques like OMSPA. These techniques are possible when two or more spacecraft are along the line of sight of the antenna and within its main beam. Frequencies in a broadband are collected, digitized, and later individual spacecraft carriers are decomposed using digital signal processing techniques. Currently, using the DSN antenna assets for experimentation is difficult, as all existing assets are fully scheduled. The Space Science Center is proud to be able to

contribute to the DSN by providing an experimental platform for the development of new and exciting technologies. This project is designed to construct the experimental platforms in hardware and software, as well as to document the effort so that this experiment can continue across the next several years.

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1.0 **Executive Summary**

The opportunistic multiple spacecraft per antenna (OMSPA) theory offers a solution for the Deep Space Network's capacity drawbacks. Due to the DSN being over-subscribed with high profile missions, they are too busy to take on small-time, unfunded, yet innovative, projects. Morehead State University is an ideal fit for this project due to our ground station and 21-meter antenna being the newest node on the Deep Space Network. Our facilities and university status are the perfect combination for legitimate experimentation. Working closely with the DSN as a partner also gives valuable experience to all students involved.

The Morehead State 21-meter antenna has a relatively smaller diameter, but with a larger beam width. This allows the DSN to capitalize by listening to multiple spacecraft at once by receiving the whole receive band in one piece and tuning the receivers to any DSN channel in the band, allowing only one spacecraft to transmit at a time. The band is received by the 21- meter at 8.4-8.5 Gigahertz by the Calisto cryogenic local noise amplifier and the signal is down-converted to a 100 MHz bandwidth from the Hydrogen MASER (microwave amplification by stimulated emission of radiation). The intermediate frequency (IF) from the received signal is at 300-400 MHz and the signal is then translated over a fiber link where it is received by our mission control center.

Once received by the mission control center, the fiber link is converted to a radio frequency (RF) signal and sent to the IF panel. Here, the data is split between the Data Tracking and Telemetry (DTT) and the B210 Ettus Research receivers. Each spacecraft frequency will be received on an individual B210 receiver. Power dividers allow us to connect multiple receivers at one point and each receiver will connect to an integrated circuit that will send the data stream over a secure internet site. From here, spacecraft operators and users can access their received data.

The OMSPA solution also incorporates a great deal of software. A Linux operating system is required to run the GNU Radio Companion software, which allows us to experiment and test our theories without hardware. Software-defined radio is also required for testing how we retrieve data. Using these software programs and the C language, we can set up our software so that it receives data, time stamps it accurately, and stores it with correct header files.

The OMSPA system underwent numerous tests before being successfully demonstrated during the tracking of the MarCO/InSight spacecraft by Morehead State University. This was the first OMSPA demonstration with CubeSats, making it a historic event! This paper will further describe the materials, testing, and design of the OMSPA concept.

To summarize, this project greatly helps the Deep Space Network, while also giving notoriety to Morehead State University. Due to Morehead's advanced ground station capabilities and close relationship with the DSN, the partnership seems to be a perfect fit. This project seeks to capture all the work that has already been done and set groundwork for future students who work on this design.

2.0 Introduction

2.1 Morehead State Ground Station/ DSS-17

A new technique called the Opportunistic Multiple Spacecraft Per Antenna (OMSPA) is being developed by scientists at the Deep Space Network (DSN), and at the Jet Propulsion Laboratory (JPL). This technique is key to allow communication with many spacecrafts from a single antenna simultaneously. Currently, this is not possible with the existing JPL-DSN infrastructure. In a historic alliance, Morehead State has been invited to be part of the DSN as the first ever external organization outside of NASA to do so. As part of this, the MSU 21 Meter Space Tracking Antenna will be used as a communications asset and to allow experimentation with new techniques like OMSPA. These techniques are possible when two or more spacecraft are along the line of sight of the antenna and within its main beam. Frequencies in a broadband are collected, digitized, and later individual spacecraft carriers are decomposed using digital signal processing techniques. Currently, using the DSN antenna assets for experimentation is difficult, as all existing assets are fully scheduled. The Space Science Center is proud to be able to contribute to the DSN by providing an experimental platform for the development of new and exciting technologies. This project is designed to construct the experimental platforms in hardware and software, as well as to document the effort so that this experiment can continue across the next several years.

The affordability of CubeSats allows more teams around the world to create their own missions from design to launch. It allows students at universities to learn how to build hardware and allows small companies to hitch their payload to rockets and put their ideas into space. At Morehead State University, students design, test, integrate, fabricate hardware all in-house. Without the relative cheapness of these CubeSat missions, many students and engineers would miss out on learning these important processes and skills. The development of these small payloads allows more science to be done for a lower price. The Space Launch System, the most powerful rocket built by NASA to date, will carry thirteen small satellites as secondary payloads on its maiden voyage. These CubeSats will provide valuable data and continue to become more valuable as small sensor technology advances.

When a CubeSat mission is underway, it is easy to see how the price and size of the spacecraft are correlated. However, the ground operations of these missions are not simple, even if they are manned by smaller teams. CubeSats have significant tradeoffs, their small form factors make it cheaper to fly newly developing technologies, but the small size also reduces the transmission power from the spacecraft, as well as space for telecommunication hardware (Abraham, MacNeal, & Heckman, 2016). This forces the ground station sizes to increase to see the same data rates as larger spacecraft, even at the same distances. Missions that go beyond geosynchronous orbit need even larger ground stations due to the inverse relationship between signal power and the square of the distance between the satellite and the ground station (Abraham, MacNeal, & Heckman, 2016). According to the paper “Enabling Affordable Communications for the Burgeoning Deep Space CubeSat Fleet”, written by Douglas Abraham, “A CubeSat in geosynchronous orbit receiving the same signal from the Earth’s surface as a CubeSat in low Earth orbit, will receive that signal with roughly one ten-thousandth the power that the low Earth orbit CubeSat does. A CubeSat at the Moon will receive that same signal with roughly one-millionth the power. And, a CubeSat at Mars will receive that same signal with roughly three trillionths the power.”. The capabilities needed to support missions that go far beyond GEO orbits are normally handled by NASA's Deep Space Network, however, the popularity of CubeSats are greatly increasing, which causes the DSN to become oversubscribed.

2.2 Deep Space Network Partnership

The partnership between Morehead State University and NASA’s Deep Space Network was an ideal match for this project. The knowledge and experience from JPL combined with Morehead State’s ground station facilities provide minimal risk development at a low cost. The DSN has four sites across the globe, Canberra, Australia; Madrid, Spain; Goldstone, California; and now, Morehead State University, Kentucky. The DSN can support a wide range communication needs due to 70 m and 34 m antennas being available at each site, except Morehead State University, where a 21 m antenna is used. Each antenna uses X-band (sometimes S-band) transmitters, along with cryogenically cooled low noise amplifiers.

Due to the DSN now running at near- capacity due to the increase of deep space CubeSat missions, they have started looking into new ways to ease help ease the load. Their approach is to (1) develop simultaneously, shared beam "multi-spacecraft" communications, (2) develop a network of support with other agencies and universities, and (3) to develop less uplink-intensive navigation technologies (Abraham, MacNeal, & Heckman, 2016). Morehead State is primarily interested in the first two ideas. The idea of multiple spacecraft in a cluster sharing one beam from the ground station antenna and downlinking simultaneously involves a great amount of experimentation, much of which was conducted at Morehead State University. Currently, there are only two receivers at each antenna (2-MSPA), meaning only two satellites can be seen at an instance at different frequencies. Downlink experiments have also been run for 4 satellites in a single beam width (4-MSPA) and for an indefinite number of spacecraft (OMSPA). These technologies would not only lessen the DSN's mission load but also provide more affordable communications for the DSN and mission partners.

2.3 Implementing the OMSPA Design at Morehead State

To run a successful OMSPA experiment at Morehead State, it was necessary to plan out testing methods and create materials lists. The hardware used for testing and demo work for this project was substantial and, without loaned hardware from the Space Science Center, this would have been a very expensive project to produce. Multiple computers were needed, along with a USRP receiver for each. This also includes all the test equipment needed (power amplifier, spectrum analyzer, antennas) and the hardware used in ground operations. The software used for this project was GNU Radio Companion, which is an operating system that deals with radio functionality. GNU Radio Companion (GRC) only runs on the Linux OS and is extremely useful in experimenting with the specific hardware used for the OMSPA design.

The experiments designed for this project test the functionality, range, and performance of the hardware. The first “milestone” test was verifying that we could see the down-converted ASTERIA signal on each computer. The second test was to verify that we could send a simulated signal to each receiver via a separate testbed computer. The third test was to see if multiple, distinct, signals could be simulated and transmitted from the testbed to the OMSPA computer cluster. Here, each radio is tuned to its corresponding, incoming signal. Once each test was verified and complete, the system was ready for the MarCO demonstration. The MarCO (Mars Cube One) demonstration was an enormous success for the OMSPA experiment, as data was recorded successfully from each spacecraft (3) launched.

3.0 Materials

3.1 Hardware

The complete bill of materials (BOM) can be found in Appendix E. Images of all hardware and hardware setups can be found in Appendix D.

3.1.1 B210 Ettus Research Receiver

The B210 uses a universal software radio peripheral (USRP) platform and continuously covers the frequency range 70 MHz to 6 GHz, which fits perfectly within the parameters of this project. Low cost experimentation is the main use of the B210 and the USRP Hardware Driver is fully supported, meaning development with GNU Radio is simple and seamless. This USRP makes use of a radio frequency integrated circuit (RFIC) direct conversion transceiver which can provide about 56 MHz of bandwidth. Four B210 USRP radios were used in experimentation (one for each computer). The B210s were connected to the fiber intermediate frequency (IF) panel in the Mission Operations Center (MOC) via a four-way power divider. A block diagram of the system can be seen in Appendix A.

3.1.2 Hack RF One

The Hack RF is an inexpensive software defined radio peripheral created by Great Scott Gadgets. The Hack RF can transmit and receive radio signals from 1 MHz to 6 GHz and is designed to allow the testing and development of experimental radio systems. During OMSPA testing, three Hack RFs were used to simulate radio signals at different frequencies using the GNU radio companion software.

3.1.3 Ground Station Equipment and Testing Equipment

Morehead State's 21 Meter system is a dual-purpose instrument, used as a ground station for small satellites and a radio telescope for astronomy research. Students who work with the ground operations team gain valuable experience in research, instrumentation, engineering design, and systems level engineering experience. The 21-meter system also acts as a test-bed for experimental systems for small satellite hardware. Currently, MSU's ground station is undergoing an upgrade to become compatible with NASA's Deep Space Network (DSN). The transition requires performance upgrades from certain instruments such as the low noise amplifier, local oscillator, down converter, etc. These instruments can be found in the lower equipment room of the 21 meter and can be controlled remotely from the mission operations center.

While performing the various system tests needed to validate the OMSPA solution, multiple instruments were used for validating the simulated signals being produced by the Hack RF(s).

The equipment used is listed below:

- HP 8349B Microwave Amplifier: This power amplifier provided power to be effective against RF losses and provides a frequency output range from 2 to 20 GHz. At 2 GHz, the amp produces an output of about 25 dBm of gain. The simulated signals transmitted from the Hack RF(s) were initially very weak and were not being picked up by the software-defined radio (SDR) in the mission operations center, so the power amplifier was added into the design.
- HP 8560E Spectrum Analyzer: This analyzer was used in verifying that specific frequencies were being successfully transmitted by the Hack RFs and received by the

B210s. The HP8560E has a continuous frequency sweep from 30 Hz to 2.9 GHz and 1 Hz resolution bandwidths.

- Horn antenna, SMA adapters, and cables: The horn antenna was used to blast the simulated signals from the Hack RFs to the 21 meter, where the signals were down converted and sent back down to the MOC over the fiber line. The cables and adapters were needed for hooking up equipment for testing and the MarCO demonstration.

3.2 Software

3.2.1 GNU Radio Companion

GNU Radio Companion (GRC) is an operating system that considers radio functionality. Incredibly useful in experimenting and testing, GRC allows one to program hardware or implement certain features of hardware into code. This software development tool provides users with a large library of signal processing blocks that can be used to create software-defined radios with cheap, available, external RF equipment. GNU radio only runs on Windows or Linux OS, however for this project the Linux OS was used. The OS ran on a VirtualBox virtual machine (VM). GNU Radio is also very handy in creating detailed flow graphs for system design. Another useful feature of GNU radio is that the user has access to various data types, including:

- Byte: 1 byte of data (8 bits per element)
- Float: 4-byte floating point
- Short: 2-byte integer
- Int: 4-byte integer
- Complex: 8 bytes (a pair of floats)

The blocks in GRC connect through data streams that have a specific data type. GNU radio will not allow a flow graph to compile at runtime if two connecting blocks do not have matching data types.

Gnu Radio Companion was used for creating different flow graphs that would transmit signals through the Hack RFs, receive signals by the B210s, create spectrum plots (fast Fourier transform or ‘FFT’ plots) that would show the transmitted and received signals, and oscilloscope plots that showed the sample rate of the received signals. Examples of the GRC flow graphs can be seen in Appendix B. The “blocks” are blocks of code that can be manipulated. New blocks can also be created. These custom blocks are called “out of tree modules” (OOTM) and are created according to specific testing parameters. They are called OOTM because they do not live within the GRC source tree. The custom OOTMs allow the user to implement their own functions and maintain the code themselves. For OMSPA, several OOTMs were created to receive data and write it to an output file. The specific functions of the OMSPA OOTMs includes; reading from the data files received by the B210s and convert them to proper GRC format (file.dat), sending GRC data files to the USRP B210, receiving data from the USRP (receive) and outputs the files to ‘output.dat’, and writing a generated ‘. wvsr’ file from the received, sampled data from the output.dat file. The “wvsr” file is specific to NASA JPL’s Very-long-baseline interferometry (VLBI) science recorder (VSR). The Wideband VSR, or WVSR, makes use of a digital baseband converter which records data straight to a hard drive with significant storage capability. From here data is sent to JPL via the ‘wvsr’ format.

3.2.2 Software Defined Radio

The software-defined radios that are used in Morehead's mission control center are very sensitive and are used primarily for the tracking of spacecraft. For this project, these SDR's were used in testing the system with the Hack RF(s) by verifying that a signal was being transmitted and seen. They were also used in the tracking of ASTERIA, MarCO A and B, and InSight, where OMSPA was tested, and subsequently demonstrated successfully. Figures and images of the software defined radio used in testing can be seen in Appendix B.

4.0 Testing Challenges and Solutions

4.1 Setup for Testing the OMSPA system

The equipment that was setup includes an OMSPA computer cluster of four, however, by making use of a KVM switch (keyboard, video, and mouse) users can easily switch between whichever OMSPA computer they need during testing or tracking. Each computer is equipped with its own B210 recorder, and each recorder will be connected to a four-way power divider. The power divider is connected to the IF panel, where the signal comes in from the 21-meter, which was operating with an S-band feed at the time. The 21-meter began operating with an X-band feed the day before the launch of MarCO, which was launched May 5th, 2018 (with InSight). Each OMSPA computer had identically cloned hard drives, where GNU radio companion was already loaded onto the Linux OS. The flow graphs that were used in GRC on each computer were, for the most part, the same. They differed in that each would be tuned to record a specific frequency from the receive band. For most of the testing, only three of the OMSPA computers were used. For the MarCO demonstration, the first three OMSPA computers were for each of the satellites being tracked, respectively. While the fourth OMSPA computer was used for reading and writing the data files. This computer cluster lived in MSU’s MOC.

On the other side of the MOC, lived the testbed computer. Here, signals were simulated using GRC and the Hack RFs, along with the power amplifier and horn antenna. A block diagram showing the overall testbed/cluster design can be seen in Appendix A. Each Hack RF plugs into the testbed computer, which runs the Linux OS, and are connected on the other end with another four-way power divider. Only three Hack RFs were used in testing, so the fourth terminal on the divider was secured with a dummy load. The other end of the power divider was connected to the HP power amplifier, which was connected to the horn antenna. Here the signal is blasted at the 21-meter, a down-converted signal is converted from RF to fiber and sent over the fiber line to the MOC. The signal is converted back to RF and connected to the IF panel, where the received IF sample is split between the B210 USRPs.

4.2 ASTERIA Pass Testing

ASTERIA, which stands for Arcsecond Space Telescope Enabling Research in Astrophysics, is a 6U CubeSat created by NASA JPL and deployed on November 20th, 2017 from the International Space Station (ISS). The ASTERIA mission seeks to demonstrate technology that can make astrophysical measurements on board a CubeSat, but mainly the mission is to train upcoming engineers. ASTERIA is being tracked by Morehead's 21 meter and offers training for the students here as well.

Since MSU tracks ASTERIA multiple times a day, it made sense to take advantage of these passes to test whether each B210 could receive the down-converted ASTERIA signal at 70 MHz. the test was a complete success, it was verified that each of the four B210 USRPs, when tuned to the 70 MHz center frequency, picked up the ASTERIA signal. Appendix B shows the oscilloscope plot and spectrum plot from this test, and a very strong signal can be seen at the 70 MHz center frequency. This test was a milestone in that it was verified that the system worked and could receive data from an actual spacecraft. It also demonstrated the sensitivity and higher noise levels of the B210s. From here, it was agreed that the next test would be to see whether we could simulate three distinct signals within a close frequency range using the Hack RFs.

4.3 Transmitting Simulated Signals with the Hack RF

Getting the Hack RF to transmit posed a few challenges. The GRC on the testbed computer needed hardware drivers installed for the Hack RFs. These drivers add new signal processing blocks to the source tree that are specific to the Hack RF. Before building the block in Linux, it needed to be determined that the testbed computer recognized the Hack RF device. The command "$ hackrf_info", when entered in to the terminal tells the user whether a device is seen. If everything goes well the user will see the devices' serial number, board ID, part ID number, etc. displayed in the terminal. When performed, the computer recognized the Hack RF that was plugged in. With the device verified, the user can download the drivers that allow for use of the OsmoSDR block which is necessary for transmitting and receiving signals with the Hack RF. The build system of the gr-osmosdr will not compile in GRC if certain dependencies are not properly installed. When the gr-osmosdr builds successfully in Linux, source and sink osmocom components will be visible and usable in the GRC library. Once the osmocom drivers were installed successfully the flow graph could be compiled.

The GRC flow graph used to transmit simulated signals from the Hack RF contains a file source. This file source is specifically chosen to be the IRIS emulator feedback playback on loop. The IRIS emulator is a device that emulates the IRIS transponder, an instrument developed by NASA JPL is the main form of communication on the Lunar IceCube mission. However, since MSU does not own an actual IRIS transponder, an emulator was created for testing purposes. The file source is a playback loop from the emulator and can be used to simulate a signal at a unique frequency. In Appendix B the flow graph and spectrum plot of the transmitted signal can be seen.

To verify that the B210s will see the down-converted signal, the Hack RF was connected to the spectrum analyzer and tuned to the transmit frequency, which was set at 2.271 GHz. The signal was seen on the spectrum analyzer, so the Hack RF was then connected to the horn antenna. An issue arose in that the signal was not seen by the SDRs in the MOC. It was assumed that the signal was too weak to be seen. The power amplifier was then brought into the system and connected between the Hack RF and the horn antenna. It provided about +20 dB of gain. This successfully produced a strong enough signal and the downconverted frequency was seen at 75 MHz. It was verified that each B210 picked up the signal when tuned to 75 MHz center frequency. The emulated signal was transmitted with +20 dB RF gain, +20 dB IF gain, 20 dB of baseband gain, and a 20 MHz sample rate. Since, getting one Hack RF was a proved success, the next step was to get three of them transmitting at once.

4.4 Transmitting Simulated Signals with multiple Hack RFs

There was a real challenge in getting each Hack RF to transmit a different frequency at the same time. The first step was to plug each Hack RF into the computer and connect them using a power divider. Then the “$ hackrf_info” command was typed into the terminal. The serial number, board ID, and part ID number for each device was displayed in the terminal. The terminal also numbered each board (0-2).

GNU radio allows the ability to go into a block and change its properties accordingly. For the osmocom sink blocks, the user must enter the specific serial number of the Hack RF for the block to connect with the device and transmit the signal. In one flow graph, there can be three osmocom sinks for each of the Hack RF devices, and each sink can be tuned to transmit a different signal. It was challenging to discover that this was the way to connect the devices with the flow graph because with just one Hack RF the computer automatically knows which device you're using. Specifically, it was a challenge because once it was discovered that the serial ID was needed to be entered in “device arguments”, which is a section of the osmocom sink block that syncs the devices to the flow graph, it still did not work. It took much further research and frustration to realize that only the last eight digits of the serial ID were needed. Once the last 8 digits were tried and entered for each osmocom sink block, the test became a success. To verify that the system would recognize these signals, the power divider connected to the Hack RFs was connected again to the spectrum analyzer. Images of the spectrum analyzer showing all three signals, the block diagram of the system, and the signals seen on the SDRs are seen in Appendix B.

The frequencies that were manually set for each Hack RF were 2.271 GHz, 2.273 GHz, and 2.275 GHz and their associated down converted signals were seen at 72 MHz, 74 MHz, and 76 MHz, respectively. The frequencies were being transmitted at an RF gain of 10 dB and an IF gain of 50 dB. The baseband gain was set to 20 dB at a bandwidth of 10 MHz. For this test, only OMSPA 1, OMSPA 2, and OMSPA 3 were used. Each B210 at the OMSPA computers were tuned to its correlated, down-converted frequency with a receive gain of 20 dB and IF frequency of 10 MHz. In appendix B, an image of each signal on the generated oscilloscopes and spectrum plots from each B210 can be seen. The success of this test was crucial in that it was verified the OMSPA system could receive a band with prominent signals and record the data on receivers tuned to the down-converted frequencies.

4.5 End-to-end Testing with JPL

End to end testing consisted of running the three Hack RFs at the same three frequencies as before and recording the associated IF on all three channels of the B210s (72, 74, 76 MHz). Unfortunately, the power going into the USRPs at the time of the end to end testing was unknown. The NASA JPL team, who consists of Doug Abraham, Sue Finley, and Zaid Towfic, could remotely SSH into each of the OMSPA computers using their IP addresses and passwords. By remotely logging in to the computers, the JPL team could verify that there was signal visibility.

During the actual test, the JPL team was only able to see the signal being recorded on the OMSPA 2 computer and therefore most of their tests were done on this computer. They also could not compile and run the flow graphs to see the generated spectrum plot, believed to be because of the dated OS on the computer. This caused significant issues during testing. While JPL was testing remotely, they sought to sample the signal at a few MHz and record the received data in the WVSR format and GNU radio complex floating-point format, where the computer splits and quantizes the data. However, OMSPA 2 was too slow to record the data at that rate and ended up dropping frames. In GRC, at runtime, if the user sees repeating “O’s” or “U’s” it means frames are being dropped and the computer is unable to save data fast enough to the disk. The data coming in from the USRP over USB 3.0 at 32 bits is saved to byte data type. As the data rate was decreased from MHz to kHz, less repeating “O’s and U’s” were seen. The highest data rate used by JPL was sampled at 400 kHz and the samples were saved in byte to a GNU radio file named “b200_zaid.grc”, which was created by JPL team partner Zaid Towfic.

Another problem that arose was the bandwidth going into the USRPs was too broad to modulate. The signals that were being transmitted were about 2 MHz too wide (Appendix B). However, on the day of the demo the bandwidth would be smaller and there would be more sampling done in the kHz range, which was plenty. To correct this, JPL asked for further testing using a different source file than the IRIS emulator playback loop with the flow graph “b200_zaid.grc”. They also asked for a measurement of the signal level going into the USRPs. These tests are described in further detail in the next section.

4.6 Measurement Testing

The goal of running these measurement tests was to find the signal power (in dBm) going into the B210s and to repeat the same test with a new file source. The file “b200_zaid.grc” was edited to include a new source file and the osmocom sink blocks for each Hack RF device and renamed “transmit_msu.grc” on the testbed computer, which is seen in Appendix B. This new file had the file source replaced so that filtered noise at 100 kHz would be transmitted at a bandwidth of 200 kHz. The frequencies for this test were changed to 2.273, 2.275, and 2.277 GHz, respectively, with a sampling rate of 200 kHz. To make sure the signal was being correctly transmitted, the spectrum analyzer was hooked up to the power amplifier. Each signal was being transmitted clearly, so the power amplifier was reconnected to the horn antenna. The received, down-converted signal was picked up by the more sensitive SDRs in the MOC and the bandwidth was much narrower (seen in Appendix B). Each OMSPA computer ran the “b200_zaid.grc” script and each B210 was tuned to 72, 74, and 76 MHz. On the fourth termination of the power divider, the fourth B210 was unconnected (as it was not used) and instead the spectrum analyzer was connected to measure the signal levels. On the spectrum analyzer the power of the signal going into the B210’s was measured at around -51 dBm. On the OMSPA computers there was no sign of repeating O’s or U’s, which meant there was no dropping of frames. The test results looked reasonable (results from JPL seen in Appendix C), however the recording was saturated due to the receive gain on the B210s being set to 70 dB. Another issue that arose was the spectrum being off by about 47 kHz (seen in Appendix B). This was noticed by Zaid and he suggested that it could be due to the transmitter and receiver not sharing a common local oscillator. However, the issue was small, and if the offset was not more than 100 kHz during the MarCO demonstration, it wouldn't be an issue. Zaid's transmitted file spectrum plot is seen in appendix C and shows slight, parabolic shaping caused by the shape of the USRP filter. Increasing the bandwidth on the channels in the USRP source setting would help to fix this.

Further testing was necessary before the setup could be approved for the MarCO demonstration. This new test consisted of running the same test as before, only now the receive gains would be changed to account for the saturation. In the file "b200_zaid.grc", which was on each OMSPA computer, there was a variable block where the receive gain could be tuned. A range of receive gains was tested at 0, 10, 20, 30, 40, 50, and 60 dB. An outputted data file was created for each receive gain value and saved on OMSPA 2, where JPL could access them and analyze them further.

Zaid Towfic further analyzed the data files from the new test and determined they looked good, aside from the frequency shift, and that receive gains between 20-50 dB worked best (clipping at 50 dB, seen in appendix B). Due to the power level being at -51 dBm, a receive gain of 30 dB would work best on the day of the MarCO demonstration, in case RF levels were higher than expected. From this test, it was agreed the system was ready for the MarCO demonstration, which is explained further in the next section.

5.0 Mars Cube One and InSight Demonstration

The Mars Cube One (MarCO) spacecraft was the first CubeSat mission to journey to Mars. MarCO is a pair of tethered, “twin communications-relay” CubeSats named MarCO A and B whose mission is to monitor stationary Mars lander, InSight ("Mars Cube One (MarCO)", 2018). Built by NASA JPL, the MarCO spacecrafts measure at 36.6 centimeters by 24.3 centimeters by

11.8 centimeters, making them six-unit CubeSats (a standard one-unit CubeSat is a 10 cm x 10 cm x 10 cm cube) ("Mars Cube One (MarCO)", 2018). InSight, accompanied by MarCO, was launched from Vandenberg Air Force Base, California on May 5th, 2018 aboard the Atlas V rocket. The success of the MarCO mission would allow for "a 'bring-your-own' communications relay option", which would help future missions to Mars during the brief, risky atmospheric entry and landing ("Mars Cube One (MarCO)", 2018).

Morehead State acted as one of the primary ground stations used for tracking MarCO/InSight. The feed for MSU's 21 meter had to be swapped the day before the launch from an S-band feed (2 to 4 GHz) to an X-band feed (8 GHz to 12 GHz) to disrupt the ASTERIA mission as little as possible. The MarCO launch was the opportune time to demonstrate the OMSPA system and record data from multiple satellites simultaneously. The transmitting frequencies of MarCO A, B, and InSight were 8.414, 8.412, and 8.427 GHz, respectively. The OMSPA system would receive each down-converted frequency and record the associated IF, where JPL could remotely access said data for further analyses and manipulation. This was a historic mission and opportunity for Morehead State to prove the validity of OMSPA with the first Mars bound CubeSats. Morehead State only tracked InSight and MarCO for 5 days, where data was recorded from each spacecraft every day using the B210s.

5.1 MarCO Mission Day 1

On May 5th, 2018 Morehead State began tracking MarCO using the X-band feed in receive only mode. The OMSPA computers 1, 2, and 3 were all set to the corresponding, down converted frequencies of MarCO A, B, and InSight. InSight transmitted for the entire pass, while MarCO A and B transmitted one at a time. OMSPA 1 was tuned to record MarCO A at 314.160 MHz, OMSPA 2 was tuned to record MarCO B at 312.117 MHz, and OMSPA 3 was tuned to record

InSight at 326.78 MHz. For the first few days of tracking the GNU radio flowgraphs on each computer were only set to record the data coming in over IF and save it to an output file (ex. Day1_Insight.dat), so there was not a generated spectrum plot for each downlink. Instead, a spectrum analyzer was attached to the fourth terminal of the power divider. A receive gain of 30 dB was used one each receiver. Here, the signals could be verified and measured. MarCO A was seen at about 10 dB carrier to noise (C/N), where the noise floor was at about -60 dB. InSight was seen about 30 dB out of the noise and the power level was at -35 dBm. MarCO B had a carrier to noise ratio of about 27 dB and the power level measured going into the USRP was about -37 dBm. MarCO B's signal was significantly stronger than MarCO A, which was due to a geometry issue at the receiver in Goldstone, CA. The data files captured from the first day were later analyzed by the JPL team and they verified that the signals looked good and did not appear to be clipped, meaning the receive gain could be increased by about 3 to 5 dB for the second day of tracking.

5.2 MarCO Mission Day 2

On May 6th, 2018 InSight was seen at a center frequency of 327.100 MHz, and subcarriers were seen at 327.38 and 326.85 MHz. The signal appeared to be weaker at -50 dBm, as the spacecraft had increased in distance form Earth. The noise level was seen at -55 dBm on the spectrum analyzer with a resolution bandwidth of 100 kHz spanned to 10 MHz. MarCO A was seen at a center frequency of 314.228 MHz at a signal strength of -61 dBm (where the noise floor was at about -71 dBm). MarCO A had a carrier to noise ratio of 21.19 dB and a signal to noise ratio of about 30 dB. By this time, 71 frames were already recorded from MarCO A, which was more than the DSN at the time. MarCO B was later seen at 312.184 MHz with a signal strength of -54 dBm (noise level at -52 dBm), so the carrier to noise ratio was at 15 dB.

Demodulated frames from MarCO can be seen in Appendix C. The first five frames were decoded by the JPL team from the second day of tracking. The signal to noise ratio, energy per bit (Eb/No), and bit error rate for each frame can be seen. A plot of the data block constellation can be seen in Appendix C, along with the ASM waveform. Day 2 was successful in that actual data was recorded and decoded from MarCO. Seeing the demodulated frames was a significant point in this project.

Certain problems arose with the recording of InSight and caused the data to be incomplete. The subcarrier frequency used for InSight (281 kHz) was too high for the sampling rate. Only one subcarrier, where telemetry is located, was seen by in the file Insight_2.dat by JPL. However, they could still extract telemetry. Another file for InSight was made called "InSight Day 2.dat". This file was meant to replace "Insight_2.dat" with a more accurate frequency, but they were mislabeled, resulting in two files. From "Insight Day 2.dat", the main carrier was seen along with one of the subcarriers. This ended up being enough data for JPL to work with. The best way to correct the issues that arose was to set the receive center frequency on one USRP to be 120 kHz off the carrier frequency for Day 3 passes. This way the entire signal (carrier and subcarriers) would be seen.

5.3 MarCO Mission Day 3

On May 7th, 2018 InSight ended up being recorded wrong, the frequency that was entered GNU Radio was a more accurate carrier and the additional 120 kHz to account for the low sampling rate was not included (by accident). This caused the collect for InSight to have a center frequency at 0 kHz offset from the carrier, and telemetry could not be collected, as only the carrier was seen.

Day 3 was successful in that data was recorded for each MarCO spacecraft. MarCO A was seen at 314.228 MHz at a signal strength of -65 dBm. The main carrier was a skinny, single tone with subcarriers. The noise floor was observed at -80 dB with a signal peak at -64 dB. The carrier to noise ratio was 16 dB and significant Doppler shift was seen on MarCO A as it transitioned into nominal mode while moving farther from Earth. On this day the 10 MHz frequency reference from the MASER (microwave amplification by stimulated emission by radiation) was hooked up to record more accurate data. MarCO B was seen late in the pass, and it was seen at 312.189 MHz center frequency.

5.4 MarCO Mission Day 4

On May 8th, 2018 each spacecraft's associated IF was recorded with file extensions "_Day 4.dat" on each OMSPA computer. MarCO A was seen at 314.228 MHz carrier frequency at -59 dB. MarCO A behaved nominally during this pass. MarCO B was seen transmitting at 312.189 MHz with a carrier to noise ratio of 15 dB. The signal switched from 1k, 25 kHz subcarrier to 8k direct modulation halfway through the pass. This made MarCO B's signal appear to be much weaker. InSight was transmitting at 327.122 MHz with a carrier to noise ratio of 12 dB.

The fourth OMSPA computer was used during these tests to record the InSight IF and test the WVSR conversion block in GNU Radio. The maximum sampling rate of the WVSR block was set at 100 kHz and the maximum sampling rate for the file sink block was set to 5 MHz. While successful recordings from MarCO A and B were acquired, the data file for InSight was accidentally erased, which explains why no carrier was seen in the file. Only one day remained to fix the errors and get successful data from InSight. These changes included recording InSight at the IF + 120 kHz on OMSPA 3 and recording InSight on OMSPA 4 to test the WVSR block at the IF + 280 kHz.

5.5 MarCO Mission Day 5

On May 9th, 2018 the final recordings of MarCO A, B, and InSight were acquired. MarCO A and B were seen at their usual frequencies. InSight was transiting at with a center frequency at 327.128 MHz and was recorded at 327.248 MHz (IF + 120 kHz). On OMSPA 4 the WVSR block was being tested using the InSight IF plus 280 kHz and was recorded at 327.408 MHz. Successful collects from each spacecraft were verified by JPL and frames from the two MarCOs were decoded, with certainty that frames would be collected from InSight as well.

Although data was successfully collected for each spacecraft, the WVSR writing block for InSight on OMSPA 4 could not be demonstrated. The WVSR test file that was downloaded (test0508209.wvsr) was examined to see if any data was properly saved. The headers were easily readable, but the data was “identically zero”, according to an email from Zaid Towfic, who downloaded said test data. The reason for this was that the conversion block used “Complex to IShort” and only took input numbers from -1 to +1 and converted them to the short data type. This caused the data to be viewed as, essentially, zero.

Unfortunately, this was the last day of tracking the spacecrafts, so the WVSR writing flow graph could not be verified. However, the way to correct this would have been to multiply the output of the WVSR source block by the following equation; $(2^{15(-1)}) = 32767$. This would be applied before the conversion due to the output of the “Complex to IShort” block being whole numbers from -32767 to +32767, according to Zaid Towfic’s follow-up email regarding the downloaded test WVSR data file. An example of the corrected WVSR flow graph is seen in Appendix C.

5.6 MarCO Mission Summary

Although various challenges and errors occurred, the MarCO/InSight demonstration was exceedingly fruitful in validating the OMSPA concept, as at least 250 frames were decoded from each spacecraft since launch. The MarCO launch sought to demonstrate multiple technologies including: downlink using the X-band feed and DSN equipment at MSU (carrier lock, symbol lock), downlink using the X-band feed and MarCO receiver system, UHF uplink simulation of InSight for MarCO testing, and the OMSPA concept using the X-band feed and SDR-based multiple receiver system. This was the first ever OMSPA demonstration with a CubeSat and Morehead State was ecstatic to be included in such a historic demonstration.

6.0 Conclusion and Recommendations

Overall, the OMSPA concept was successfully verified during the MarCO/InSight demonstration. The Deep Space Network's over-subscribed schedule can be lightened and capitalized upon due to the opportunistic tracking of multiple spacecraft during scheduled downlink times. Where each satellite can be heard transmitting all the time, at different frequencies, in the same beam. Only one satellite at a time can communicate with the ground station, where transmit packets are sent via uplink. Recorders set up at the ground station, one for each transmitting spacecraft, are tuned to the corresponding down converted frequencies.

Morehead State University offered an experimental, legitimate test facility for the Deep Space Network in an efficient and cost-effective way. The 21-meter, which was used for its smaller diameter, yet large beam width, received the entire band from 8.4 to 8.5 GHz. The signal was then down converted to a 100 MHz band width and sent over a fiber link to the control center, where the RF signal is split at the IF panel, and the associated received IF sample is split between the USRP receivers. The digitized downlink is saved for later, after the SDR's channelize the band to record the spectra.

It was a privilege to work on this project due to its innovation, success, and the benefit of working with the distinguished partners of the JPL team. The significance of OMSPA in the aerospace industry is due to the DSN's ability to track more spacecraft at once. Many issues arose during testing and the MarCO demonstration. Some more significant problems included: not seeing signals on the SDRs, time stamping the data files, runtime/compile errors, and gathering all the required materials. The key to solving these were patience and focus. Sometimes the solutions were obvious, as others took quite a bit of troubleshooting. Although many problems occurred, this was still a very successful project, as it produced real proof of the concept goals.

This project had another goal; to create a foundation for future students to forward the progress on this far-reaching project. Chronicling the work that has been done, as well as the work that is currently being done is extremely important. Others who replicate this work will build of this foundation and add their own innovations. This mission was a huge achievement for Morehead State University, the Jet Propulsion Laboratory's Deep Space Network, and for all students and staff involved.

7.0 Bibliography

Abraham, D. S., & Finley, S. G. (February 15, 2015). Opportunistic MSPA Demonstration #1: Final Report. *IPN Progress Report*, 1-27. Retrieved September 5, 2017, from https://ipnpr.jpl.nasa.gov/progress_report/42-200/200B.pdf.

Abraham, D. S., MacNeal, B. E., & Heckman, D. P. (2016). *Enabling Affordable Communications for the Burgeoning Deep Space Cubesat Fleet*(pp. 1-20, Tech.). Pasadena, CA: Jet Propulsion Laboratory, California Institute of Technology.

Krajewski, J. (Ed.). (n.d.). Mars Cube One (MarCO). Retrieved June 7, 2018, from https://www.jpl.nasa.gov/cubesat/missions/marco.php

What is Software Defined Radio. (n.d.). Retrieved June 7, 2018, from https://www.wirelessinnovation.org/assets/documents/SoftwareDefinedRadio.pdf

8.0 Appendices

Appendix A – Block Diagrams

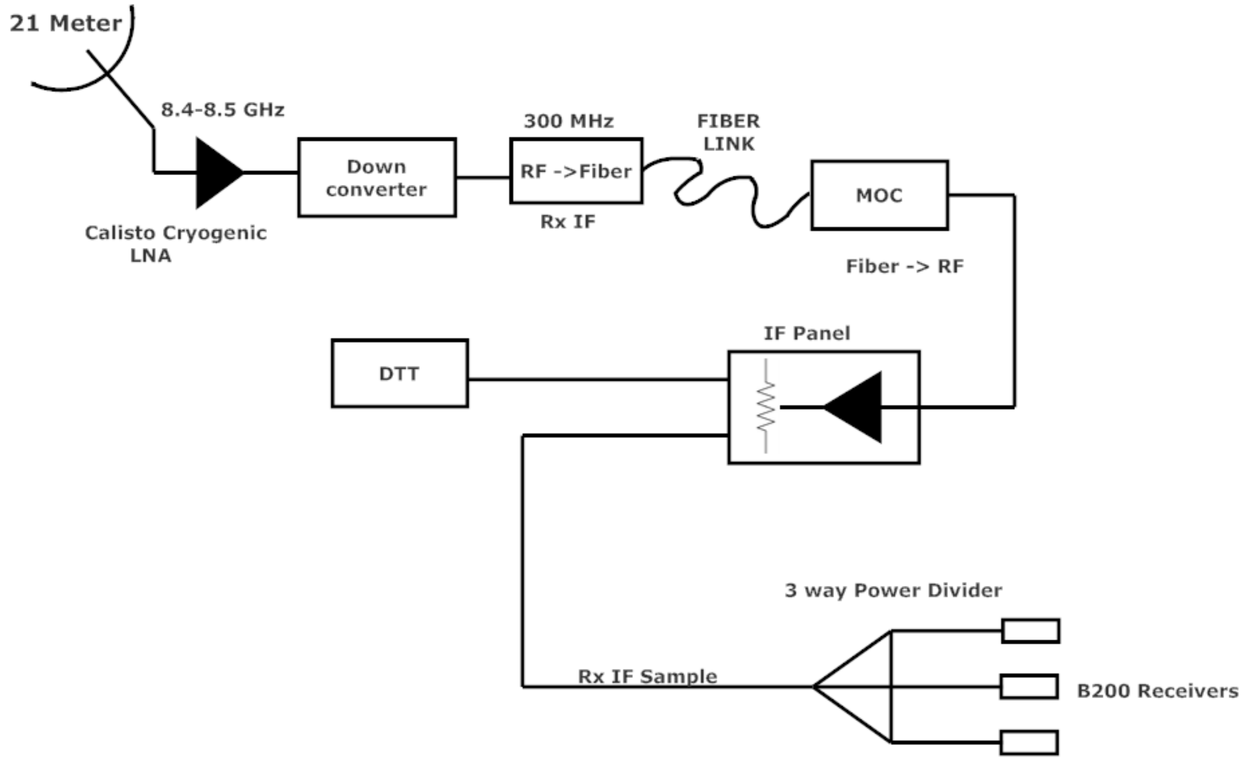


Figure 1: This image shows the receive path of Morehead State's ground station for the OMSPA experiment.

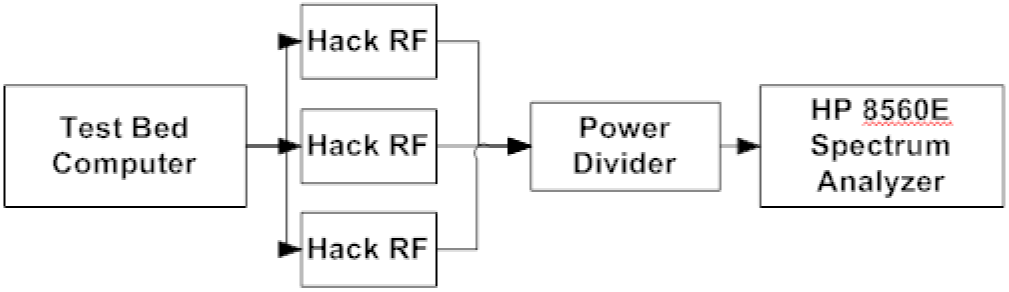


Figure 2: This image shows the test setup for verifying the signals being transmitted from the Hack RFs.

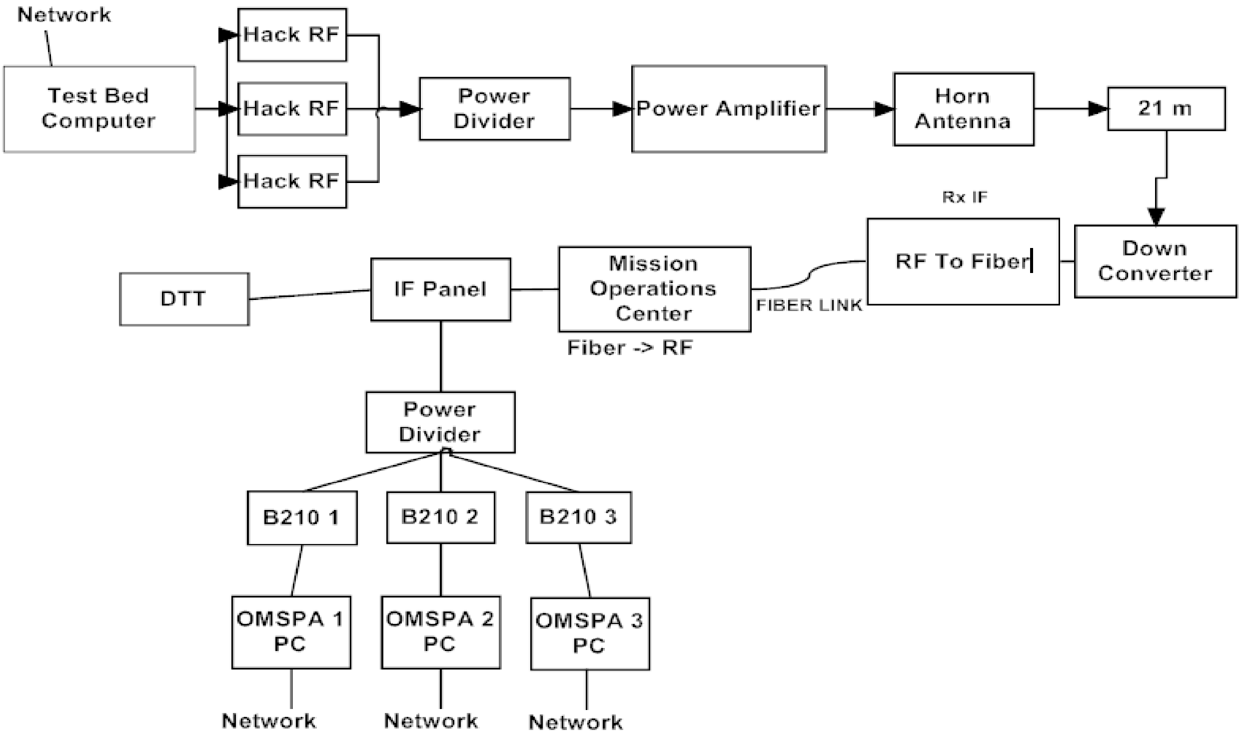


Figure 3: This image depicts the full system test setup for simulating multiple signals using the Hack RFs.

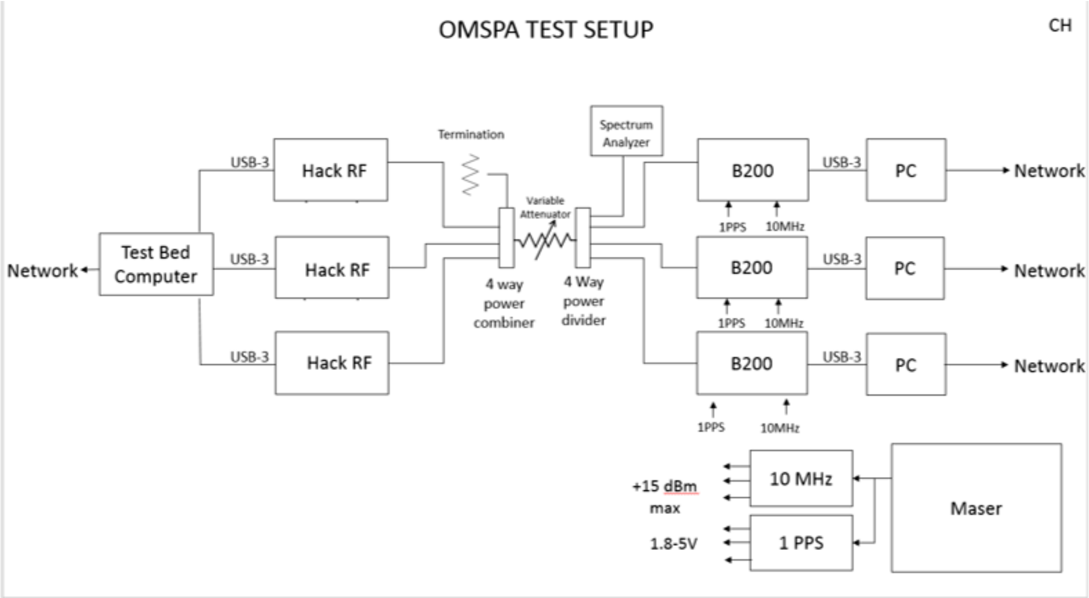
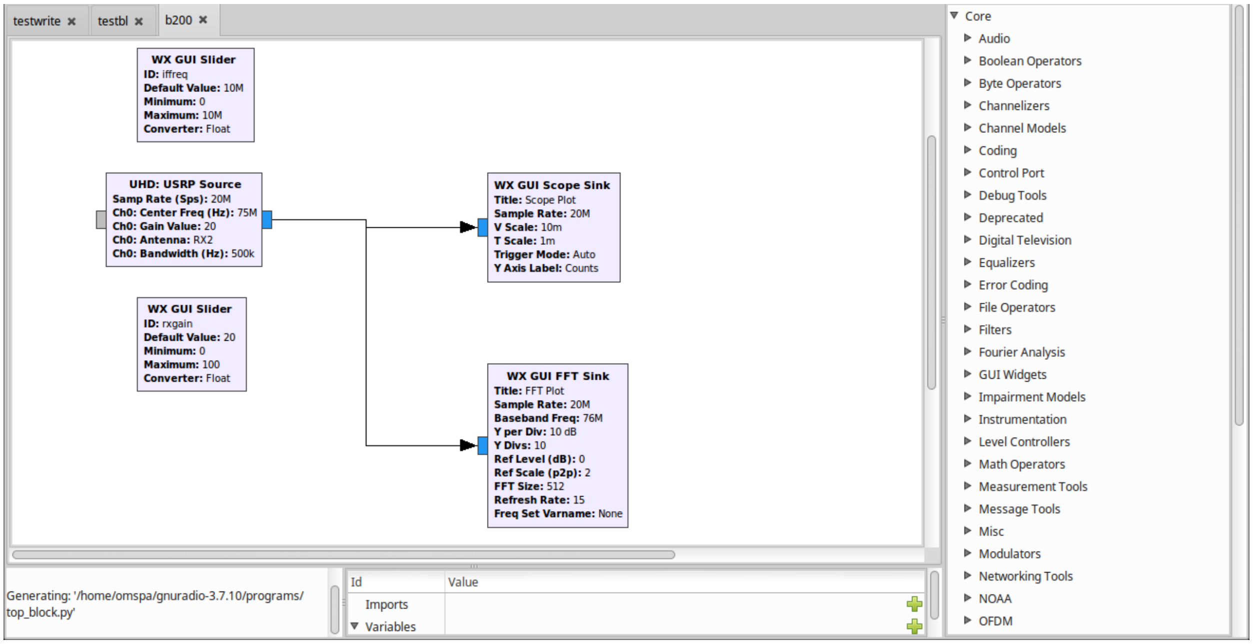


Figure 4: This block diagram, created by MSU ground station operator Chloe Hart, is slightly outdated, yet shows how the MASER is connected in the system.

Appendix B – Testing Results

ASTERIA Pass Testing



WX GUI Slider
ID: iffreq
Default Value: 10M
Minimum: 0
Maximum: 10M
Converter: Float

UHD: USRP Source
Samp Rate (Sps): 20M
Ch0: Center Freq (Hz): 75M
Ch0: Gain Value: 20
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 500k

WX GUI Slider
ID: rxgain
Default Value: 20
Minimum: 0
Maximum: 100
Converter: Float

WX GUI Scope Sink
Title: Scope Plot
Sample Rate: 20M
V Scale: 10m
T Scale: 1m
Trigger Mode: Auto
Y Axis Label: Counts

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 20M
Baseband Freq: 76M
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 512
Refresh Rate: 15
Freq Set Varname: None

Generating: '/home/omspa/gnuradio-3.7.10/programs/top_block.py'

Figure 5: This image shows the GRC flow graph used on OMSPA 3. The UHD: USRP source connects to the B210 USRP and the block is tuned to receive the ASTERIA signal.

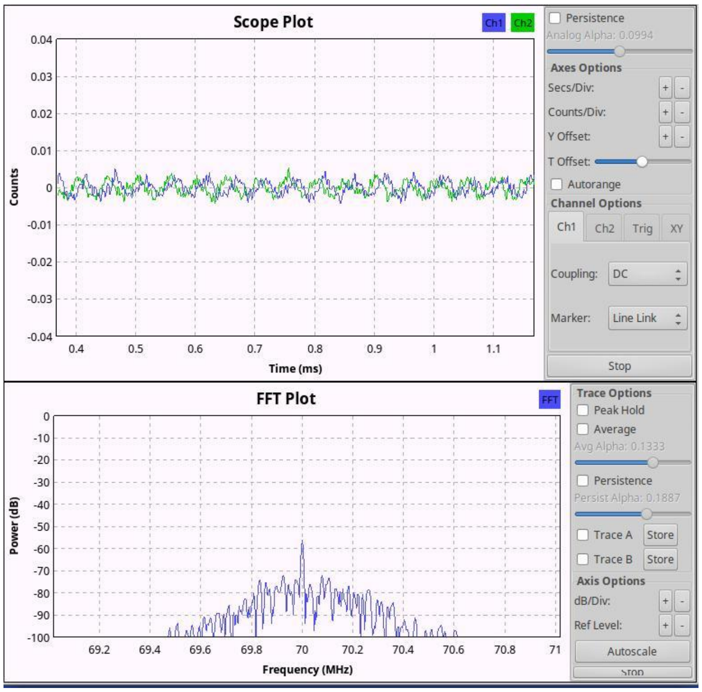
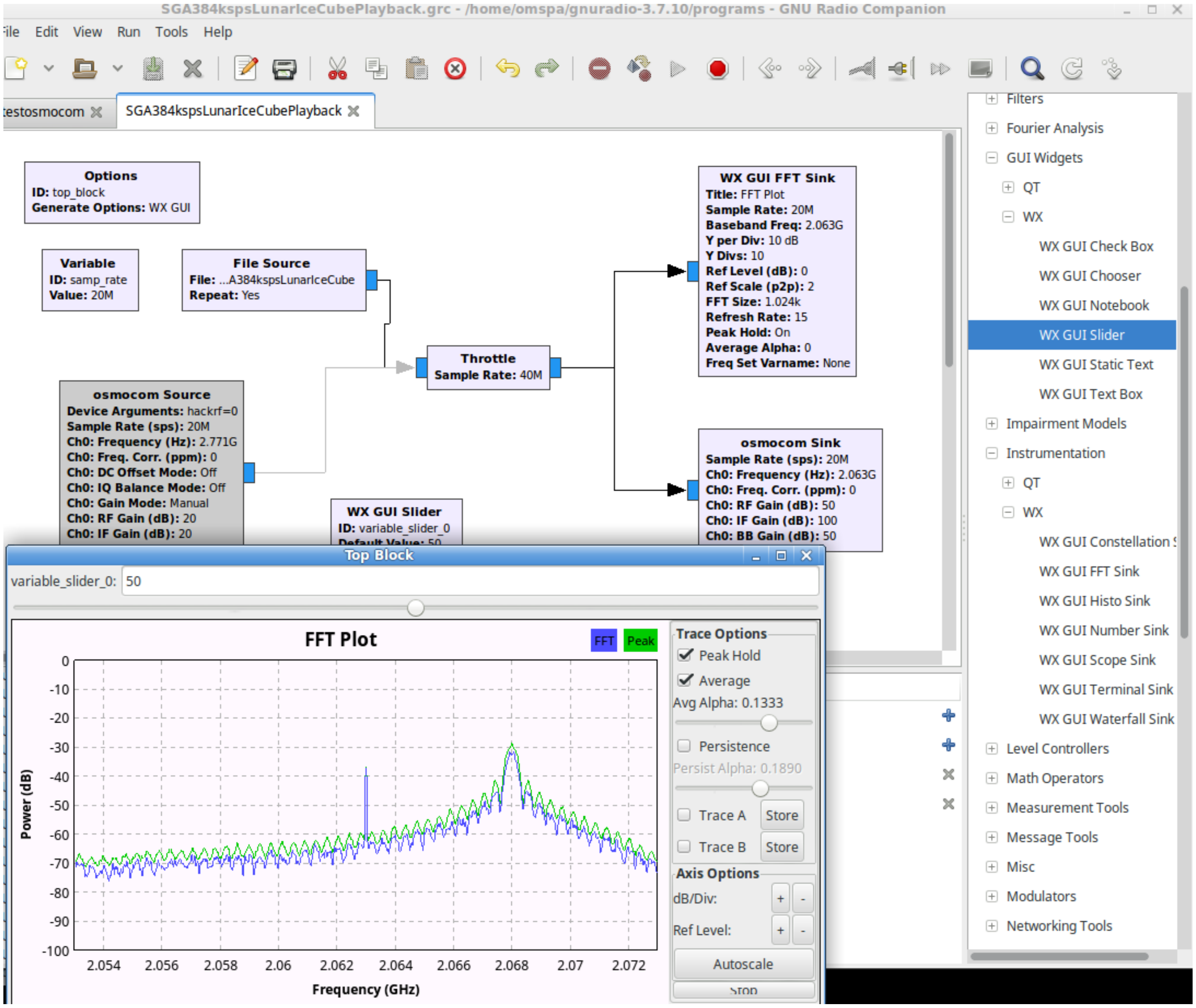


Figure 6: This image shows the spectrum created by the GRC flow graph. The ASTERIA signal can be seen at 70 MHz.

IRIS Emulator Testing



SGA384kspsLunarIceCubePlayback.grc - /home/omspa/gnuradio-3.7.10/programs - GNU Radio Companion

Options
ID: top_block
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 20M

File Source
File: ...A384kspsLunarIceCube
Repeat: Yes

Throttle
Sample Rate: 40M

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 20M
Baseband Freq: 2.063G
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Peak Hold: On
Average Alpha: 0
Freq Set Varname: None

osmocom Source
Device Arguments: hackrf=0
Sample Rate (sps): 20M
Ch0: Frequency (Hz): 2.771G
Ch0: Freq. Corr. (ppm): 0
Ch0: DC Offset Mode: Off
Ch0: IQ Balance Mode: Off
Ch0: Gain Mode: Manual
Ch0: RF Gain (dB): 20
Ch0: IF Gain (dB): 20

WX GUI Slider
ID: variable_slider_0
Default Value: 50

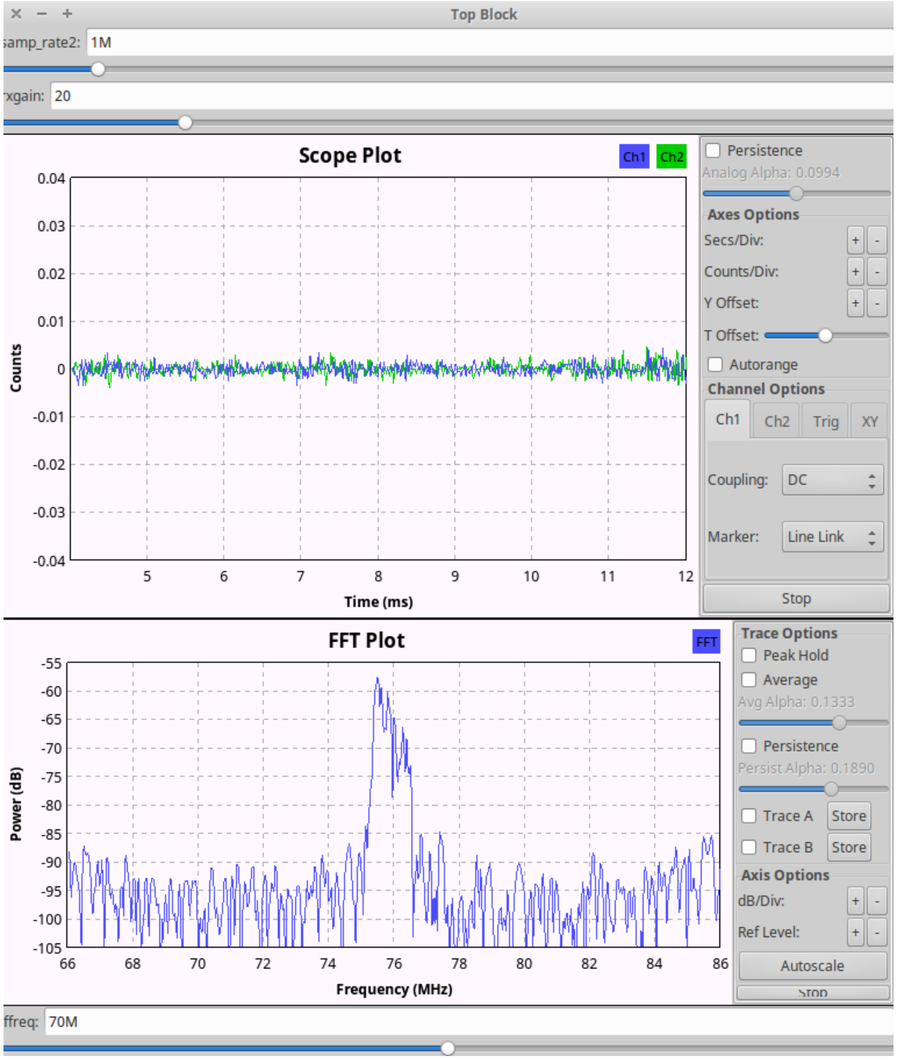
osmocom Sink
Sample Rate (sps): 20M
Ch0: Frequency (Hz): 2.063G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 50
Ch0: IF Gain (dB): 100
Ch0: BB Gain (dB): 50

Top Block

variable_slider_0: 50

☑ Peak Hold
☑ Average
Avg Alpha: 0.1333
☐ Persistence
Persist Alpha: 0.1890
☐ Trace A
☐ Trace B

Figure 7: This image shows the GRC flow graph that was on the testbed computer. The FFT plot shows what the raw signal being transmitted looks like. The file source was the IRIS emulator feedback loop and the signal transmitted was at 2.063 GHz.



amp_rate2: 1M

xgain: 20

ffreq: 70M

☐ Persistence

Analog Alpha: 0.0994

☐ Autorange

Coupling: DC

Marker: Line Link

☐ Peak Hold

☐ Average

Avg Alpha: 0.1333

☐ Persistence

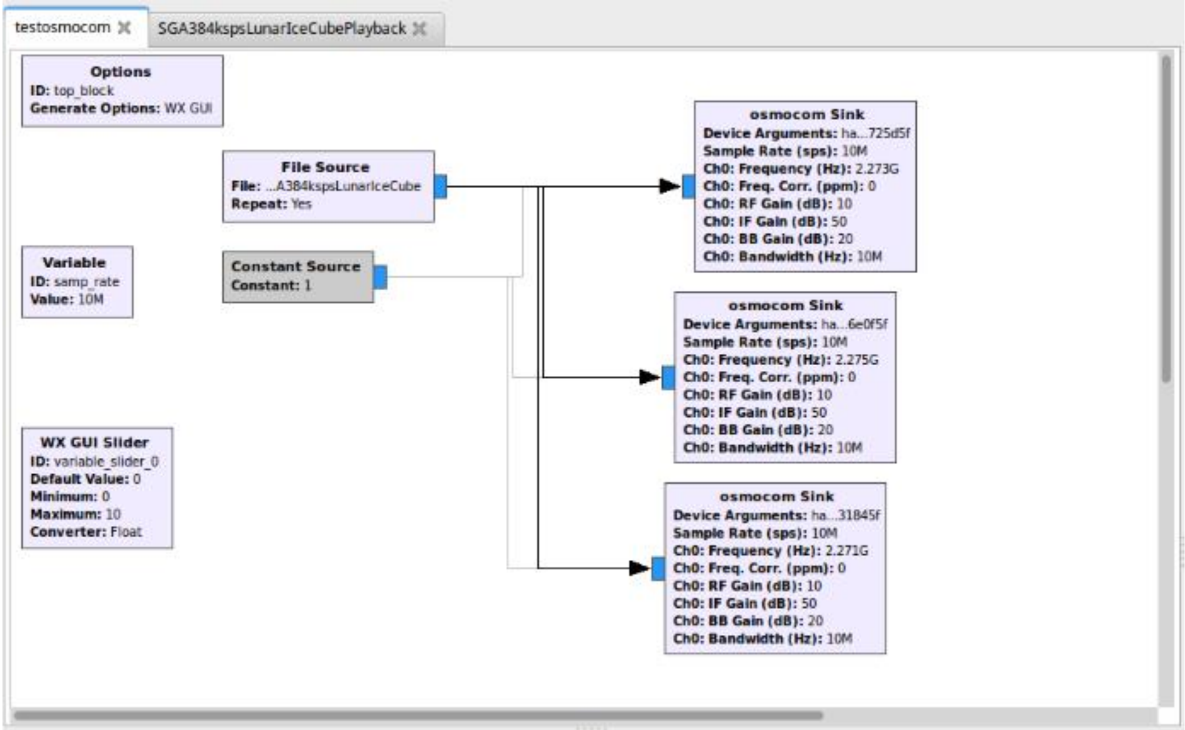
Persist Alpha: 0.1890

☐ Trace A

☐ Trace B

Figure 8: This image shows the oscilloscope and spectrum plots generated by the “b200” flowgraph in GRC on the OMSPA 2 computer. The down converted frequency was 75 MHz.

IRIS Emulator Playback with three Hack RFs



Options
ID: top_block
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 10M

WX GUI Slider
ID: variable_slider_0
Default Value: 0
Minimum: 0
Maximum: 10
Converter: Float

File Source
File: ...A384kspsLunarIceCube
Repeat: Yes

Constant Source
Constant: 1

osmocom Sink
Device Arguments: ha...725d5f
Sample Rate (sps): 10M
Ch0: Frequency (Hz): 2.273G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 50
Ch0: BB Gain (dB): 20
Ch0: Bandwidth (Hz): 10M

osmocom Sink
Device Arguments: ha...6e0f5f
Sample Rate (sps): 10M
Ch0: Frequency (Hz): 2.275G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 50
Ch0: BB Gain (dB): 20
Ch0: Bandwidth (Hz): 10M

osmocom Sink
Device Arguments: ha...31845f
Sample Rate (sps): 10M
Ch0: Frequency (Hz): 2.271G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 50
Ch0: BB Gain (dB): 20
Ch0: Bandwidth (Hz): 10M

Figure 9: The three osmocom sink blocks that are connected to each Hack RF via serial number. The file source is the IRIS emulator feedback. Each sink is tuned to transmit a different frequency.

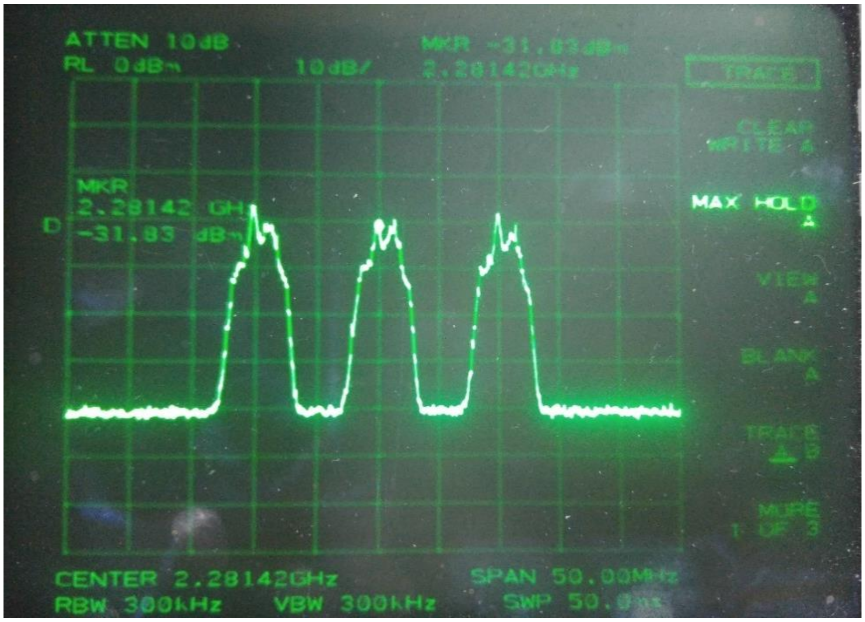


Figure 10: All three signals verified on the spectrum analyzer before hooking the Hack RFs up to the rest of the system.

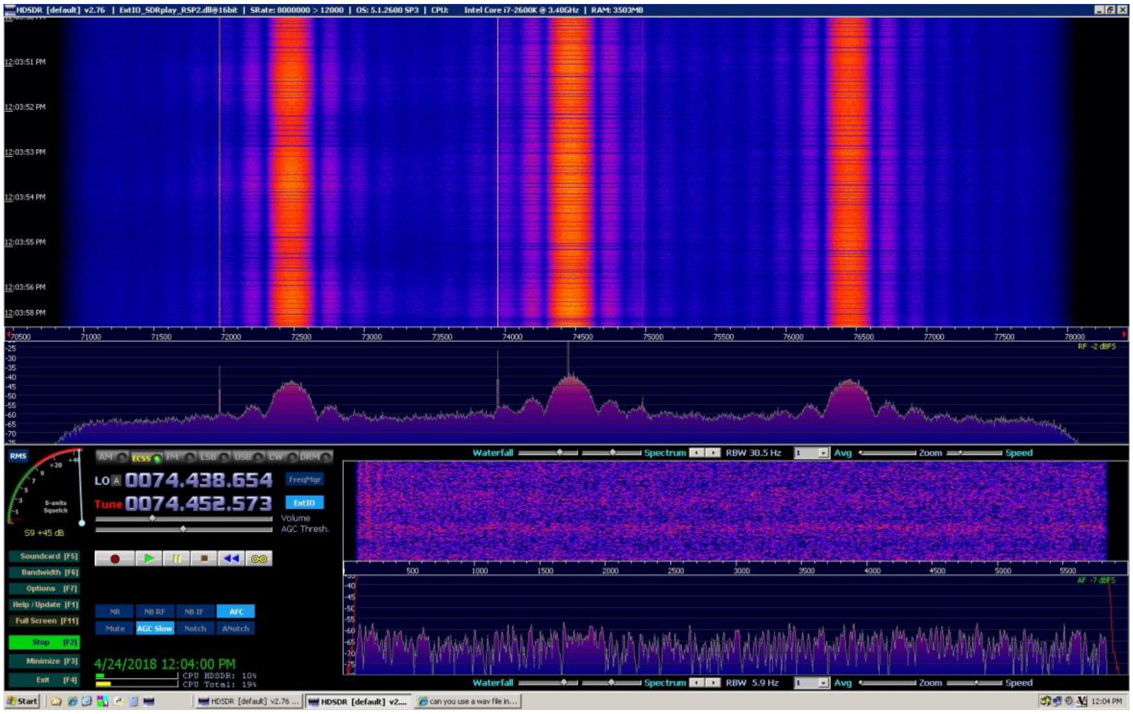
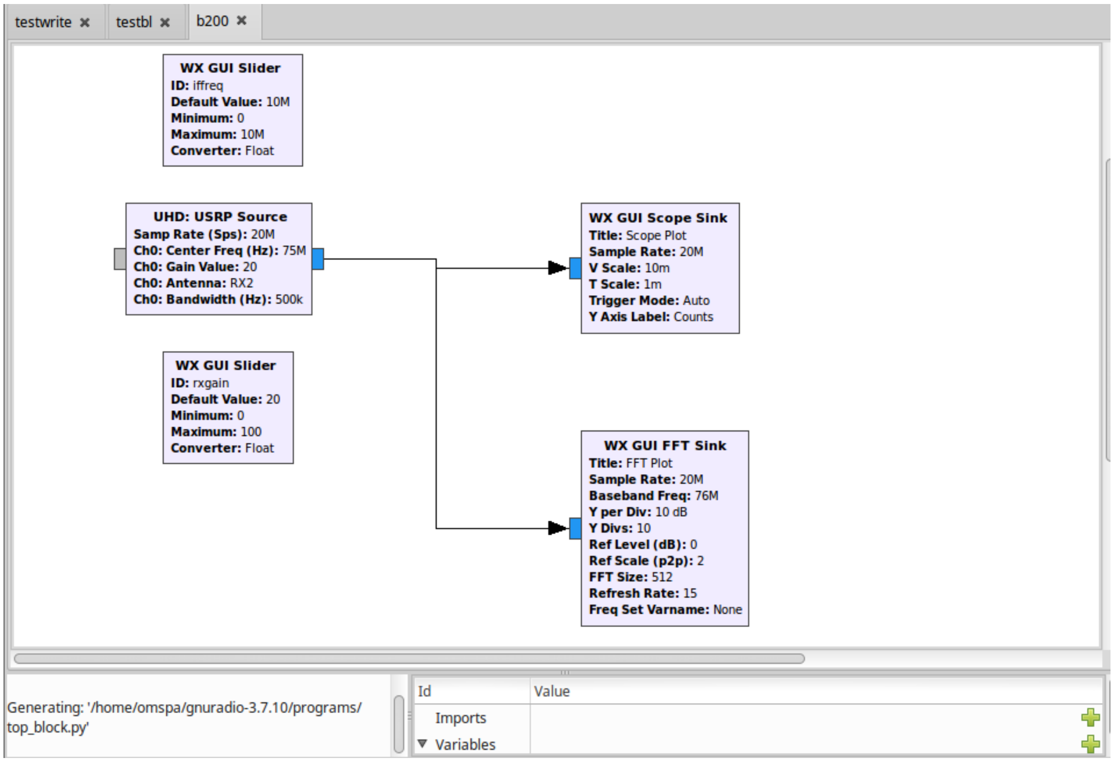


Figure 11: The carrier and modulation from the simulated, down converted signals. This image is taken from the more sensitive SDRs in Morehead State's MOC.



WX GUI Slider
ID: iffreq
Default Value: 10M
Minimum: 0
Maximum: 10M
Converter: Float

UHD: USRP Source
Samp Rate (Sps): 20M
Ch0: Center Freq (Hz): 75M
Ch0: Gain Value: 20
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 500k

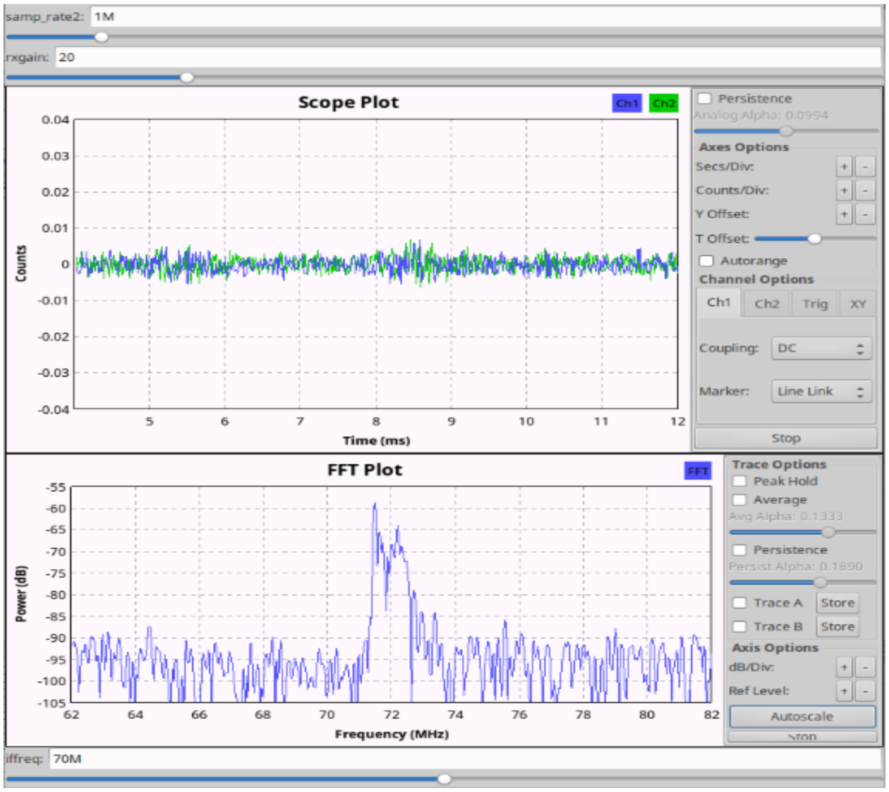
WX GUI Slider
ID: rxgain
Default Value: 20
Minimum: 0
Maximum: 100
Converter: Float

WX GUI Scope Sink
Title: Scope Plot
Sample Rate: 20M
V Scale: 10m
T Scale: 1m
Trigger Mode: Auto
Y Axis Label: Counts

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 20M
Baseband Freq: 76M
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 512
Refresh Rate: 15
Freq Set Varname: None

```
Generating: '/home/omspa/gnuradio-3.7.10/programs/
top_block.py'
```

Figure 12: An example of the receive flow graph on the OMSPA 3 computer. The same file was used on each computer but tuned to separate frequencies.


samp_rate2: 1M

rxgain: 20

Analog Alpha: 0.0994

Coupling: DC

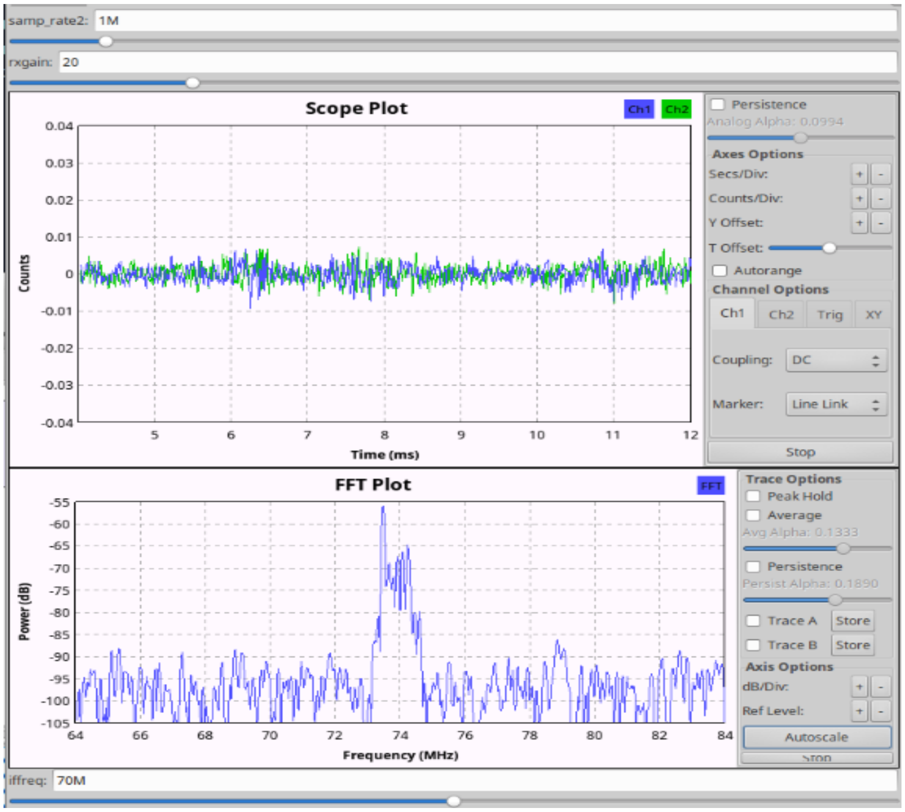
Marker: Line Link

Avg Alpha: 0.1333

Persist Alpha: 0.1890

iffreq: 70M

Figure 13: The simulated signal on OMSPA 1 – tuned to down converted frequency at 72 MHz.


samp_rate2: 1M

rxgain: 20

Analog Alpha: 0.0994

Coupling: DC

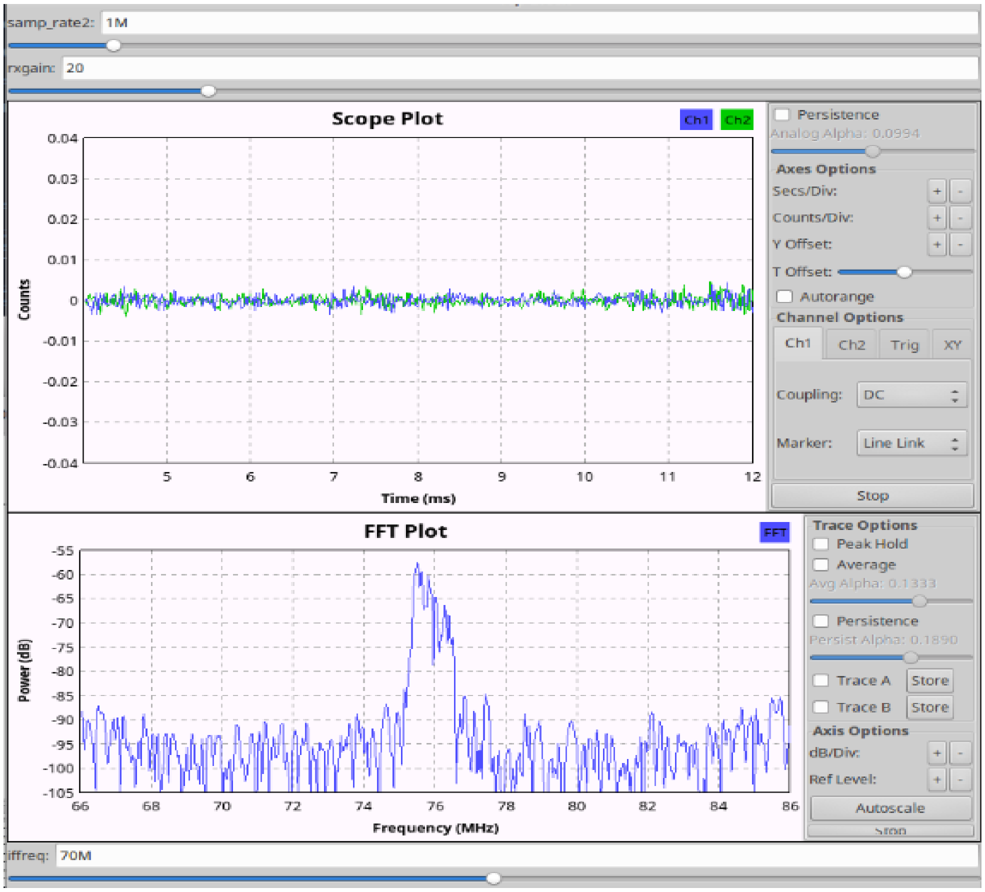
Marker: Line Link

Avg Alpha: 0.1333

Persist Alpha: 0.1890

iffreq: 70M

Figure 14: The simulated signal on OMSPA 2 – tuned to down converted frequency at 74 MHz.



samp_rate2: 1M

rxgain: 20

Analog Alpha: 0.0994

Coupling: DC

Marker: Line Link

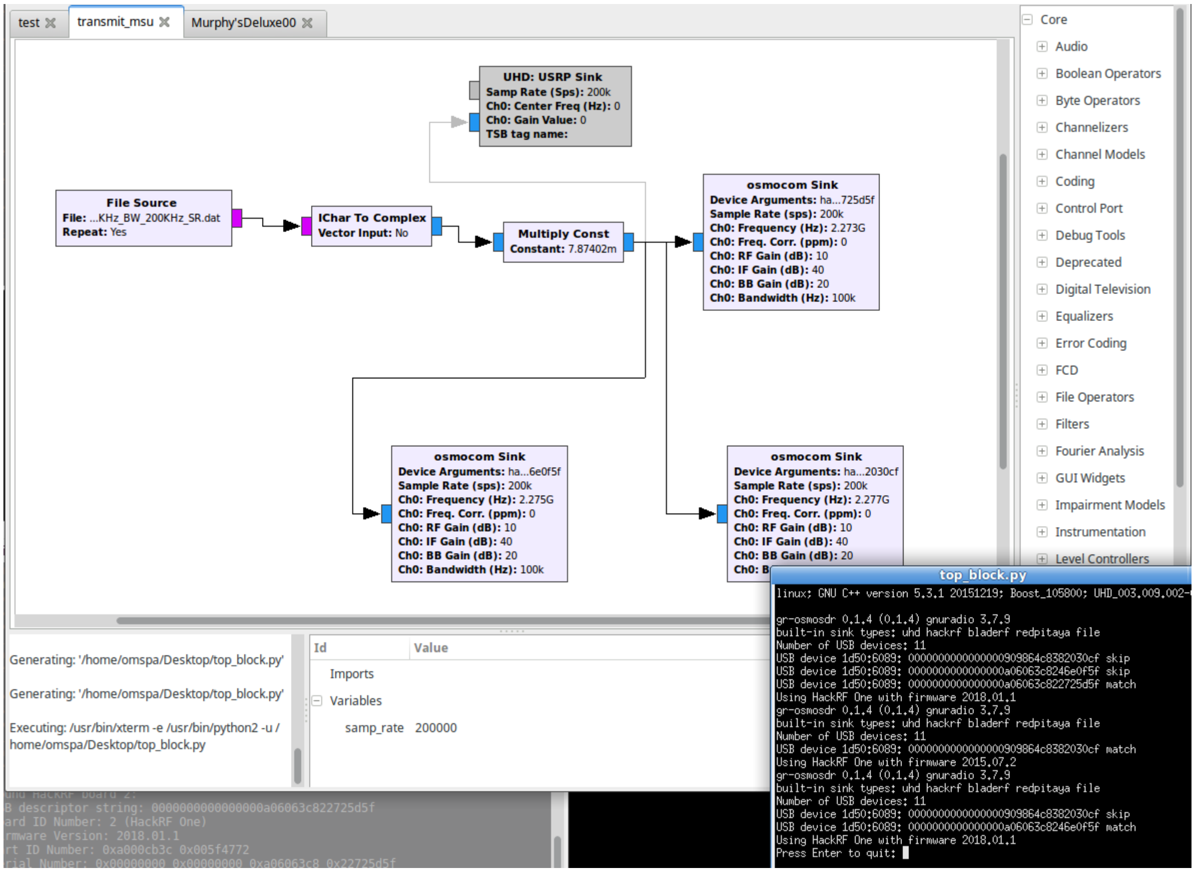
Avg Alpha: 0.1333

Persist Alpha: 0.1890

iffreq: 70M

Figure 15: The simulated signal on OMSPA 3 – tuned to down converted frequency at 76 MHz.

End- to-end and Measurement Testing



UHD: USRP Sink
Samp Rate (Sps): 200k
Ch0: Center Freq (Hz): 0
Ch0: Gain Value: 0
TSB tag name:

File Source
File: ...KHz_BW_200KHz_SR.dat
Repeat: Yes

IChar To Complex
Vector Input: No

Multiply Const
Constant: 7.87402m

osmocom Sink
Device Arguments: ha...725d5f
Sample Rate (sps): 200k
Ch0: Frequency (Hz): 2.273G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 40
Ch0: BB Gain (dB): 20
Ch0: Bandwidth (Hz): 100k

osmocom Sink
Device Arguments: ha...6e0f5f
Sample Rate (sps): 200k
Ch0: Frequency (Hz): 2.275G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 40
Ch0: BB Gain (dB): 20
Ch0: Bandwidth (Hz): 100k

osmocom Sink
Device Arguments: ha...2030cf
Sample Rate (sps): 200k
Ch0: Frequency (Hz): 2.277G
Ch0: Freq. Corr. (ppm): 0
Ch0: RF Gain (dB): 10
Ch0: IF Gain (dB): 40
Ch0: BB Gain (dB): 20
Ch0: B

```
Generating: '/home/omspa/Desktop/top_block.py'

Generating: '/home/omspa/Desktop/top_block.py'

Executing: /usr/bin/xterm -e /usr/bin/python2 -u /
home/omspa/Desktop/top_block.py
```

Id	Value
Imports	
Variables	
samp_rate	200000

```
und HackRF board 2:
B descriptor string: 0000000000000000a06063c822725d5f
ard ID Number: 2 (HackRF One)
rmware Version: 2018.01.1
rt ID Number: 0xa000cb3c 0x005f4772
rial Number: 0x00000000 0x00000000 0xa06063c8 0x22725d5f
```

```
linux; GNU C++ version 5.3.1 20151219; Boost_105800; UHD_003.009.002-

gr-osmosdr 0.1.4 (0.1.4) gnuradio 3.7.9
built-in sink types: uhd hackrf bladerf redpitaya file
Number of USB devices: 11
USB device 1d50:6089: 0000000000000000909864c8382030cf skip
USB device 1d50:6089: 0000000000000000a06063c8246e0f5f skip
USB device 1d50:6089: 0000000000000000a06063c822725d5f match
Using HackRF One with firmware 2018.01.1
gr-osmosdr 0.1.4 (0.1.4) gnuradio 3.7.9
built-in sink types: uhd hackrf bladerf redpitaya file
Number of USB devices: 11
USB device 1d50:6089: 0000000000000000909864c8382030cf match
Using HackRF One with firmware 2015.07.2
gr-osmosdr 0.1.4 (0.1.4) gnuradio 3.7.9
built-in sink types: uhd hackrf bladerf redpitaya file
Number of USB devices: 11
USB device 1d50:6089: 0000000000000000909864c8382030cf skip
USB device 1d50:6089: 0000000000000000a06063c8246e0f5f match
Using HackRF One with firmware 2018.01.1
Press Enter to quit: █
```

Figure 16: This image shows the new file source used for simulating signals. The GRC library can also be seen to the right.

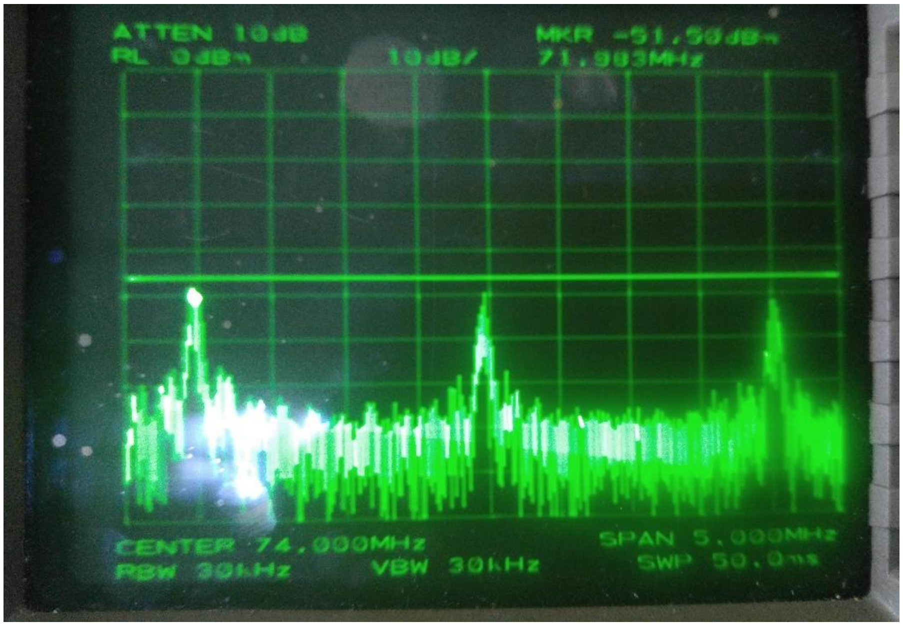


Figure 17: All three simulated signals being verified on the spectrum analyzer. From the new 100 kHz bandwidth signal source.

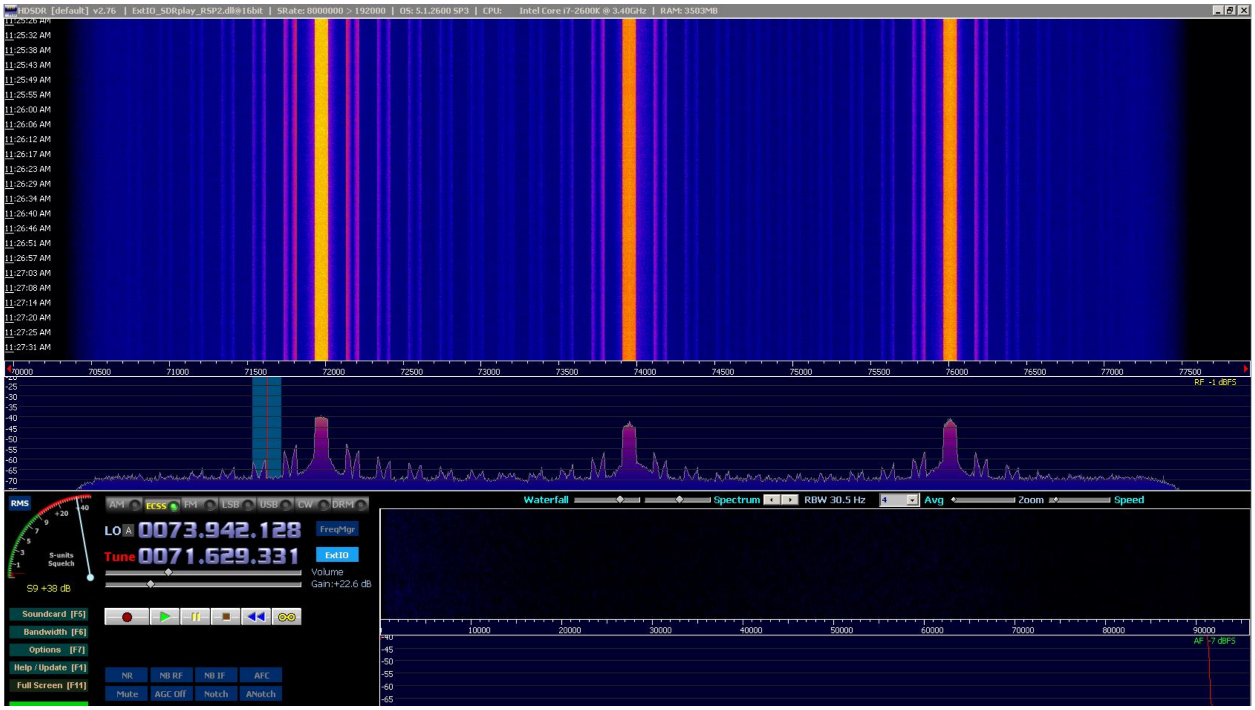


Figure 18: This image shows the narrower bandwidth with the new 100 kHz bandwidth signal source.

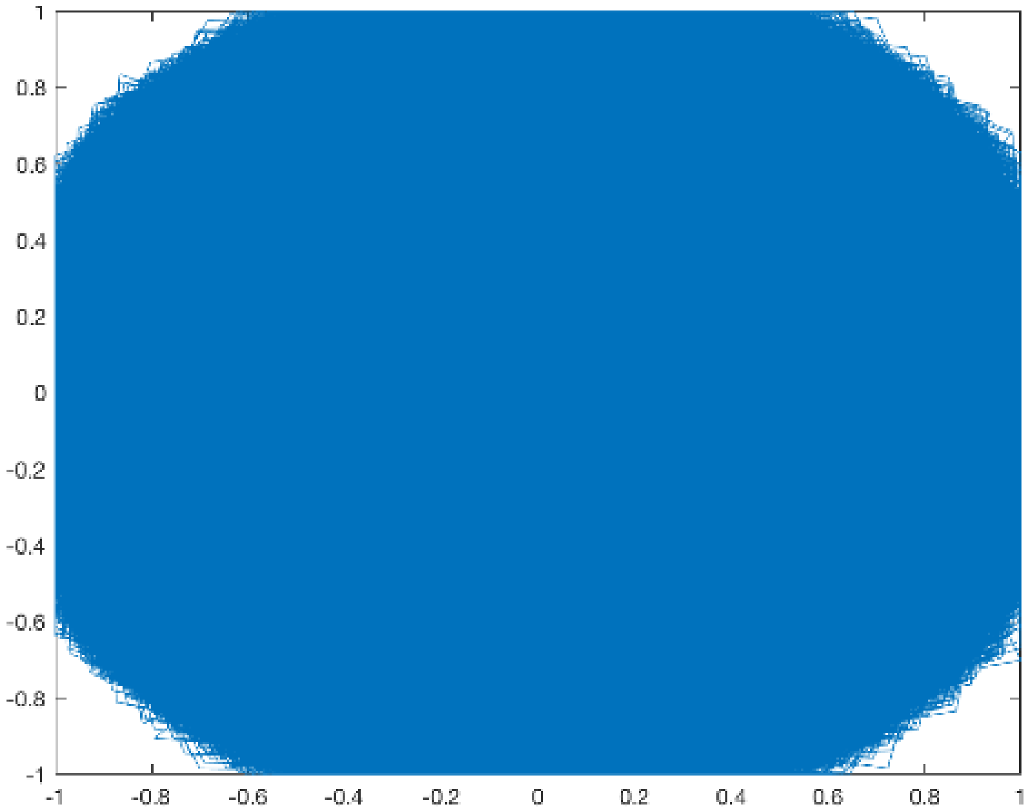


Figure 19: This image shows the saturated signal from the recording using “b200_zaid” where the receive gain was set too high (70 dB). This image was created by Zaid Towfic at NASA JPL.

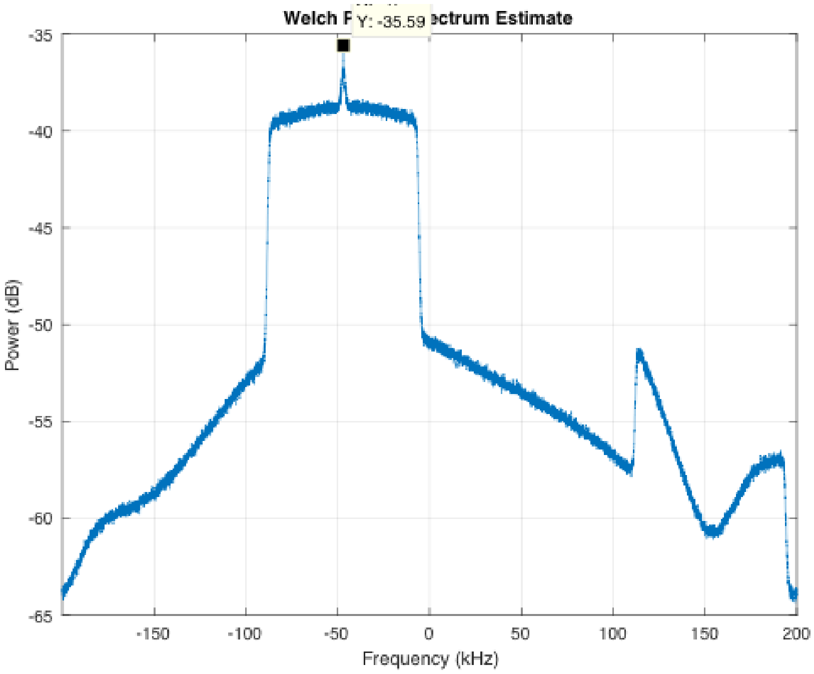


Figure 20: This image shows the signal from the new 100 kHz signal source to be off by about 47 kHz. This image was created by Zaid Towfic at NASA JPL.

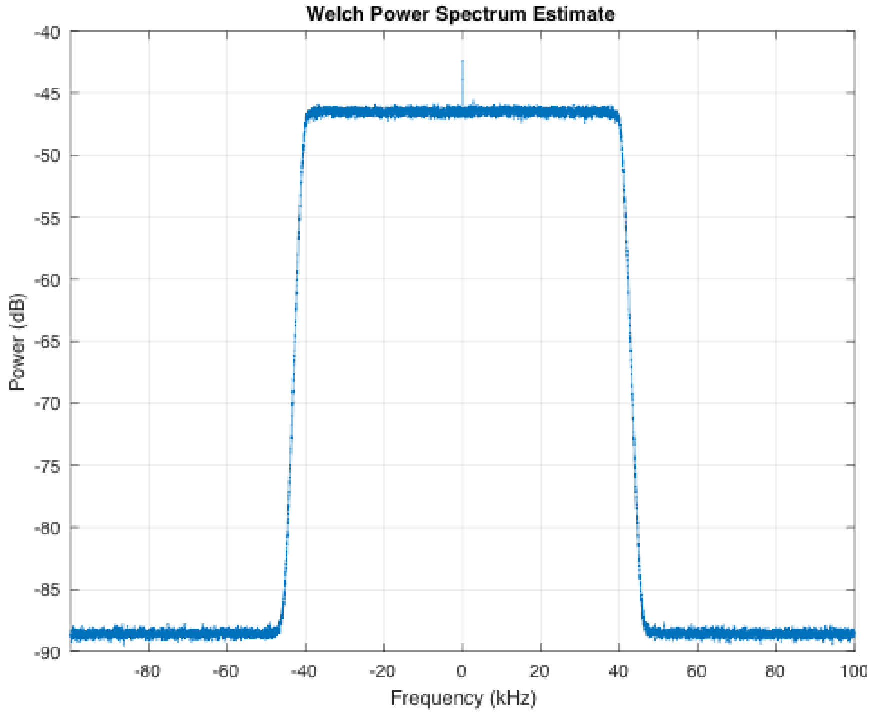
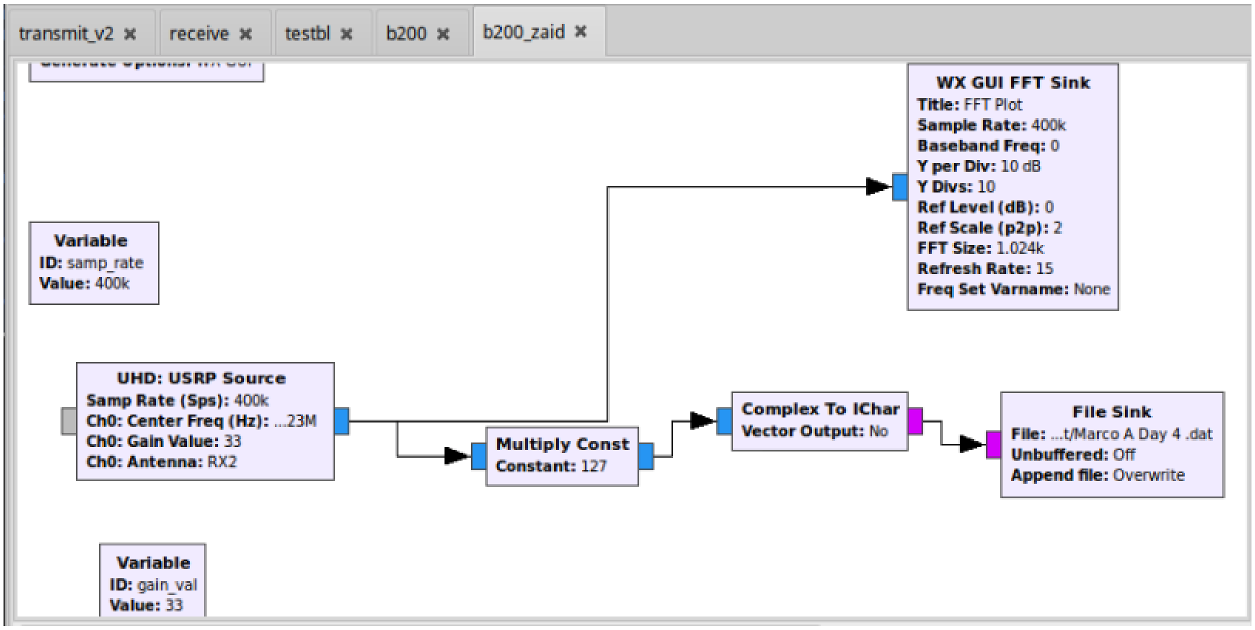


Figure 21: This image shows slight shaping on the received spectrum due to the shape of the USRP filter.

Appendix C – MarCO/InSight Demonstration Results



WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 400k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None

Variable
ID: samp_rate
Value: 400k

UHD: USRP Source
Samp Rate (Sps): 400k
Ch0: Center Freq (Hz): ...23M
Ch0: Gain Value: 33
Ch0: Antenna: RX2

Multiply Const
Constant: 127

Complex To IChar
Vector Output: No

File Sink
File: ...t/Marco A Day 4 .dat
Unbuffered: Off
Append file: Overwrite

Variable
ID: gain_val
Value: 33

Figure 22: The GRC flow graph for MarCO A on OMSPA 1. The flow graph generates a spectrum plot to show the signal and outputs the data to file sink.

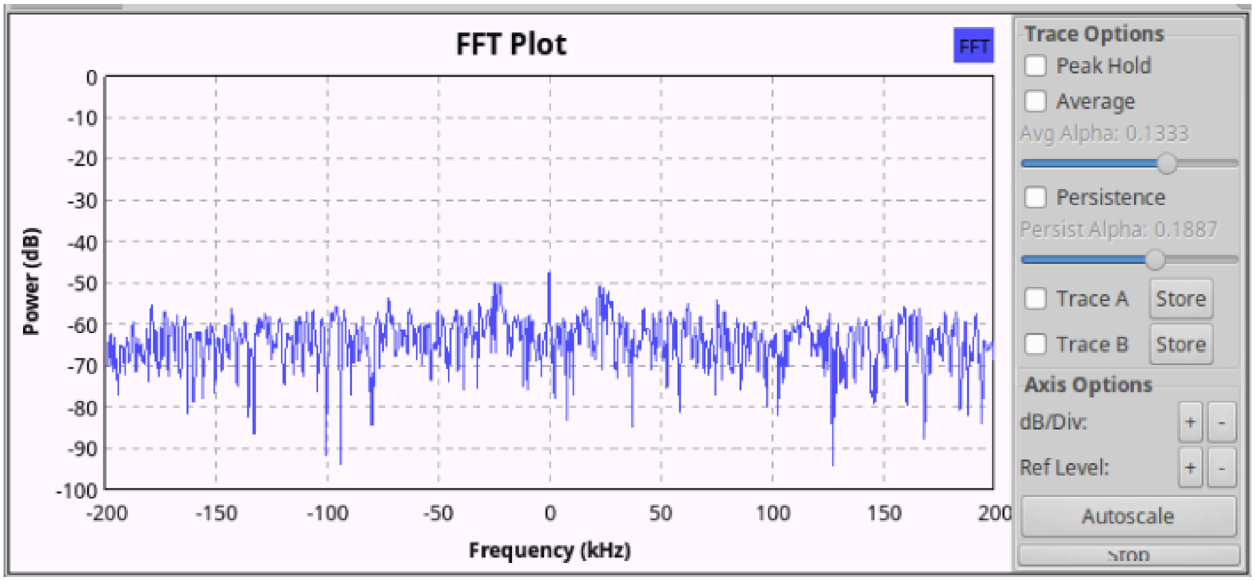
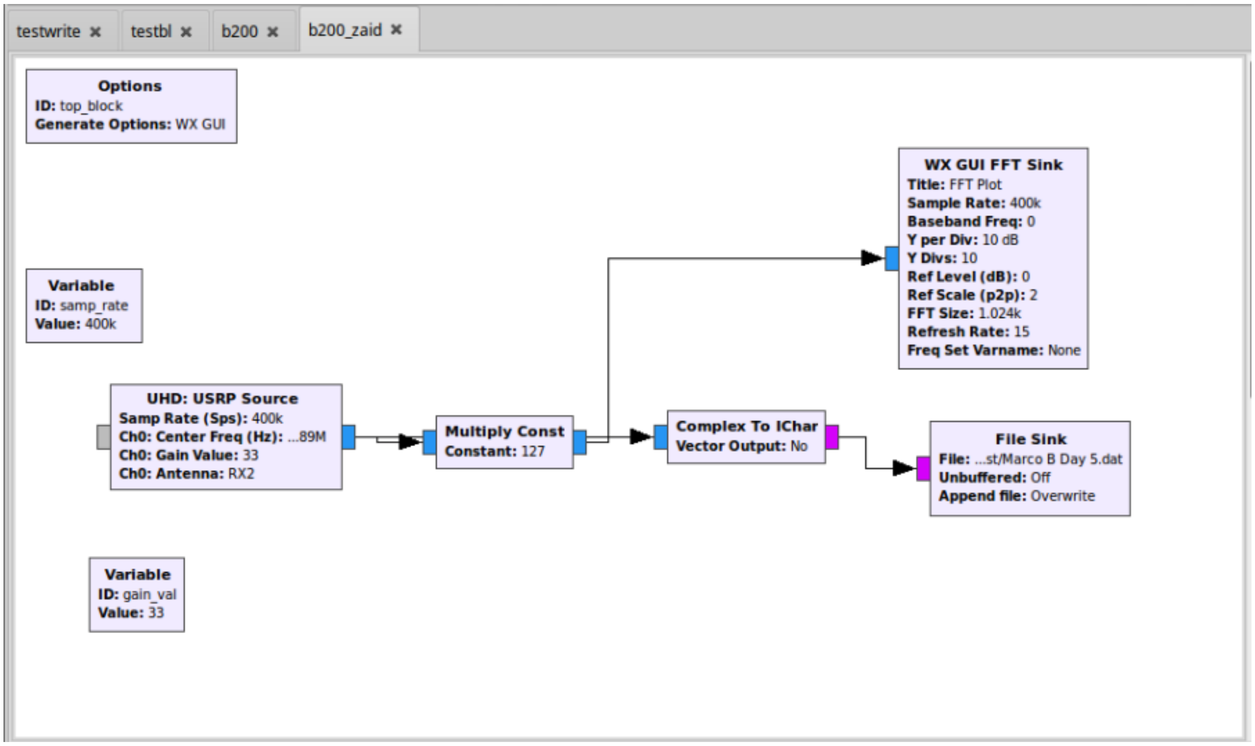


Figure 23: This plot was generated by the flow graph in the previous image. The carrier and modulation from MarCO A is seen about the center frequency.



Options
ID: top_block
Generate Options: WX GUI

Variable
ID: samp_rate
Value: 400k

UHD: USRP Source
Samp Rate (Sps): 400k
Ch0: Center Freq (Hz): ...89M
Ch0: Gain Value: 33
Ch0: Antenna: RX2

Multiply Const
Constant: 127

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 400k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None

Complex To IChar
Vector Output: No

File Sink
File: ...st/Marco B Day 5.dat
Unbuffered: Off
Append file: Overwrite

Variable
ID: gain_val
Value: 33

Figure 24: The GRC flow graph for MarCO B on OMSPA 2. The flow graph generates a spectrum plot to show the signal and outputs the data to file sink.

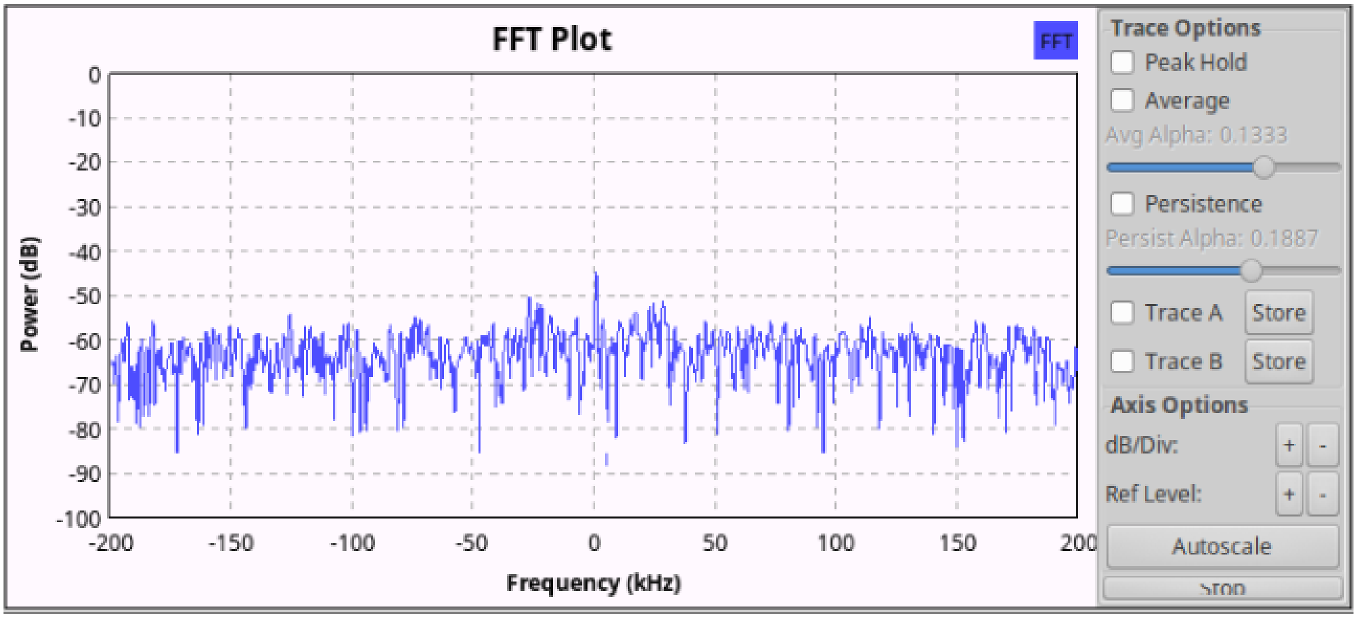
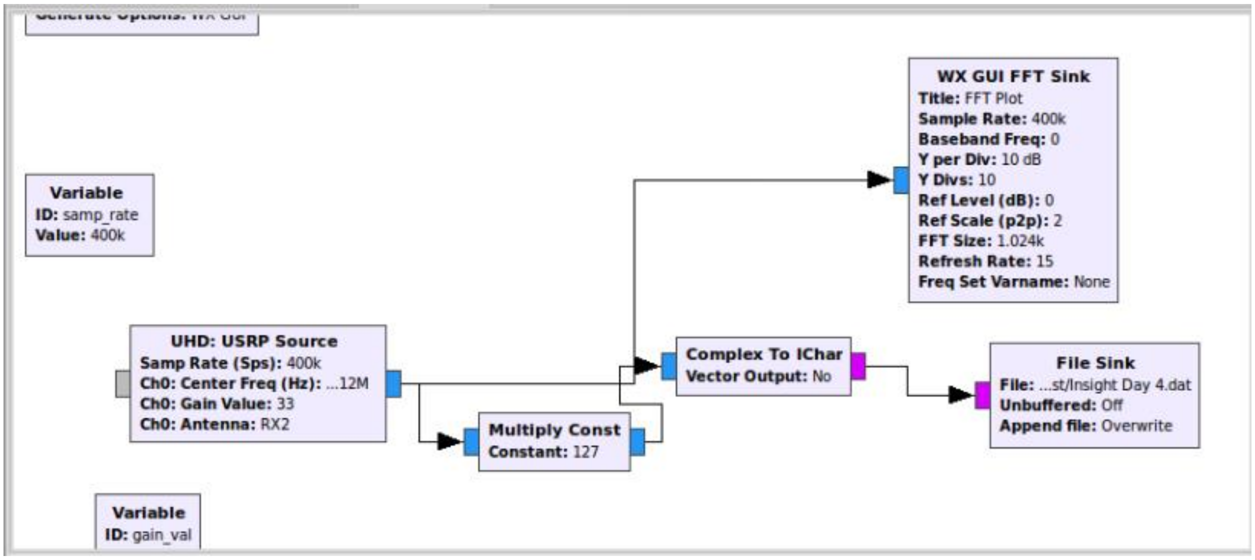


Figure 25: This plot was generated by the flow graph in the previous image. The carrier and modulation from MarCO B is seen about the center frequency.



Variable
ID: samp_rate
Value: 400k

UHD: USRP Source
Samp Rate (Sps): 400k
Ch0: Center Freq (Hz): ...12M
Ch0: Gain Value: 33
Ch0: Antenna: RX2

Multiply Const
Constant: 127

Complex To IChar
Vector Output: No

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 400k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None

File Sink
File: ...st/Insight Day 4.dat
Unbuffered: Off
Append file: Overwrite

Variable
ID: gain_val

Figure 26: The GRC flow graph for InSight on OMSPA 3 on day 4 of tracking. The flow graph generates a spectrum plot to show the signal and outputs the data to file sink.

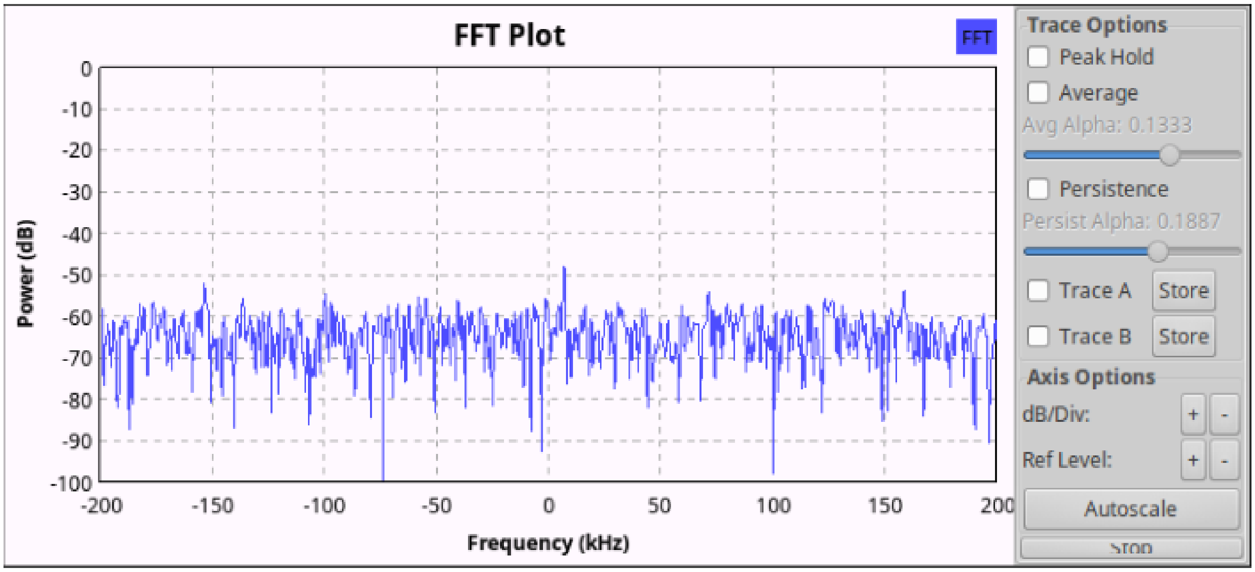
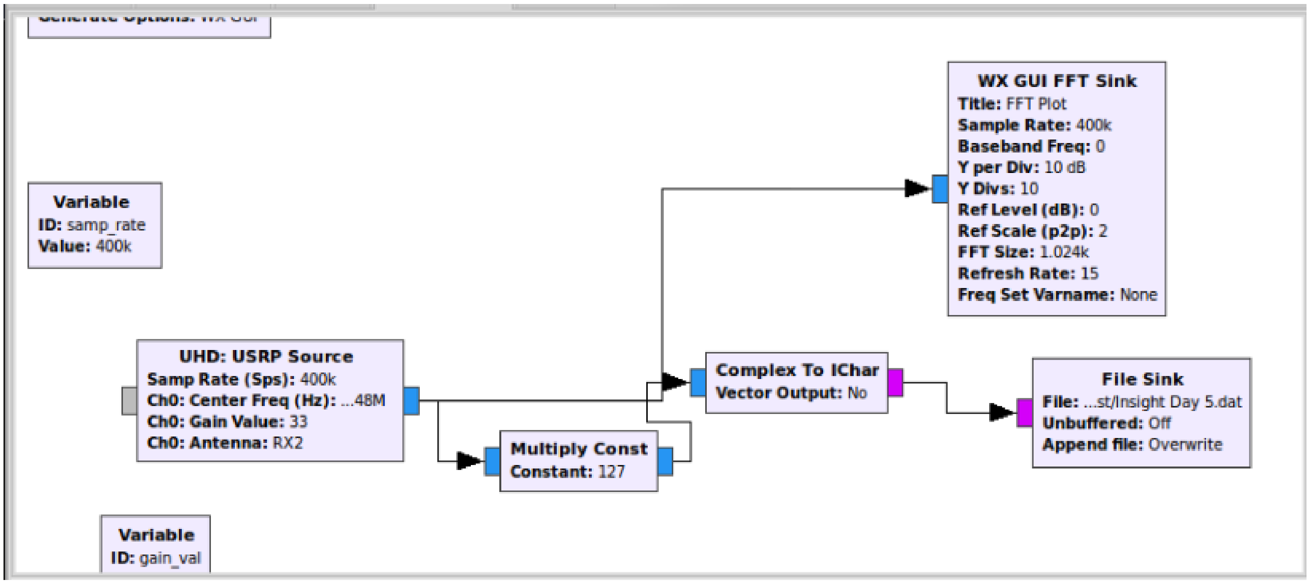


Figure 27: This plot was generated by the flow graph in the previous image. The carrier and modulation from InSight can be seen about the center frequency. This data was corrupted due to overwritten data.



Variable
ID: samp_rate
Value: 400k

UHD: USRP Source
Samp Rate (Sps): 400k
Ch0: Center Freq (Hz): ...48M
Ch0: Gain Value: 33
Ch0: Antenna: RX2

Multiply Const
Constant: 127

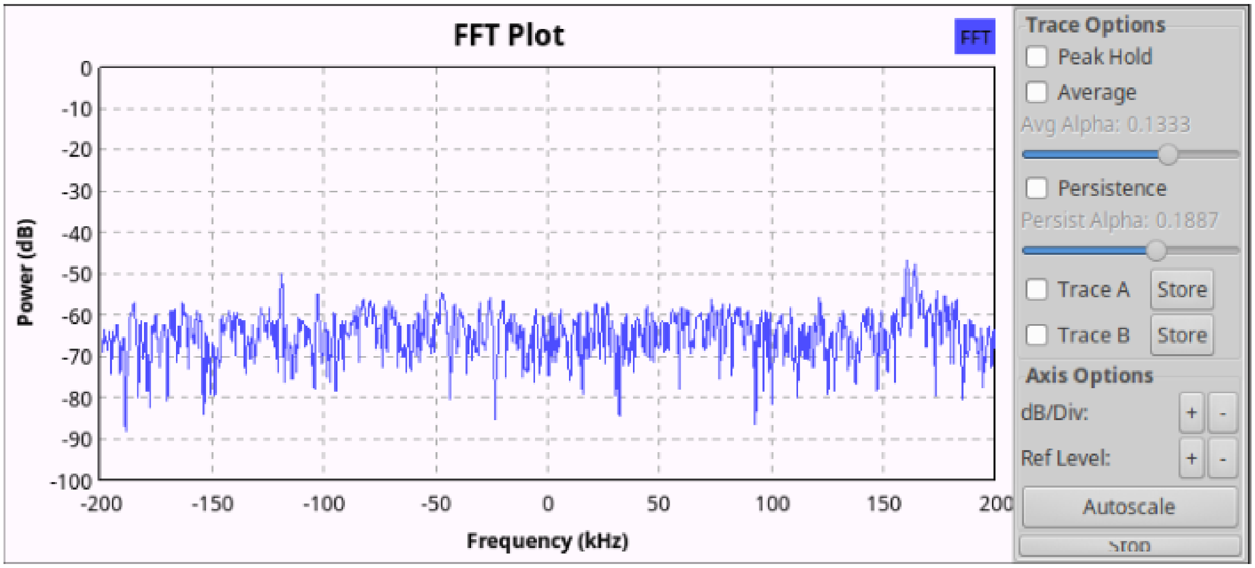
Complex To IChar
Vector Output: No

WX GUI FFT Sink
Title: FFT Plot
Sample Rate: 400k
Baseband Freq: 0
Y per Div: 10 dB
Y Divs: 10
Ref Level (dB): 0
Ref Scale (p2p): 2
FFT Size: 1.024k
Refresh Rate: 15
Freq Set Varname: None

File Sink
File: ...st/Insight Day 5.dat
Unbuffered: Off
Append file: Overwrite

Variable
ID: gain_val

Figure 28: The GRC flow graph for InSight on OMSPA 3 on day 5 of tracking. The flow graph generates a spectrum plot to show the signal and outputs the data to file sink.



☐ Peak Hold
☐ Average
Avg Alpha: 0.1333
☐ Persistence
Persist Alpha: 0.1887
☐ Trace A
☐ Trace B

Figure 29: This plot was generated by the flow graph in the previous image. The carrier and modulation from InSight can be seen. This collect was successful in that both carriers were captured.

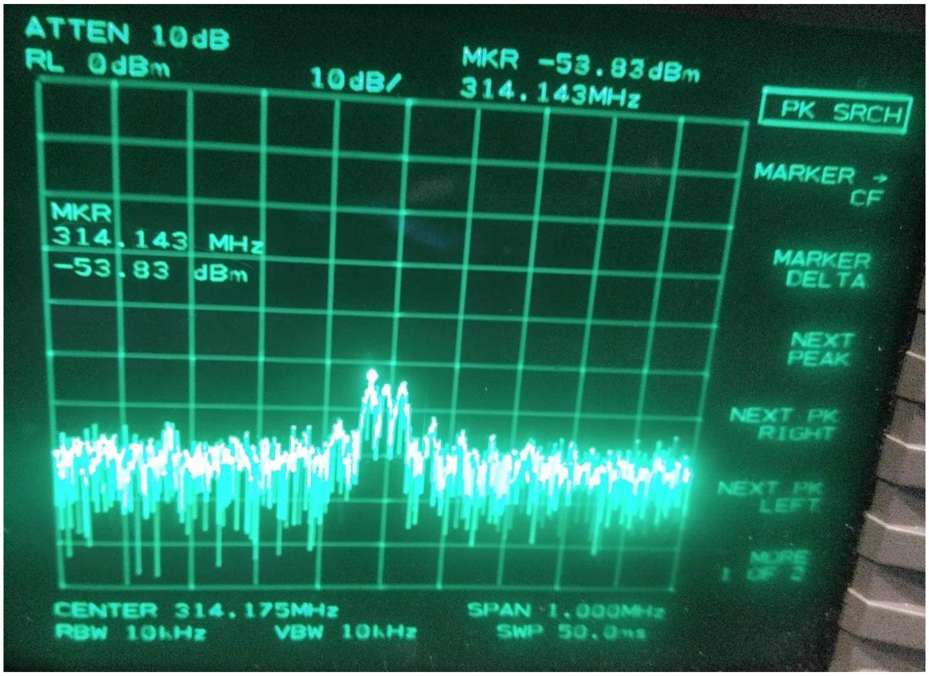


Figure 30: The spectrum analyzer, hooked up to the fourth terminal of the power divider, showing the signal from MarCO A. The spectrum analyzer helped verify that signals were being recorded when FFT plots were not yet being generated by the GRC files.

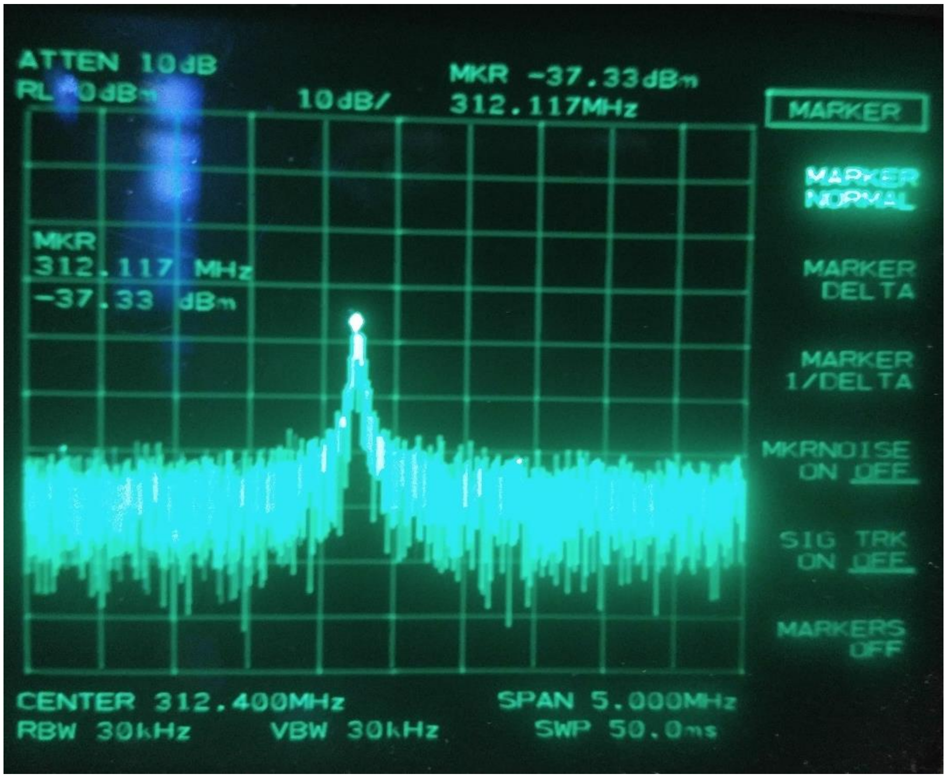


Figure 31: MarCO B’s signal being verified on the spectrum analyzer.

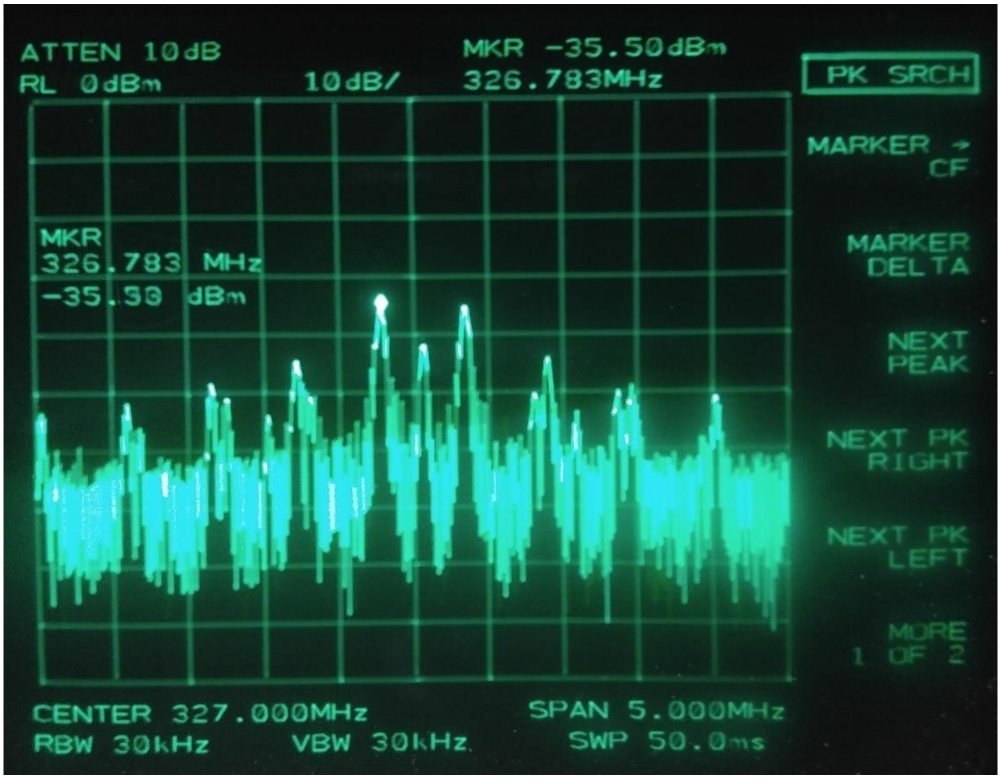
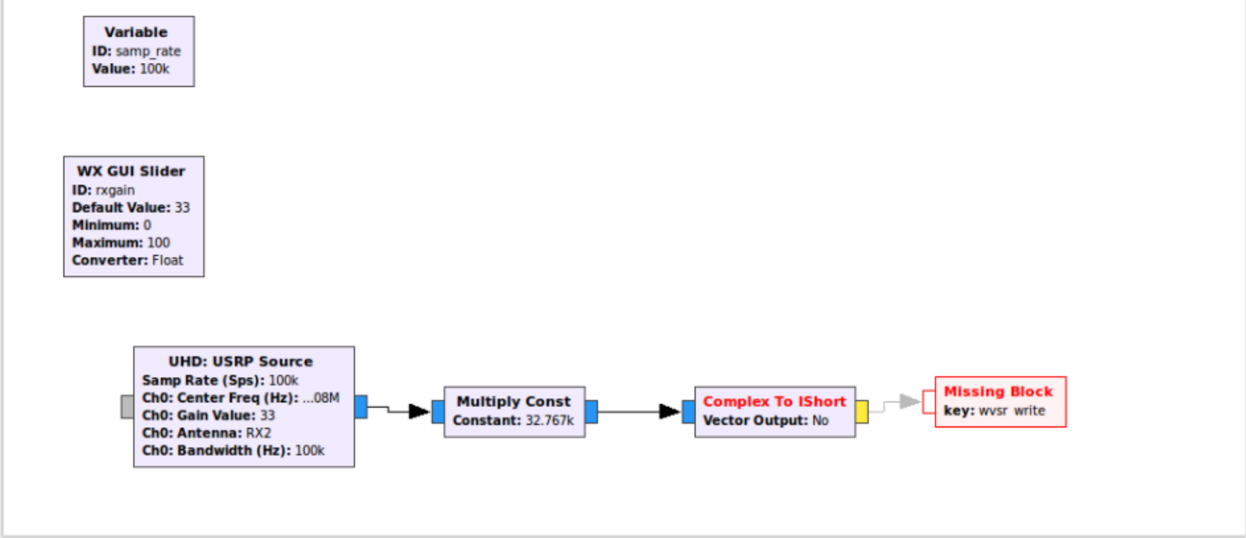


Figure 32: InSight's signal being verified by the spectrum analyzer. A peak is seen on a subcarrier at 326.783 MHz.


Variable
ID: samp_rate
Value: 100k

WX GUI Slider
ID: rxgain
Default Value: 33
Minimum: 0
Maximum: 100
Converter: Float

UHD: USRP Source
Samp Rate (Sps): 100k
Ch0: Center Freq (Hz): ...08M
Ch0: Gain Value: 33
Ch0: Antenna: RX2
Ch0: Bandwidth (Hz): 100k

Multiply Const
Constant: 32.767k

Complex To IShort
Vector Output: No

Missing Block
key: wvsr_write

Figure 33: This flow graph was used on OMSPA 4 to read and write the incoming signal from InSight to WVSR format.

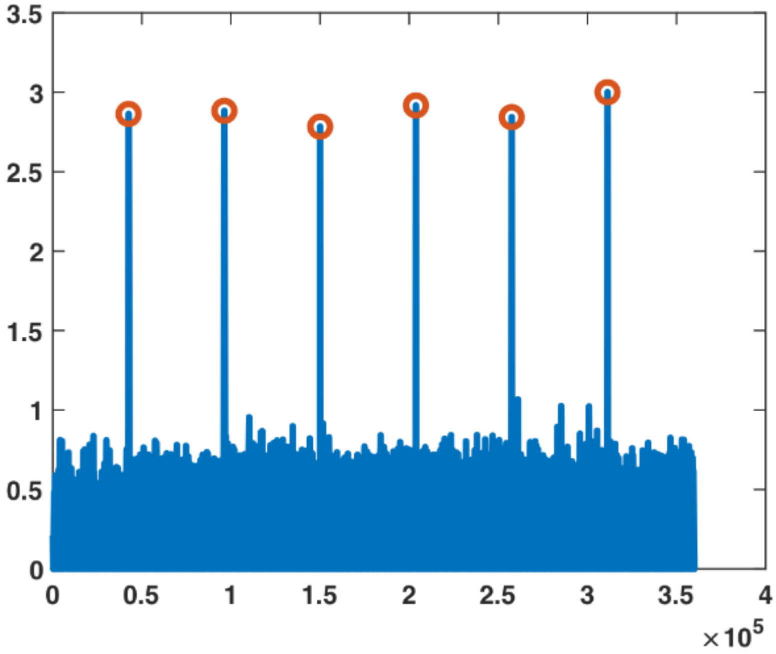


Figure 34: Received data from the MarCO spacecrafts. This image was created by Zaid Towfic at JPL.

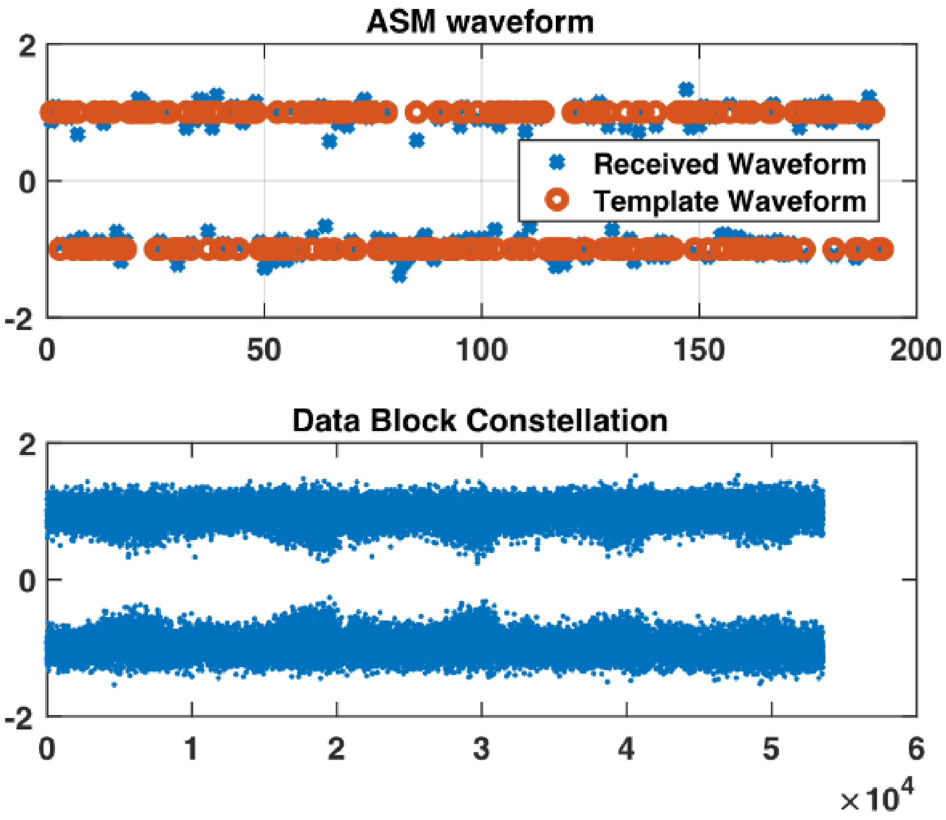
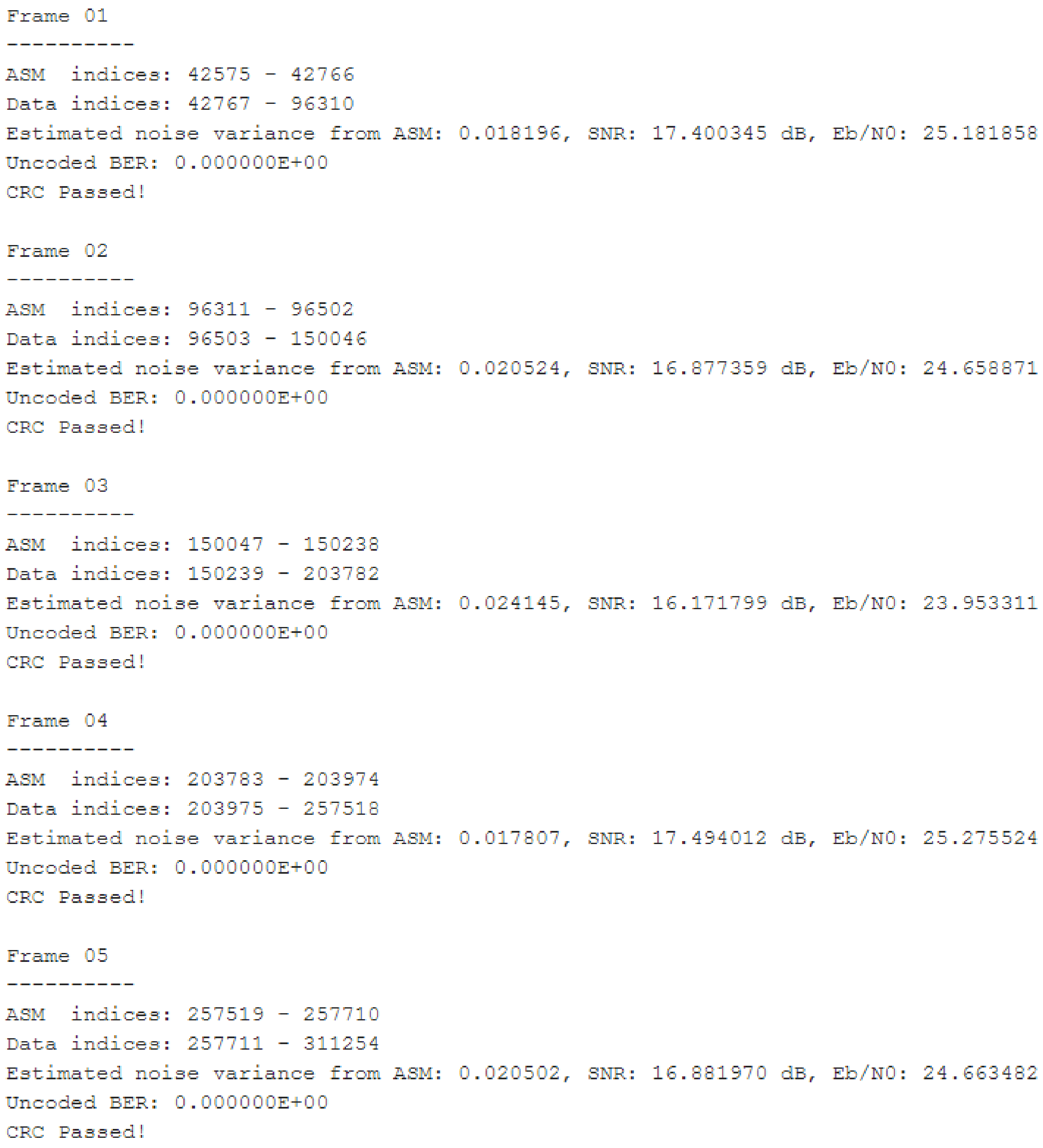


Figure 35: This image shows the ASM waveform from the MarCO spacecraft and shows the operations of the system compared to a standard. The data block constellation is shown on the bottom and displays constellations of the received data block and is demodulated. This image was created by Zaid Towfic at JPL.



```
Frame 01
----------
ASM  indices: 42575 - 42766
Data indices: 42767 - 96310
Estimated noise variance from ASM: 0.018196, SNR: 17.400345 dB, Eb/N0: 25.181858
Uncoded BER: 0.000000E+00
CRC Passed!

Frame 02
----------
ASM  indices: 96311 - 96502
Data indices: 96503 - 150046
Estimated noise variance from ASM: 0.020524, SNR: 16.877359 dB, Eb/N0: 24.658871
Uncoded BER: 0.000000E+00
CRC Passed!

Frame 03
----------
ASM  indices: 150047 - 150238
Data indices: 150239 - 203782
Estimated noise variance from ASM: 0.024145, SNR: 16.171799 dB, Eb/N0: 23.953311
Uncoded BER: 0.000000E+00
CRC Passed!

Frame 04
----------
ASM  indices: 203783 - 203974
Data indices: 203975 - 257518
Estimated noise variance from ASM: 0.017807, SNR: 17.494012 dB, Eb/N0: 25.275524
Uncoded BER: 0.000000E+00
CRC Passed!

Frame 05
----------
ASM  indices: 257519 - 257710
Data indices: 257711 - 311254
Estimated noise variance from ASM: 0.020502, SNR: 16.881970 dB, Eb/N0: 24.663482
Uncoded BER: 0.000000E+00
CRC Passed!
```

Figure 36: These are the first five frames decoded from MarCO. This image was created by Zaid Towfic at JPL.

Appendix D – Hardware

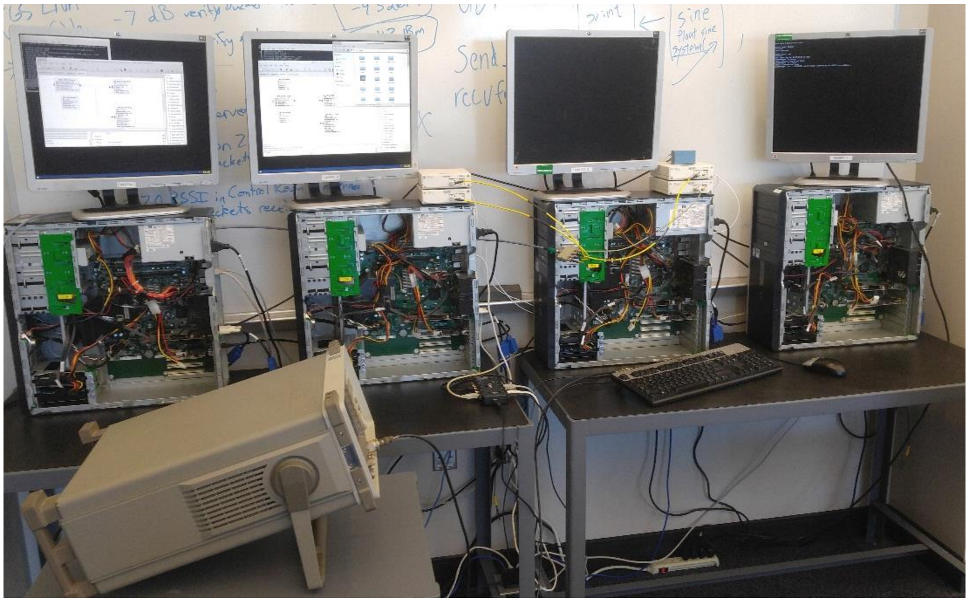


Figure 37: This image shows the OMSPA computer cluster in the MSU MOC.

Figure 38: This image shows the testbed computer. The three Hack RFs, horn antenna, and power amplifier are all seen.

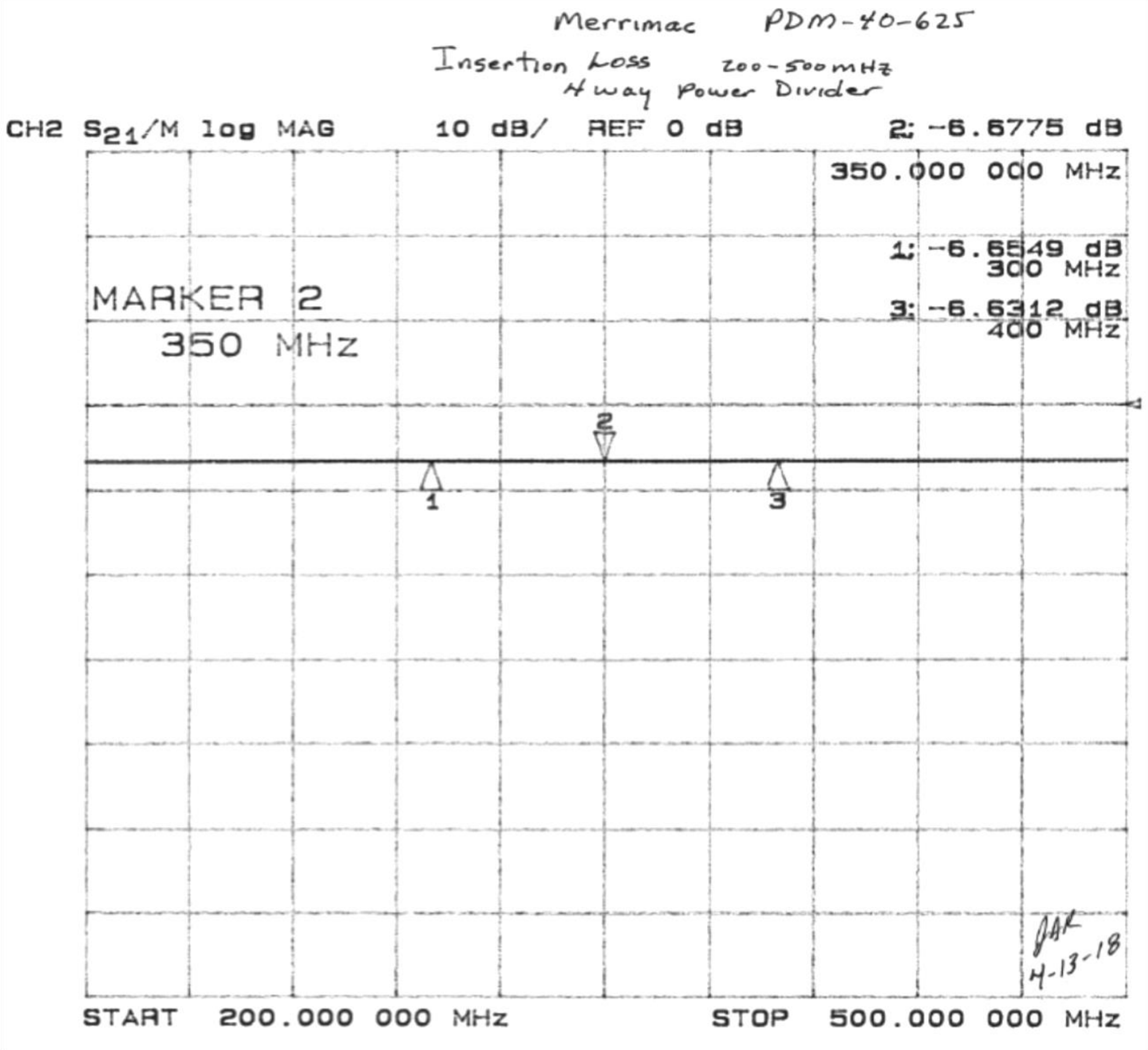


Figure 39: This spectrum plot shows the insertion loss of the four-way power divider used for connecting the USRPs.

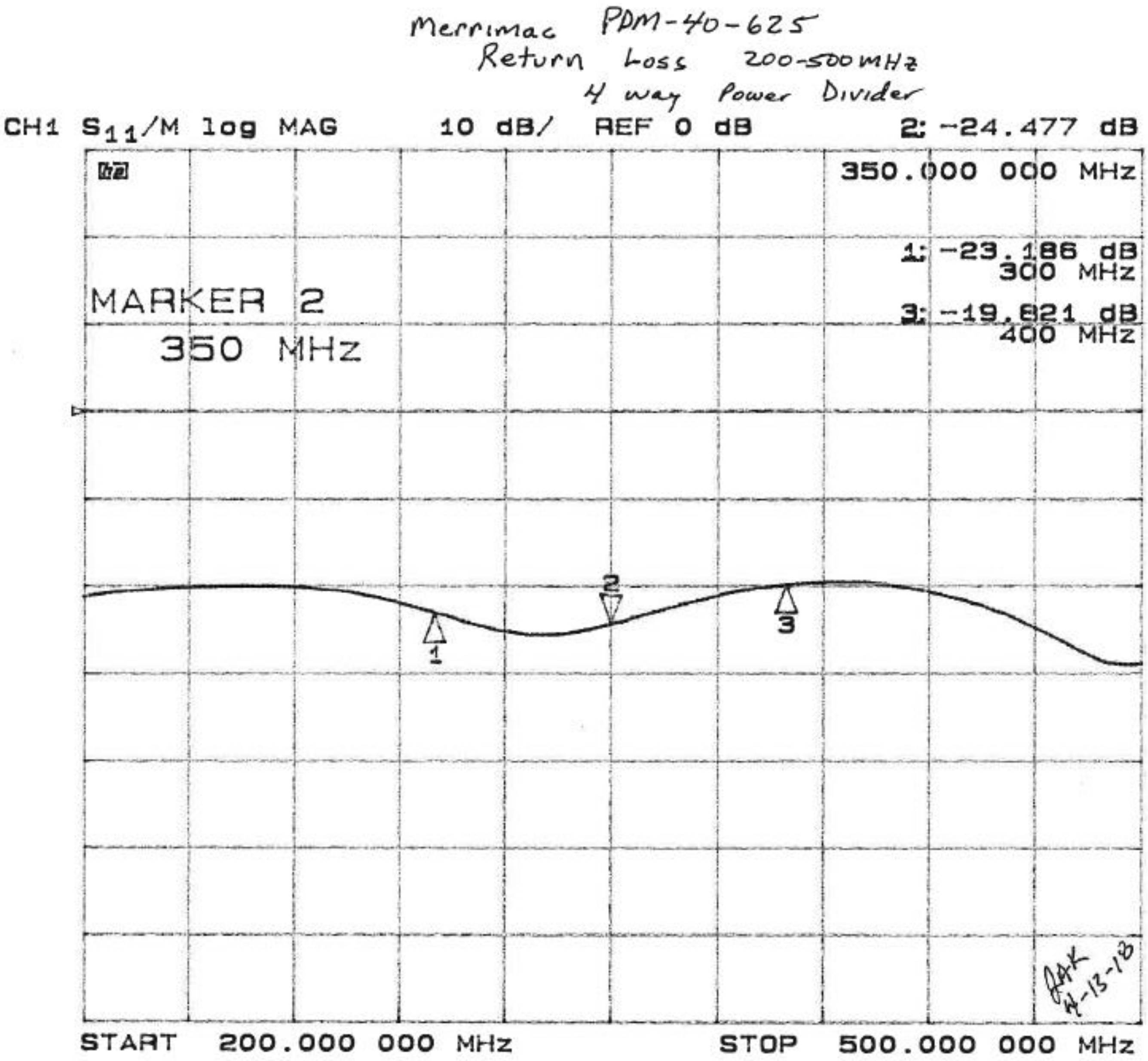
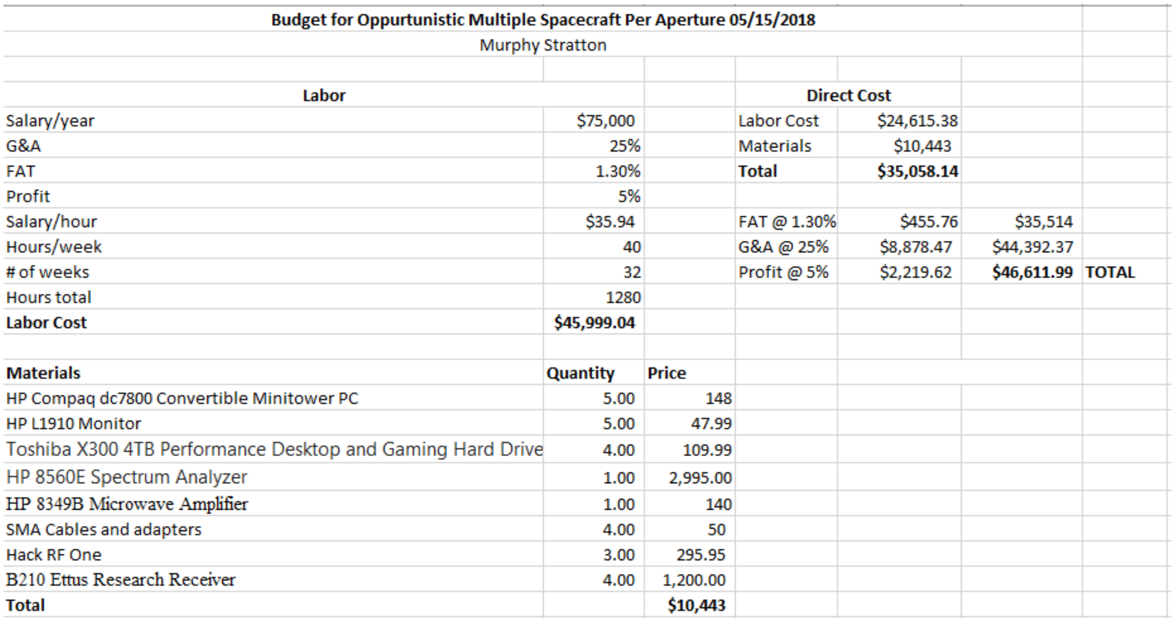


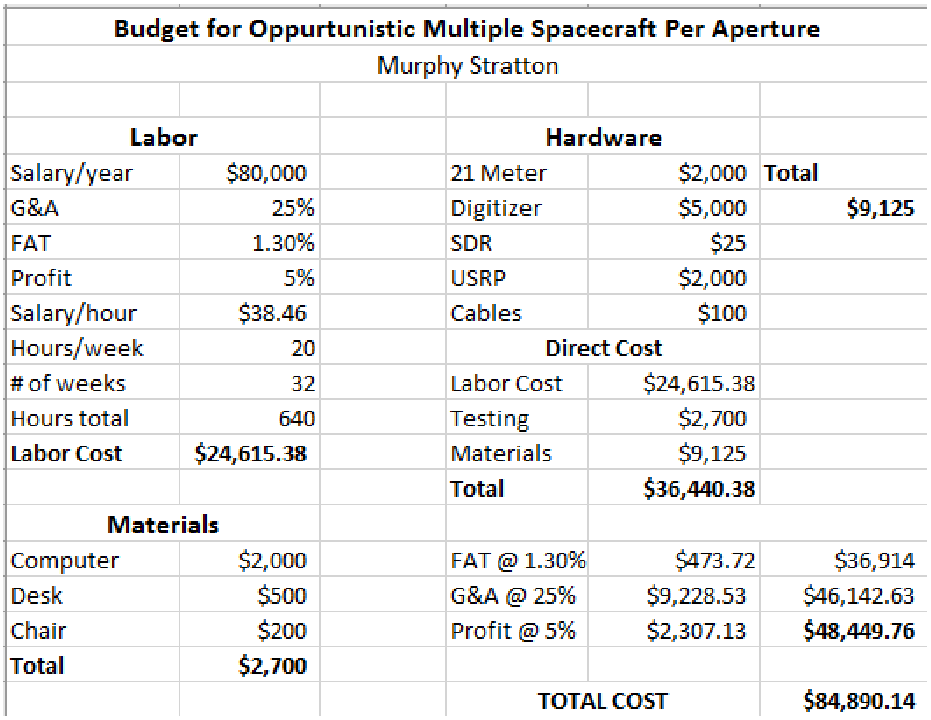
Figure 40: This spectrum plot shows the return loss of the four-way power divider used for connecting the USRPs.

Appendix E – Bill of Materials



Budget for Oppurtunistic Multiple Spacecraft Per Aperture 05/15/2018						
Murphy Stratton						
Labor			**Direct Cost**			
Salary/year	$75,000		Labor Cost	$24,615.38		
G&A	25%		Materials	$10,443		
FAT	1.30%		**Total**	**$35,058.14**		
Profit	5%					
Salary/hour	$35.94		FAT @ 1.30%	$455.76	$35,514	
Hours/week	40		G&A @ 25%	$8,878.47	$44,392.37	
# of weeks	32		Profit @ 5%	$2,219.62	**$46,611.99**	**TOTAL**
Hours total	1280					
Labor Cost	**$45,999.04**					
Materials	**Quantity**	**Price**				
HP Compaq dc7800 Convertible Minitower PC	5.00	148				
HP L1910 Monitor	5.00	47.99				
Toshiba X300 4TB Performance Desktop and Gaming Hard Drive	4.00	109.99				
HP 8560E Spectrum Analyzer	1.00	2,995.00				
HP 8349B Microwave Amplifier	1.00	140				
SMA Cables and adapters	4.00	50				
Hack RF One	3.00	295.95				
B210 Ettus Research Receiver	4.00	1,200.00				
Total		**$10,443**				

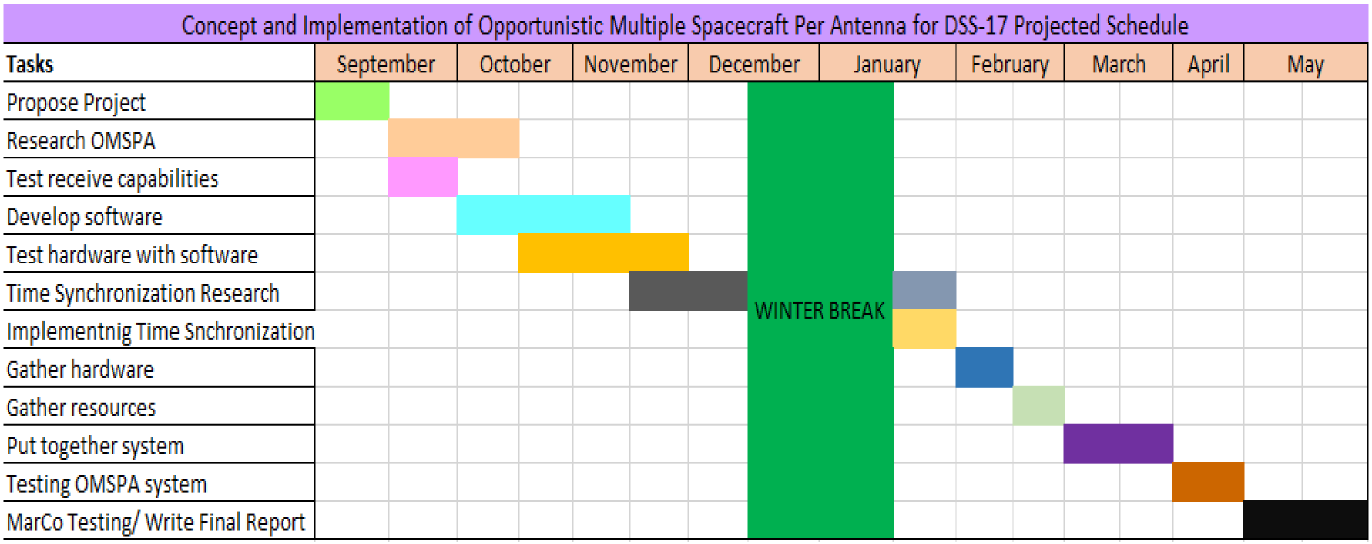
Figure 41: This is the most current BOM. It differs from figure 2 (see below) in that the hardware section is omitted. The hardware was not included because it was not required to pay for the 21-meter services.



Budget for Oppurtunistic Multiple Spacecraft Per Aperture					
Murphy Stratton					
Labor			**Hardware**		
Salary/year	$80,000		21 Meter	$2,000	**Total**
G&A	25%		Digitizer	$5,000	**$9,125**
FAT	1.30%		SDR	$25	
Profit	5%		USRP	$2,000	
Salary/hour	$38.46		Cables	$100	
Hours/week	20		**Direct Cost**		
# of weeks	32		Labor Cost	$24,615.38	
Hours total	640		Testing	$2,700	
Labor Cost	**$24,615.38**		Materials	$9,125	
			Total	**$36,440.38**	
Materials					
Computer	$2,000		FAT @ 1.30%	$473.72	$36,914
Desk	$500		G&A @ 25%	$9,228.53	$46,142.63
Chair	$200		Profit @ 5%	$2,307.13	**$48,449.76**
Total	**$2,700**				
			TOTAL COST		**$84,890.14**

Figure 42: The original BOM is less precise, as it is missing testing equipment and includes unnecessary hardware.

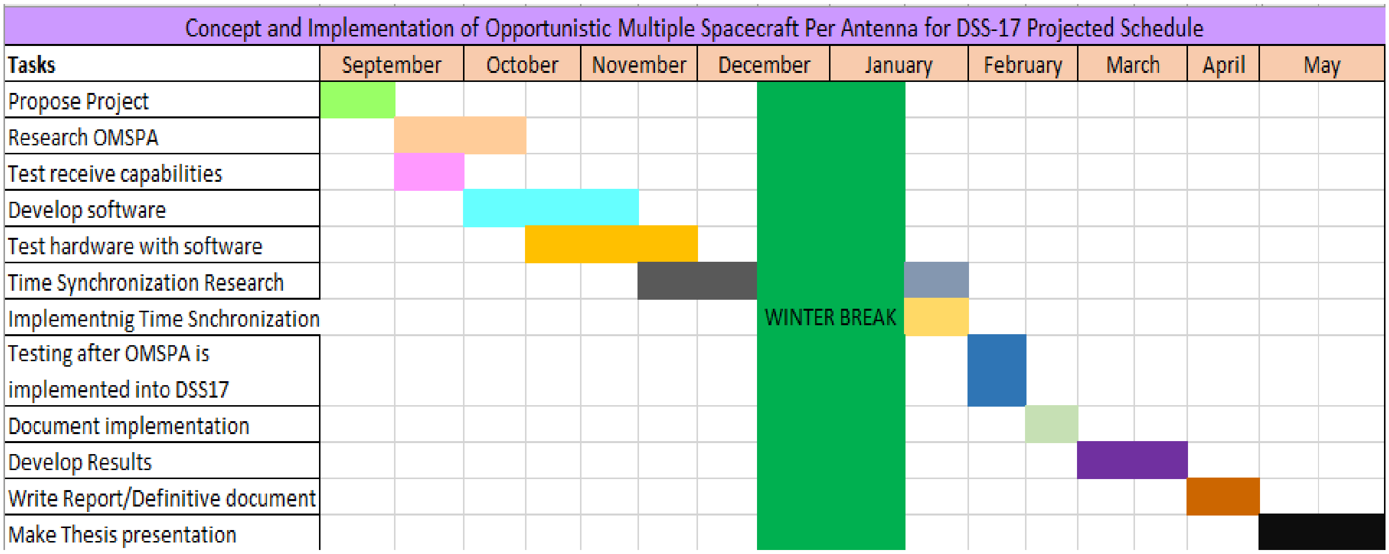
Appendix F – Project Timeline



Concept and Implementation of Opportunistic Multiple Spacecraft Per Antenna for DSS-17 Projected Schedule

Tasks	September	October	November	December	January	February	March	April	May
Propose Project	■			■	■				
Research OMSPA	■	■		■	■				
Test receive capabilities	■			■	■				
Develop software		■	■	■	■				
Test hardware with software		■	■	■	■				
Time Synchronization Research			■	■	■				
Implementnig Time Snchronization				WINTER BREAK	WINTER BREAK ■				
Gather hardware				■	■	■			
Gather resources				■	■	■			
Put together system				■	■		■		
Testing OMSPA system				■	■			■	
MarCo Testing/ Write Final Report				■	■				■

Figure 43: The most up to date timeline. This timeline was created after all testing and demonstrations were complete.



Concept and Implementation of Opportunistic Multiple Spacecraft Per Antenna for DSS-17 Projected Schedule

Tasks	September	October	November	December	January	February	March	April	May
Propose Project	■			■	■				
Research OMSPA	■	■		■	■				
Test receive capabilities	■			■	■				
Develop software		■	■	■	■				
Test hardware with software		■	■	■	■				
Time Synchronization Research			■	■	■				
Implementnig Time Snchronization				WINTER BREAK	WINTER BREAK ■				
Testing after OMSPA is implemented into DSS17				■	■	■			
Document implementation				■	■	■			
Develop Results				■	■		■		
Write Report/Definitive document				■	■			■	
Make Thesis presentation				■	■				■

Figure 44: This image shows the outdated timeline for OMSPA and was created in September 2017. This timeline is messy and out of order and many tasks were changed during the end of the project.

Murphy Catherine Stratton
180 Lee Ave
Morehead, KY 40351
mcstratton@moreheadstate.edu

Education:

Morehead State University, M.S. in Space Systems Engineering, Morehead, KY
May 2018
Morehead State University, B.S. in Space Sciences, Morehead, KY
May 2016

Work Experience:

Morehead State University Space Science Center
Morehead, KY
Graduate Assistant *Fall 2016-Present*

- Assisted with tracking passes for the Jet Propulsion Laboratory ASTERIA mission using Morehead State University's ground station.
- Collaboration with the Jet Propulsion Laboratory on the Opportunistic Multiple Spacecraft per Antenna (OMSPA) solution.
- Assisted in integration of the ADCS subsystem for the CXBN-2 satellite.
- Delivered creative subsystem drawings for the Lunar Ice Cube mission for Safety and Data Management.
- Led team meetings in lieu of boss when absent, delivered detailed meeting notes afterwards.
- Supervised and instructed undergraduate courses and labs (DC circuits, Introduction to Electronics, AC circuits).
- Lead facility tours for prospective students, school groups, regional groups, and V.I.P visitors.

Morehead State University Space Science Center
Morehead, KY
Gear-Up Camp Instructor
Summer 2017

- Developed introductory STEM curriculum for high school students.
- Instructed campers in engineering and electricity basics (soldering, wiring circuits, interpreting data).

Morehead State University Space Science Center
Morehead, KY
Undergraduate Research Assistant
Summer 2013- 2016

- Created and tested solar panels for various satellites (KySat-2, BeakerSat, CXBN)
- Assisted in environmental testing of satellites (shake testing, thermal vacuum testing).
- Assisted in UHF tracking of launched satellites (UniSat-5, UniSat-6, Kysat-2) using 21 meter and ground station.

- Developed Testing and Documentation report of the Cosmic X-ray Background Nanosatellite (CXBN-2) Magnetorquers.

Summer Internship at Space Tango, LLC.
Lexington, KY
Engineering Intern
Summer 2016

- Developed assisted in thermal modelling and analysis for the cell culturing module aboard the Tango Lab.
- Collected information on various thermal insulating materials.
- Produced a “cold call” list for the marketing/business team.

Kentucky Innovation Network
Morehead, KY
Student Entrepreneurial Coordinator/Intern
February 2014- 2015

- Assistant instructor for SpacePREP, a space engineering workshop for young women. Also assisted in preparation.
- Moderated meetups to connect students and entrepreneurs.
- Developed and presented STEM based presentations for surrounding schools to promote STEM education and Morehead State University.
- Produced electronics models to put in exhibit at Highlands Museum in Ashland, KY.

Senior Thesis Work
Morehead, KY
Status: Complete
Fall-Spring 2016
Design and Implementation of a 3-Axis Magnetorquer System for CXBN-2
Work: Testing and documentation for the three-axis magnetic torque system onboard CXBN-2. I provide research, designs, innovations, testing, and documentation to produce a definitive document proving the validity and versatility of the 3-axis system.

Master’s Thesis Work
Morehead, KY
Status: Complete
Fall-Spring 2018
The Implementation of Opportunistic Multiple Spacecraft Per Antenna Concepts on the MSU-STA Deep Space Station 17
Work: Documentation and implementation of the Opportunistic Multiple Spacecraft per Antenna (OMSPA) solution at Morehead ground station DSS-17. This is key to allow communication with many spacecrafts from a single antenna simultaneously. These techniques are possible when two or more spacecrafts are along the line of sight of the antenna and within its main beam. Frequencies in a broad band are collected, digitized, and later individual spacecraft carriers are decomposed using digital signal processing techniques.

Professional Development:

- Attended launch of Elana 4 mission aboard Minotaur rocket in Wallops Island, VA in 2013
- Attended Small Satellite conference in Logan, Utah in 2014
- Presented research at the Kentucky Academy of Science in Lexington, KY in 2014
- Presented research at the Celebration of Student Scholarships at Morehead State University in 2014
- Attended Amateur Radio Convention in Dayton, Ohio in October 2015

STEM Outreach/ Volunteer Experience:

- **SpaceTrek 2013 & 2014**: Assisted as peer mentor/ counselor for summer camp for Junior/Senior high school girls to teach them basic engineering skills and simulate a complete space mission by building and launching CricketSat.
- **Summer Camp for Children of Migrant families 2014:** Assisted as tour guide, camp instructor, and preparation.
- **Richardson Scholars Summer Camp 2014:** Assisted students in building their own “Jiggy Bots” and learning basic engineering skills.
- **International Observe the Moon Night Sept. 6th, 2014**: Citizens from surrounding area come to observe the moon through our telescopes (mainly for families with younger children). I volunteered to help people use the telescopes and teach them different things about our moon.
- **Volunteer at Gateway Helping Hands Food Bank March-April 2016:** Created food boxes for the homeless and needy, worked food drives and assisted in outreach for the community.

Skills/Training:

- Licensed amateur radio operator, Thermal Vacuum Chamber training, Shaker Table training, Systems Toolkit Level 1 certification, GNU Radio Companion, MATLAB, Linux OS, Solidworks, 42, Training on Morehead State’s Ground Station, Proficient with laboratory equipment (spectrum analyzers, oscilloscopes, etc.), Experience in Altium, Express PCB, Programming experience: Core Flight Executive, Basic, C, C++, Python, Soldering/ Microsoldering, Microsoft Office (Word, Excel, PowerPoint, etc.)

Related Courses:

- **Undergraduate**: DC/ AC Circuits, Intro to Computer Science, Calculus I-IV, Satellites and Space Systems I/ II, Digital Control Systems- Space Application, Wireless Communications, Engineering Phys I/II, Differential equations, Advanced Space Systems, RF/Microwave Systems and Antennas, Digital Signal Processing I, Satellite Communications
- **Graduate**: Space Mission Analysis and Design, Thermal and Structural Analysis, Spacecraft Design and Fabrication, Linear Systems, Advanced Processor Systems, Spacecraft Sensors and Remote Sensing, Advanced Digital Signal Processing, Modeling and Simulation, Core Flight Executive, Advanced Space Communications