The Yale Space Station
/ Shoot for the Moon */*

Submitted in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science in
Electrical Engineering & Computer Science

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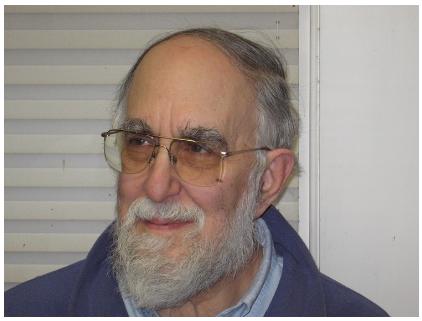
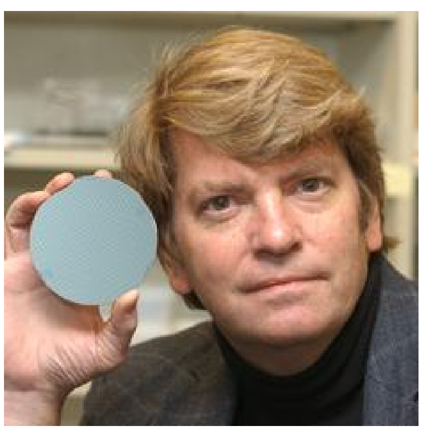
Advisor: Professor Wenjun Hu

May 13, 2021

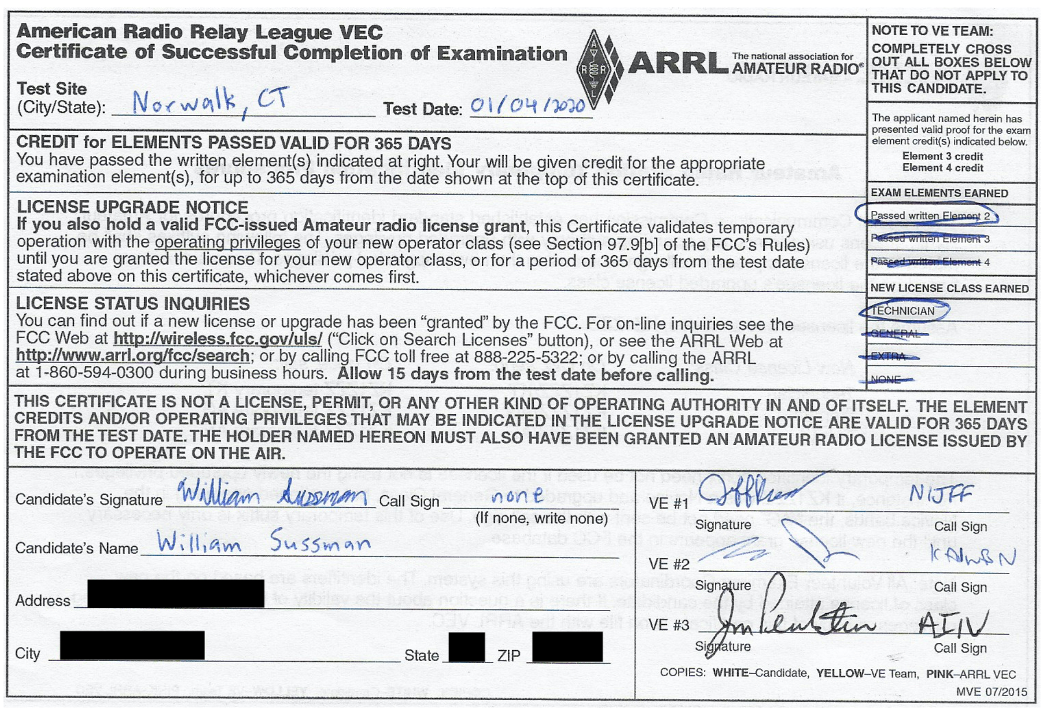


I dedicate the software to Professor of Computer Science Stanley Eisenstat, who taught me data structures and systems programming in his signature course sequence, CS 223 and CS 323. He passed away on December 17, 2020.



I dedicate the hardware to Professor of Electrical Engineering Mark Reed, who taught me electronics in his signature course, EE 200, and was a close adviser as DUS and IEEE branch counselor. He passed away on May 5, 2021.

The story of the Yale Space Station begins in Fall 2019. I took a writing seminar called "Democracy and Sustainability" with Professor Michael Fotos, and was tasked with analyzing an institution of my choice. As an Electrical Engineering & Computer Science major, I chose to study the U.S. Amateur Radio Service. I found that "the means of communication, radio spectrum, is both nonexcludable and subtractable—nonexcludable because anyone can transmit with the appropriate equipment; subtractable because frequencies are finite and single-use—and therefore wireless communication has a commons problem," but "the rules in use by amateur radio operators have allowed them to sustain the wireless communication commons for over a century." One such rule is a license requirement: In order to transmit on the ham bands, one must first obtain a license from the Federal Communications Commission by passing an exam about the regulations. I realized that my investigation sufficiently prepared me for the exam, so I took and passed it on January 4, 2020 (Figure 1).



American Radio Relay League VEC
Certificate of Successful Completion of Examination

ARRL The national association for AMATEUR RADIO®

Test Site (City/State): Norwalk, CT **Test Date:** 01/04/2020

NOTE TO VE TEAM: COMPLETELY CROSS OUT ALL BOXES BELOW THAT DO NOT APPLY TO THIS CANDIDATE.

The applicant named herein has presented valid proof for the exam element credit(s) indicated below.
Element 3 credit
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CREDIT for ELEMENTS PASSED VALID FOR 365 DAYS
You have passed the written element(s) indicated at right. Your will be given credit for the appropriate examination element(s), for up to 365 days from the date shown at the top of this certificate.

EXAM ELEMENTS EARNED
Passed written Element 2
~~Passed written Element 3~~
~~Passed written Element 4~~

LICENSE UPGRADE NOTICE
If you also hold a valid FCC-issued Amateur radio license grant, this Certificate validates temporary operation with the operating privileges of your new operator class (see Section 97.9[b] of the FCC's Rules) until you are granted the license for your new operator class, or for a period of 365 days from the test date stated above on this certificate, whichever comes first.

NEW LICENSE CLASS EARNED
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LICENSE STATUS INQUIRIES
You can find out if a new license or upgrade has been "granted" by the FCC. For on-line inquiries see the FCC Web at **http://wireless.fcc.gov/uls/** ("Click on Search Licenses" button), or see the ARRL Web at **http://www.arrl.org/fcc/search**; or by calling FCC toll free at 888-225-5322; or by calling the ARRL at 1-860-594-0300 during business hours. **Allow 15 days from the test date before calling.**

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Candidate's Signature William Sussman Call Sign none (If none, write none)
Candidate's Name William Sussman
Address [redacted]
City [redacted] State [redacted] ZIP [redacted]

VE #1 Signature Call Sign N1JFF
VE #2 Signature Call Sign KA1WBN
VE #3 Signature Call Sign AI1V

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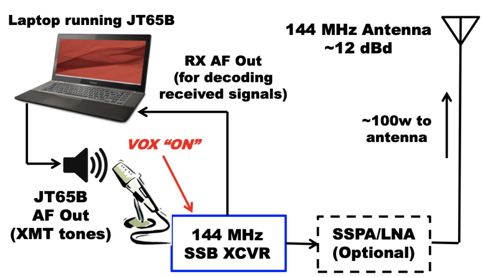
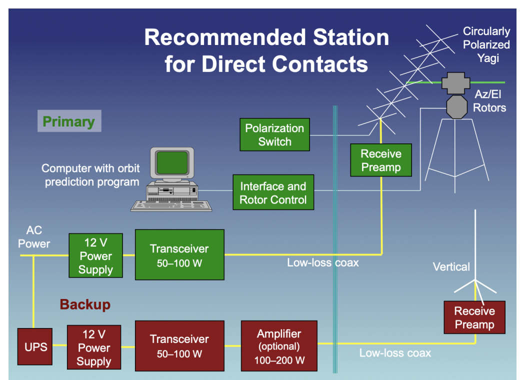
Figure 1: Proof that I passed the amateur operator license exam.

I wanted to use my new license, but ham radio equipment is expensive,

Figure 2: The Yale IEEE Student Branch.



(a) EME



(b) ISS

Figure 3: Diagrams excerpted from the EME and ISS guides.

so I began to explore ham radio projects that could be taken on by the Yale IEEE Student Branch (Y-IEEE; Figure 2), which I co-chaired at the time. I found this guide for Earth-Moon-Earth (EME) communication, a technique in which radio waves are bounced off the Moon (Figure 3a). I also found this guide for contacting the International Space Station (ISS; Figure 3b). With the right design, the first goal seemed to imply the second: If we can reach the Moon and back, then we can reach any satellite that uses the same frequencies.

Thus the Yale Space Station was born. I assembled a small team of Y-IEEE members, and on February 28 pitched the idea in a meeting with Chris Incarvito, Associate Provost for Science Initiatives; Vince Wilczynski, SEAS Deputy Dean; and Electrical Engineering professors Mark Reed, Roman Kuc, and Hong Tang. The proposal was approved, and on March 5 the Yale Science & Engineering Association (YSEA) awarded Y-IEEE a $5,000 grant for the project. I went home on March 7 and planned to resume work after spring break.

That spring break never ended. The World Health Organization declared COVID-19 a global pandemic on March 11, and I could not return to Yale until June 11, only to retrieve my belongings. It was impossible to resume work on the Space Station until I returned more permanently in Fall 2020. I reassembled the team, but the technical work had to be done by myself due to physical distancing and occupancy limits. On October 28, we met on Zoom with Associate Provost Incarvito; Dev Hawley, Director of Facilities Operations and University Planning; and Anthony Kosior, Director of Facilities, Utilities, and Engineering to discuss potential roofs for the Space Station (Figure 4). However, a roof was not provided until March 11, 2021 (Figure 5).

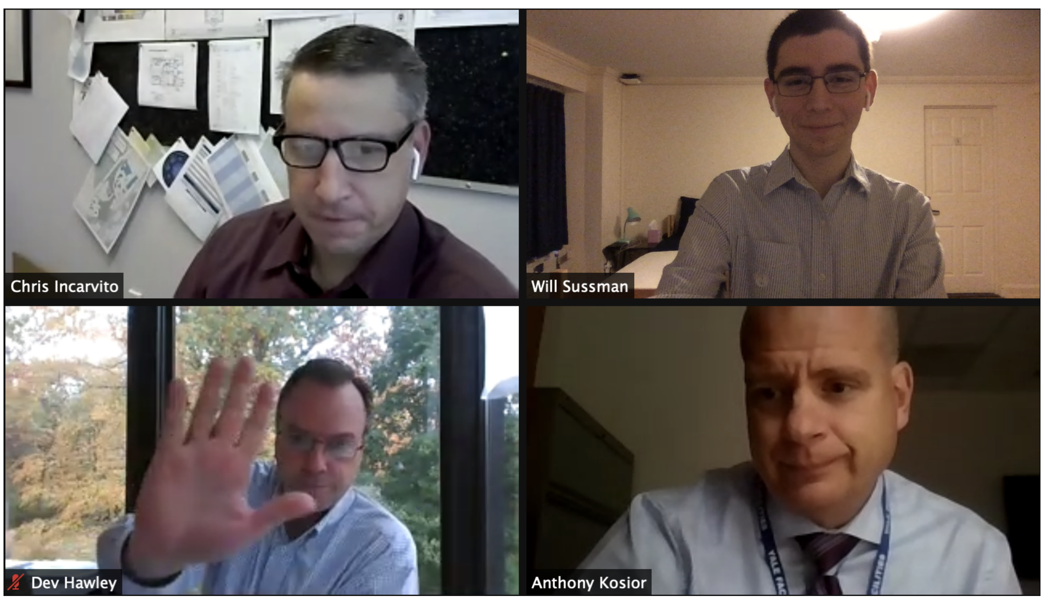


Figure 4: Meeting with administration in October 2020.

In the meantime, I began to design the system and order equipment. For signals to reach their targets in space, they must be targeted. Not only are directional antennas required, but also the means to point them in the right direction. I chose these azimuth/elevation rotators (Figure 6), which

Figure 5: The Space Station is on top of the Environmental Science Center.

determined the form of much of the Station: The rotators are mounted on a mast supported by a tripod, with a cross boom through the azimuth rotator. On one end of the cross boom is a 144 MHz antenna, and on the other end is a 440 MHz antenna. Four 150-foot cables run to "Mission Control," one for the 144 MHz antenna, one for the 440 MHz antenna, and one each for the two rotators. Ideally the antenna cables would be as short as possible to minimize noise, but since I did not know the distance to Mission Control until a roof was provided, 150 feet turned out to be longer than necessary. Shortening the cables remains future work.

The antenna cables do not connect directly to the antennas. EME is weak-signal communication, which necessitates preamplifiers. There are two varieties: "mast-mount" preamplifiers amplify received signals *before* they travel through the cable to Mission Control, whereas "in-shack" preamplifiers amplify received signals *after* they travel through the cable. I chose the mast-mount variety for an important reason, illustrated in the following example.

Assume that an antenna receives 2 units of signal power and 1 unit of noise power; that its cable adds 1 unit to the noise power; and that its preamplifier doubles both the signal power and the noise power (Figure 7). With an in-shack configuration, the signal is destroyed in the cable. With

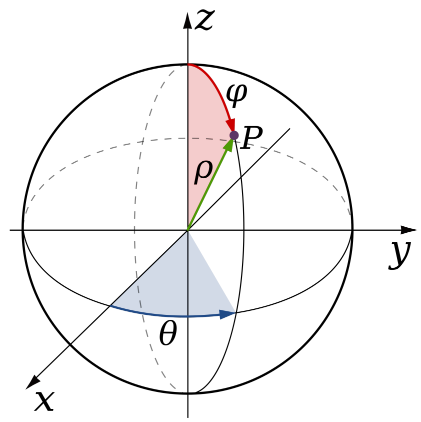


Figure 6: Azimuth and elevation coordinates specify a direction in 3D space.

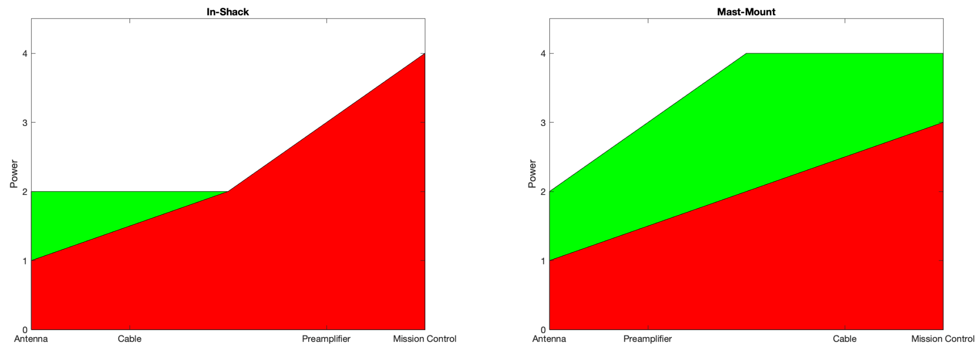
a mast-mount configuration, however, even though the preamplifier doubles the noise power, the doubled signal power can survive the cable. Order matters.

Amplification requires external power. Conveniently, the mast-mount preamplifiers I chose for the 144 MHz antenna and for the 440 MHz antenna draw energy from the existing coaxial cables, injected as DC by their in-shack controllers. Additionally, they automatically switch on during reception and off during transmission. The only other parts they require are 12-foot feed lines for the 144 MHz antenna and for the 440 MHz antenna, an adapter to convert the 144 MHz feed port to the appropriate type (a flaw of the particular antenna model), and, within Mission Control, 3-foot coaxial cables to connect the radio to the controllers for the 144 MHz preamplifier and for the 440 MHz preamplifier.

There are a few more components within Mission Control. The radio is powered by a switching supply and is connected to a PC which can control it. (Linear power supplies were also available, but the recommended model, which was discontinued, was a switching supply.) The PC also controls the azimuth/elevation rotators via an interface device. Finally, if the Station is struck by lightning, it would be good to at least protect Mission Control, so there is one arrestor for the 144 MHz cable, one for the 440 MHz cable, and one each for the two rotator cables.

The hardware can be summarized with the block diagram in Figure 8 and is pictured in Figure 9.

The PC is running Ubuntu 20.04.2.0 LTS. It was important to add its



(a) Signal destroyed in cable.

(b) Signal survives.

Figure 7: In-shack vs. mast-mount configuration.

MAC address to Yale Network Registration and connect to the "yale wireless" network, since YaleGuest blocks NTP packets, which is problematic for time-division multiplexing.

To set up Minicom for communication with the rotator interface device, I ran the following commands:

```
$ sudo apt-get update && sudo apt-get upgrade
$ sudo apt-get install minicom
$ sudo minicom -s
```

Then, under "Serial port setup," I set the Serial Device to /dev/ttyS1 and the Bps/Par/Bits to 9600 8N1. Some commands worked as intended; some did not.

To set up WSJT-X for weak-signal processing, I downloaded wsjtx_2.3.1_amd64.deb and ran the following commands:

```
$ sudo apt install libgfortran5 libqt5widgets5 libqt5network5 \
  libqt5printsupport5 libqt5multimedia5-plugins libqt5serialport5 \
  libqt5sql5-sqlite libfftw3-single3 libgomp1 libboost-all-dev \
  libusb-1.0-0
$ sudo dpkg -i wsjtx_2.3.1_amd64.deb
$ sudo adduser $USER dialout && sudo reboot
```

WSJT-X depends on Hamlib, so that library is installed automatically.

To set up Gpredict for satellite tracking (Figure 10a) and automatic antenna positioning and satellite communication, I ran the following command:

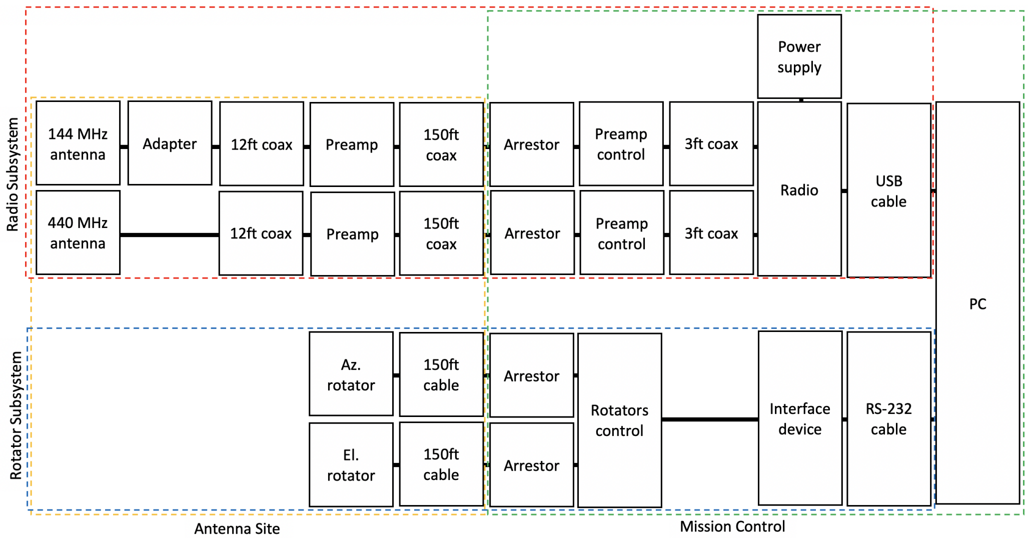


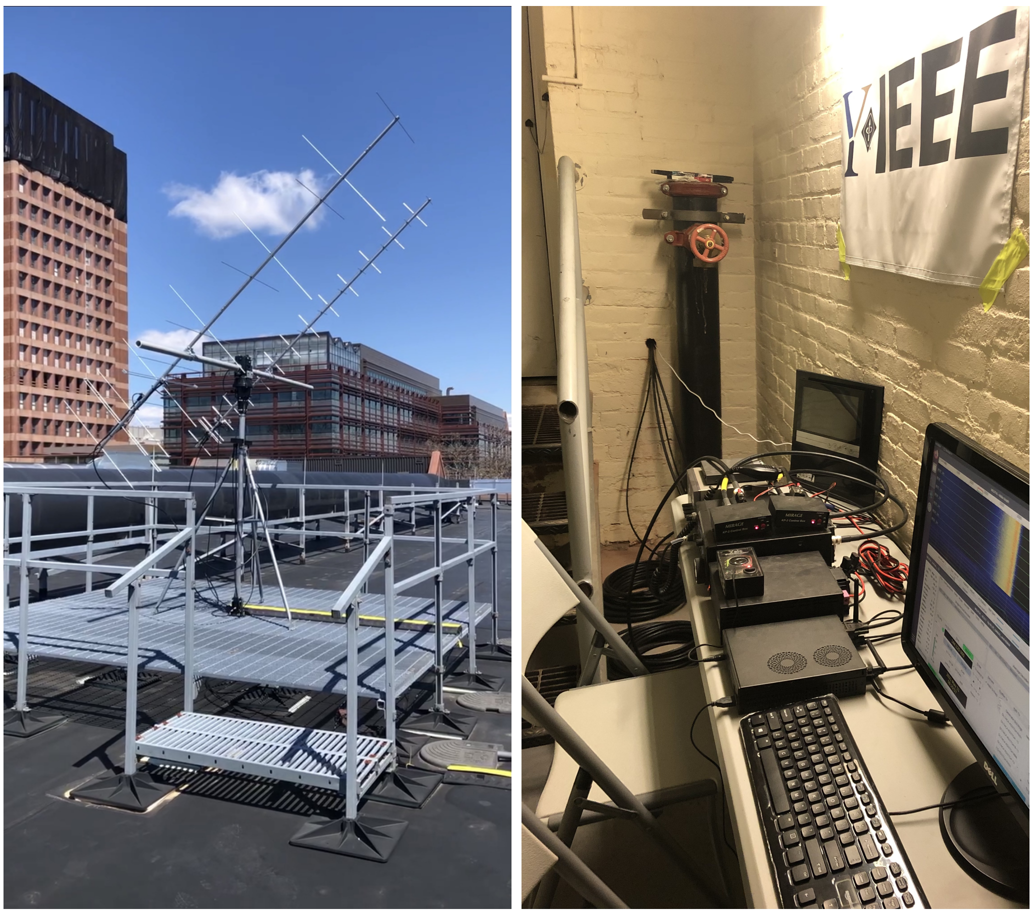
Figure 8: Logical and physical partitions of the Space Station.

```
$ sudo apt-get install gpredict
```

The automatic features rely on Hamlib command-line utilities rotctl and rigctl, respectively. Unfortunately, rigctl does not currently support the particular radio model, and although rotctl supports the rotator interface device, it did not work as intended. I decided to leave Gpredict for future work and focus on EME with manual operation of the rotators' controller.

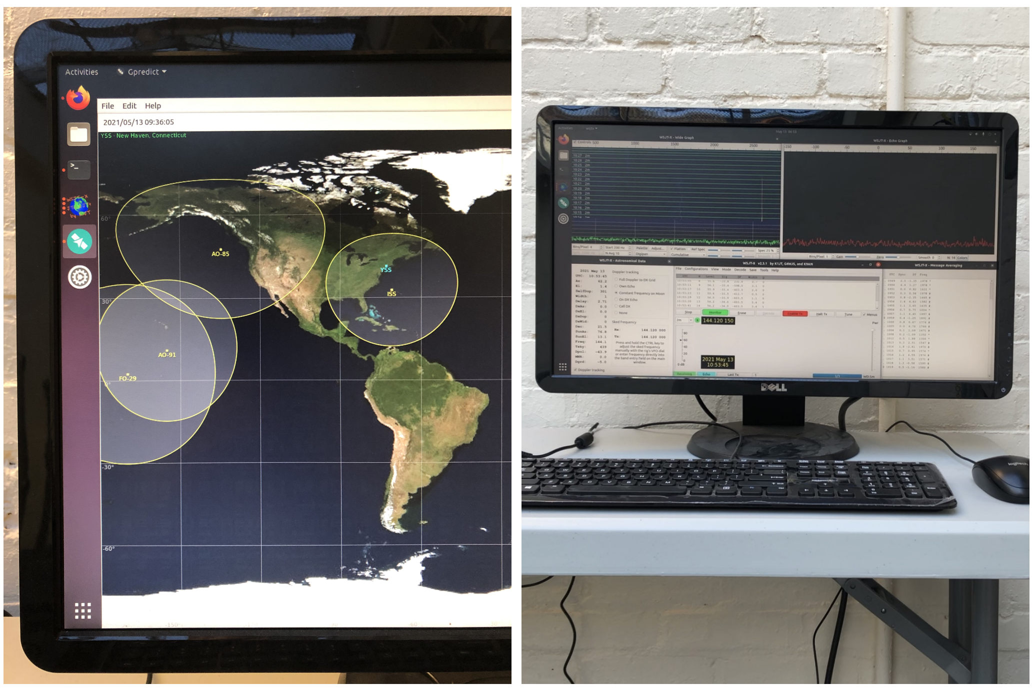
I have been able to directly intercept others' transmissions to the Moon, and confirm that others have been able to directly intercept mine. However, so far I have been unable to receive transmissions bounced off the Moon (Figure 10b). This is likely due to astronomical factors described in this reference book. Since good conditions are not forecast until this report is due, I will try again after submission.

I would like to thank all the faculty, staff, administrators, sponsors, and informal advisers who contributed to this project. In particular, I thank my advisor, Professor Wenjun Hu; I thank Professor Roman Kuc and Professor Mark Reed for their support; I thank Safety Engineer John Campbell for all his help building and testing the Station; I thank the members of W1YU for their assistance, especially Scott Matheson; and I thank YSEA, SEAS, EHS, Berkeley College, and—as of this week—the NASA Connecticut Space Grant Consortium for funding the project.



(a) Antenna Site (b) Mission Control

Figure 9: The hardware. Notice the hole drilled for the cables.



(a) Gpredict shows the ISS within range. (b) Unsuccessful WSJT-X echo test.

Figure 10: Screenshots of the software.