RADIO LINK ANALYSIS AND CHARACTERIZATION OF PAST AND FUTURE CAL POLY CUBESATS

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So many have influenced my love of engineering, and provided the necessary support for me to grow as a person, that it is not possible to name each and every person. Some people do deserve the all too brief mention here, as they come to mind most easily.

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>
> To my friends, who were so often forgiving of my crazy schedule and chose to wait rather than leave me in their dust, I want to extend my deepest gratitude and love. I'm free now! We will have more adventures, hopefully none of which take place in a classroom!
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> To my family, I love you all deeply. We've been through a lot, and I'm excited to see what happens to all of us, now that we've nearly all run towards our dreams in life. You are the reason the sun rises in the morning, the rock and foundation of life.

Good luck all that follow. Remember, the 'road less travelled' is vastly more rewarding in the end.

ABSTRACT

Cal Poly's satellites design team, PolySat, has three satellites in Low Earth Orbit (LEO) and four more planned to launch within the next two years. Radio communication of past and current orbiting satellites has been an exercise in frustration, prompting significant research into the satellite-side of the radio link by several other Senior Projects and Thesis papers. However, minimal effort has been spent on evaluating why these problems were discovered only once the satellites reached orbit. This paper details the downfalls of relying heavily on link budgets and improper long range test setups, then experimentally determines the sensitivity of PolySat's primary ground station, Marconi. Results are compared to theoretical link budgets to determine incorrect parameters that need to be changed.

The ultimate goal of this testing is to pave the way for the 'New Bus' ground station. This in-development ground station uses satellite hardware to simplify ground operations and increase uplink/downlink performance and robustness. In depth sensitivity testing discovered an extremely high noise temperature of 4365K on Marconi, which will likewise limit performance on the New Bus ground station due to a similar antenna configuration. Downlink requirements will not be met until the ground station's noise floor is decreased.

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1 Introduction

1.1 Background

Cal Poly and Stanford cooperatively created the CubeSat design specification in 1999, specifying a standard form-factor for small satellites, called CubeSats. CubeSats are specified in *U's*, and fit within a generic deployment mechanism called the Poly Pico Orbital Deployer, or P-POD. P-PODs, filled with CubeSats, are bolted to large launch vehicles carrying 'Primary' payloads. Once the launch vehicle reaches orbit, the P-PODs open to eject the CubeSats (secondary payloads) into orbit.

CubeSats effectively decrease the barrier of entry to space. Today, this CubeSat standard specifies standard form-factors in multiples of 'Units' or "U's". More than 50 university CubeSats have reached orbit since 2001, with 11 more launched in August 2012 [1], indicating a blooming opportunity for students to reach space with creations of their own. The CubeSat program is a successful application of Cal Poly's motto 'Learn By Doing', and will receive Cal Poly's continued support to achieving educational value without high costs. Figure 1 is an example of a 1U CubeSat.

FIGURE 1: CAL POLY'S FIRST CUBESAT, CP1

CubeSats provide an interesting challenge in design and development, running counter to much of the rest of the Aerospace industry. They are considered nano or pico-satellites, bearing the following constraints from the CubeSat standard:

- 1U, 1.5U, 2U, and 3U form-factors
- Mass limited between 1.33kg to 4kg
- Volume constrained:
    - 10x10x10 cm to 10x10x30cm

Due to the minimal size and volume, as well as the nature of acting a secondary payload, CubeSats are:

- Power limited
- Generally 'small' budgets
- Short Timelines
- Limited to most orbits

Developers have not been deterred by the constraints. Despite technical obstacles, realized applications include atmospheric science missions, early earthquake detectors, bio-chemical experiments, and prototype testing.

CubeSats today generally fall into one of two categories of capability, as shown in Table 1:

	Low End (1U)	High End (3U)
Processing Speed	4 - 20MHz 8-bit Microprocessor	iPhone 3GS Range (400MHz ARM, 32-bit)
Communications Data Rate	1.2 - 9.6 kbps	2.4kbps - 1.5mbps (with FEC)
Storage	128Kb to 4Mb (EEPROM)	>8GB (SD, NAND, PCM, RAM)
Software	Embedded C	Linux or other RTOS
Power Generation	~1W	>10W
Pointing Capabilities	Tumbling (no pointing)	<1° knowledge and pointing
Ground Station Capabilities	Amateur implementation: • Small Yagi (~15dBi) • 5° pointing • Second Hand Radios	Professional Support: • Large (>8m) dishes (>30dBi) • <1° Pointing • Professional Hardware and Operators

TABLE 1: CURRENT CUBESAT CAPABILITIES [2,3]

The mission drives the capabilities, so CubeSat designers do not follow this table strictly. In many cases however, the design path boils down to two options: 1Us are used for very limited missions with limited timelines, while 3Us are used in a bulk of the cutting edge science missions. These cutting edge missions, requiring larger, more capable 3U CubeSats have become the lead in recent launches. Figure 2 shows the trend of CubeSat launches.

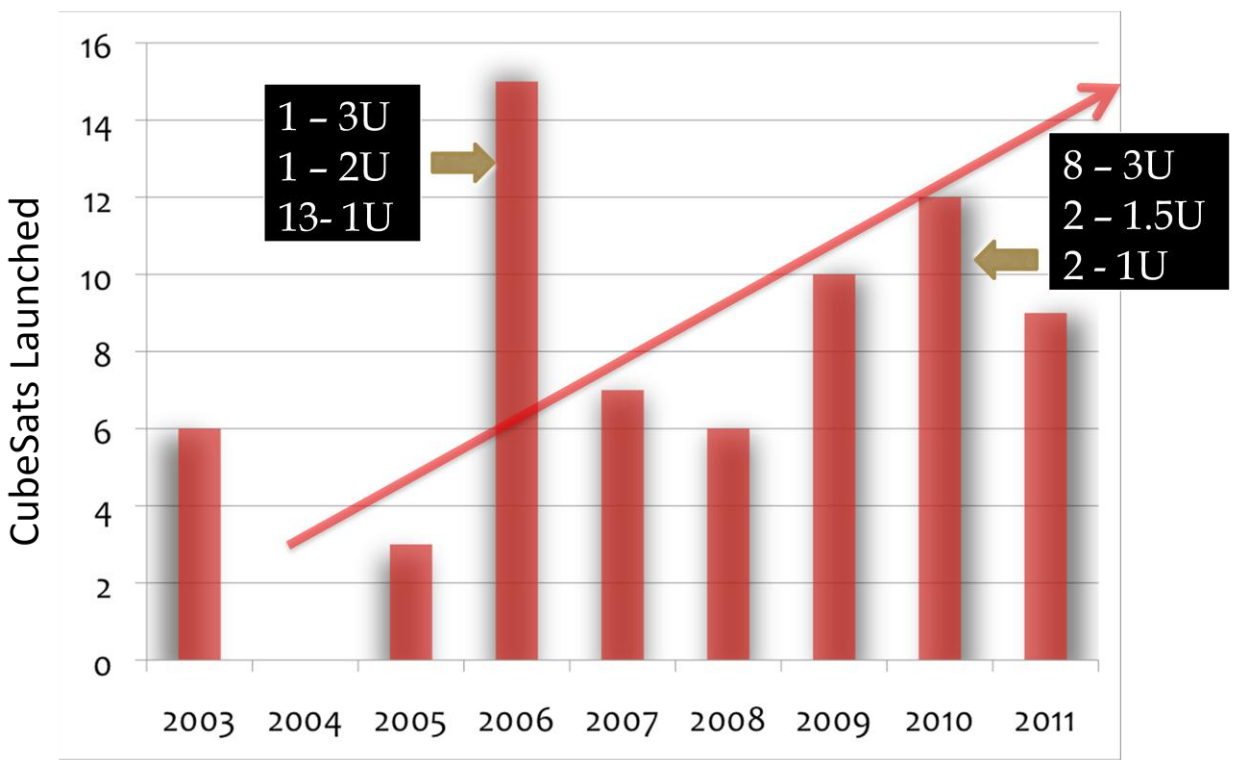

FIGURE 2: CUBESAT LAUNCHES BETWEEN 2003 AND 2011 [1]

1.2 Senior Project Motivation

Cal Poly's CubeSat program, PolySat, began in 1999. Following the 'Learning By Doing' philosophy of Cal Poly, the small group of students slowly built up a common satellite architecture, growing in complexity each iteration. The first four satellites launched were all 1U's, which had payloads which did not require horrendously complex capabilities. The satellites required communication with the ground, so PolySat assembled two ground stations to handle bidirectional communication duties. As is still common for many University CubeSats [4], the ground stations were based off of Amateur radio hardware [5], inheriting the wealth of experience from the Amateur community which proved extremely useful during design and implementation. However, we've had tremendous problems communicating with our orbiting satellites which still continue to this day. Uplink has been particularly difficult, despite a large amount of effort in characterizing and upgrading past satellite receive hardware [6,7,8,9, 10].

Over the last two years, we've integrated all lessons learned into a 'New Bus', a third generation electrical avionics architecture. The New Bus is the core electronics to all new satellites, incorporating a power regulation system (EPS), radio daughterboard (UHF Daughterboard, see Figure 3), and Command and Data Handling (C&DH) functionality. Lessons from past experience were incorporated in the New Bus' design and development, and one obvious improvement that needed to be made was with the radio [11].

FIGURE 3: UHF DAUGHTERBOARD

Previously, the best sensitivity the satellite receiver could reach was -101dBm [10]. This was significantly worse than the transceiver was rated to, but the maximum potential of the old design was never reached. The new UHF radio design has an experimentally determined sensitivity of -118dBm [11], or an improvement of 17dB. Further, the new transceiver is capable of much higher data rates and a variety of modulation schemes, prompting investigation into different radio parameters.

A new ground station is in development which hopes to leverage the advanced capabilities of the New Bus. This ground station would theoretically be more sensitive than those based off of set-top Amateur hardware, and dramatically reduce complexity. Where before a server rack was necessary to store all the ground station equipment, the new ground station would fit in the palm of a hand. Before fully implementing a ground station based off of the New Bus, more information needs to be gathered on the current ground station. Weak points need to be understood, and expectations gauged through experimentation.

2 PolySat Ground Stations

2.1 Legacy Ground Stations: Marconi and Hertz

Cal Poly's two ground stations have been operational for nearly a decade, although major updates have occurred over the years. Many CubeSats were originally designed to operated on Amateur radio (HAM) frequencies, and benefitted tremendously from piggy-backing off of the Amateur community. All CPx satellites (except CP1) use PCBs designed by Cal Poly students, specifically adapted for operation on the 70cm Amateur radio band and compatible with Amateur radio hardware. To talk to our satellites, two ground stations were assembled: Hertz and Marconi. Block diagrams of both ground stations are attached in Appendix A, Figures 26 and 27.

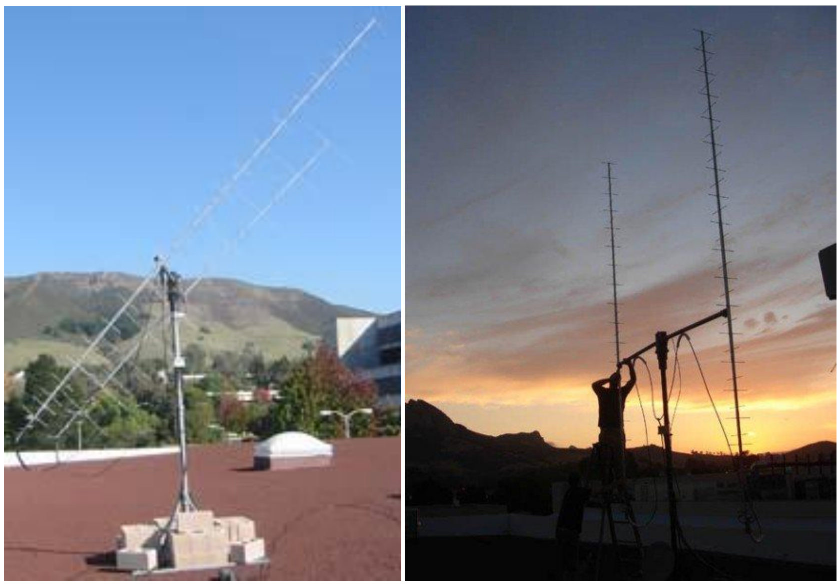

FIGURE 4: HERTZ (LEFT) AND MARCONI (RIGHT)

These ground stations use commercial Amateur-specific radios, capable of VHF and UHF frequencies, designed by Yaesu. The demodulated signal is broken out to a Windows XP computer running a software Terminal Node Controller (TNC) called MixW. Amplification is used on both the receive and transmit sides. A 20dB Pre-Amp boosts the received signal down to the Yaesu's sensitivity range of -115dBm [13]. When transmitting, an RF Amp amplifies the output from the Yaesu to 100W (50dBm).

Both Marconi and Hertz are mounted on the roof of the Advanced Technology Lab. Bulky coax lines run down to our server rack where the radio and workstations perform the necessary control functions. Marconi is the primary UHF ground station, with two arrayed Yagis with a gain of 19.1dBi. Hertz has separate UHF and VHF antennas, with a 3dB lower gain than Marconi at UHF. Hertz is primarily used for training and backup operations.

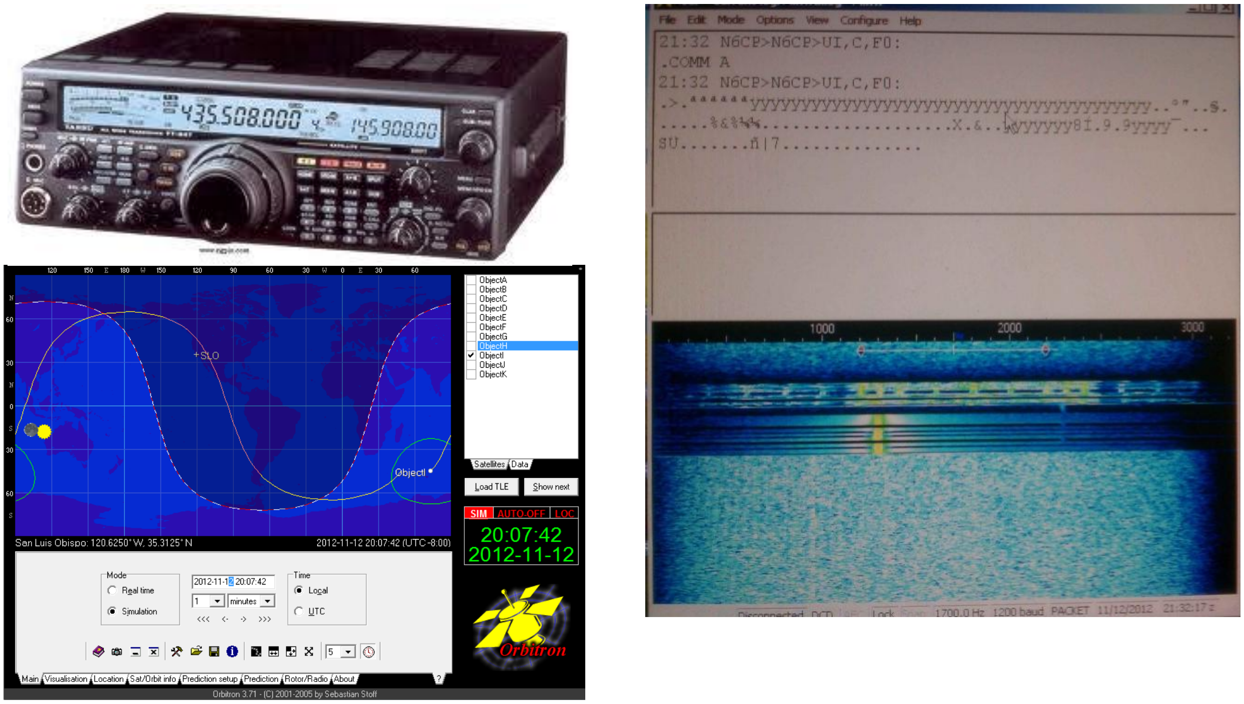

FIGURE 5: YAESU RADIO, ORBITRON, AND MIXW DECODING A CP3 BEACON

A variety of Amateur and internally designed software programs control the antenna pointing, Doppler shift, decoding, and mission data upload to a web server. In total, four programs are relied upon for operations:

- MixW → Software TNC
- Orbitron → Orbit prediction and Doppler shift calculations
- CPxO → Cal Poly operator, internally designed program for decoding data and command queue
- Auto Pass Operator (APO) → Rotor and Radio Control

This setup has worked adequately since its inception, and has been used during CP3, CP4, CP5, and CP6 operations. All launched satellites had poor communication links, despite optimistic link budgets and significant improvements on the satellite side. With the arrival of the 'New Bus', the team has decided to create a new ground station for more reliable communication and upgraded performance.

2.2 New Bus (NB) Ground Station

In 2010, PolySat completely redesigned the mechanical, electrical, and software architectures. Specific benefits can be found in other Thesis Papers and Senior Projects by past team members. In summary, advancing IC technology has enabled significantly more powerful and capable electronics, allowing an increase in computing performance by 100-fold while simultaneously decreasing volume by 80%. Smaller manufacturing sizes has also benefited RF components; the New Bus' radio transceiver is 10dB more sensitive than the old satellite radio, while significantly more flexible. Where before we were limited to approximately 9.6kbps, the new radio can reach speeds to 600kbps and use a variety of modulation schemes [11].

The largest change in moving to a more capable electronics system is that we can now leverage Linux as the Flight Software. Our satellite has approximately the same performance as an old Smartphone, can network with TCP/IP, fast enough to run complex programs such as orbit propagators, and simpler for students to work with. Marconi and Hertz required a PC, support radio and RF equipment, and were basically limited to using a hodge-podge of Amateur freeware and internally design software, making ground operations complex and fickle. The SystemBoard and UHF radio daughterboard, Figure 6, handle all of the same functionality in an integrated package, and is already well understood by students in our lab. The ultimate goal is to have the ground station use essentially the same hardware and software as our satellites, consolidating efforts and knowledge bases.

FIGURE 6: NEW BUS AVIONICS: SYSTEMBOARD AND UHF RADIO DAUGHTERBOARD COMBO

Technical benefits in the move exist as well. The older Yaesu is sensitive down to -115dBm at 1200bps, while the NB can adequately decode 9.6kbps down to -118dBm. The Yaesu's input filter must also be bypassed to support 9600kbps, and any faster results in performance problems: moving beyond a 20kHz bandwidth requires a new setup, as the microphone port on the computer has its own filter [5]. Basically, while the current ground station is excellent for 1200 or 9600 baud connections, moving beyond creates new obstacles.

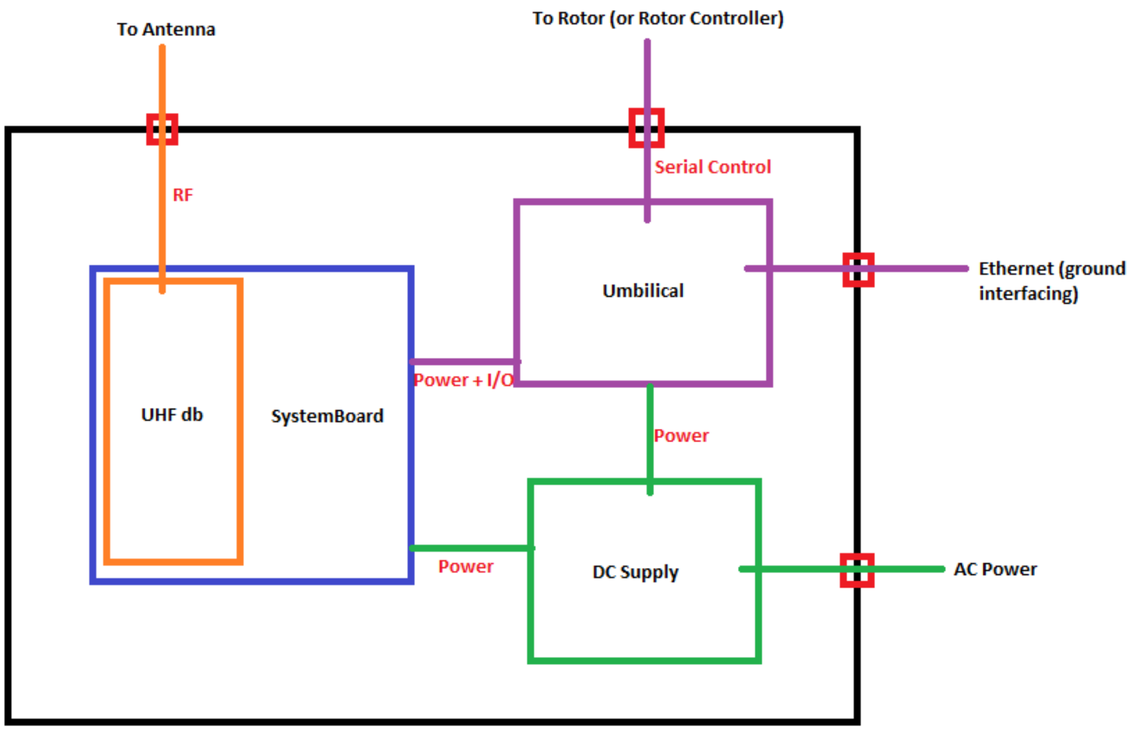

FIGURE 7: NEW BUS GROUND STATION BOX

Moving to a more consolidated setup means we can place all equipment on the roof, right next to the antennas. The coax losses were not a huge concern, but lower line losses and a less noisy location do help. The NB would be placed in a weatherproof enclosure. Support hardware would be necessary, and configured in Figure 7:

- The 'Umbilical' board is an already completed PCB
  - Breaks out lines to control the rotors
  - Ethernet controller and connector for internet connectivity
- DC Power Supply
  - Step 120V AC down to 4.2V

The NB ground station will likely use the same Antennas, Pre-Amp, and 100W RF-Amp as Marconi, although the exact design is to be determined. The NB ground station's initial tests are performed using Marconi, switching the Yaesu for the NB.

3 Project Scope

CP8 (IPEX), CP9, and CP10 (ExoCube) have vastly larger data downlink requirements than any past mission, requiring a move to higher data rates and/or longer link time per day [12]. This project experimentally simulates a variety of orbital distances and elevations, compares downlink performance to the last generation communications system, and explores weaknesses in the current ground station which need to be remedied before the new ground station can be considered feasible. Tasks include:

- Experimentally verify old link budget assumptions and test setups
- Compare baseline capabilities between old PolySat ground station and planned upgraded ground station
- Explore higher data rates and different modulation schemes with new bus
- Determine weak points in the current ground station and suggest solutions to meet internally generated goals

Requirements	Justification
Equal or better performance at baseline than old ground station • 1200bps old Ground Station • 9.6kbps new Ground Station	Old ground station had minimally acceptable downlink margin
≥100kbps at 350km, starting at 15° Elevation	CP9 generates a large amount of mission data, with only 30 day orbital lifetime. Mission data budget specifies at least 100kbps to downlink everything
≥38.4kbps at 650km, starting at 10° Elevation	CP10's payload generates several MB/day. Science Team specifies 2MB/day (raw data) as acceptable.

TABLE 2: REQUIREMENTS AND SPECIFICATIONS FOR NEW BUS GROUND STATION

4 Past Testing and Simulation Methodology

4.1 Link Budgets

Link budgets are used to determine the feasibility of a radio link. Budgets can be simple, where the user only adds losses, gains, and sensitivities to find a rough estimate, or they can be complex and factor in pointing losses, thermal noise, and a variety of other factors. In the right hands, a link budget is useful. In the wrong hands, misleading and disastrous. First we'll take a look at a simple link budget in Figure 8.

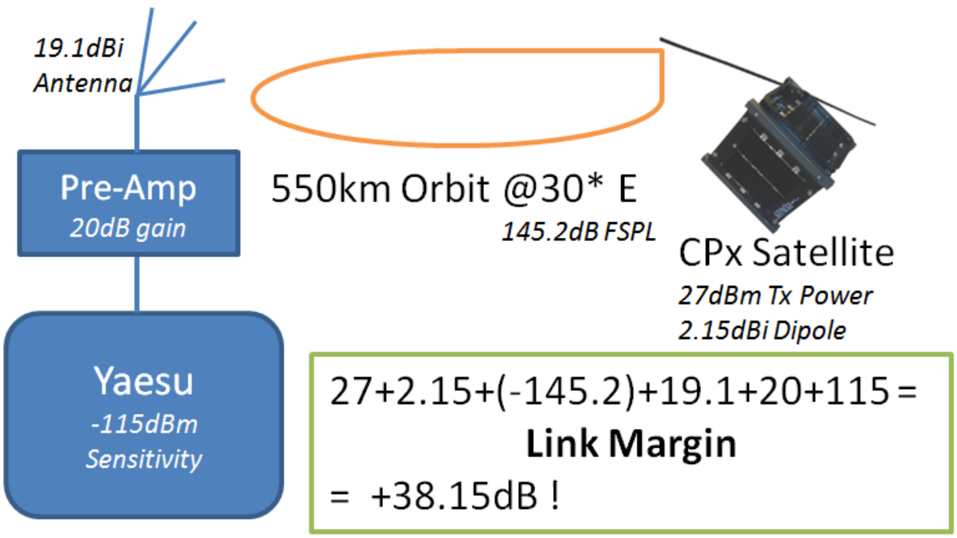

FIGURE 8: OVERLY SIMPLE LINK BUDGET

Judging by this rough budget, we have 38.15dB margin on the downlink side, a tremendous success. However, this in no way reflects reality. So the question is, what needs to be added to the model to make it useful?

The venerable Jan A. King (W3GEY/VK4GEY), AMSAT charter member, has created (with help) an excellent link budget document which provides a great starting point [14]. This document, titled the 'AMSAT/IARU Annotated Link Model System', is a nineteen page spreadsheet which details:

- Orbital Slant Range and Free Space Path Loss (see Figure 9)
- Transmit powers delivered to the antenna, including line/connector losses and matching
- System Noise Temperatures, including LNAs, insertion losses, galactictic/atmospheric noise, and receiver bandwidths
- Antenna gains, pointing inaccuracies, and polarization losses
- Modulation BER and SNR (or E_b/N_O) requirements

This spreadsheet provides excellent notes on each step of the process, and is robust enough to provide basic confidence in a link.

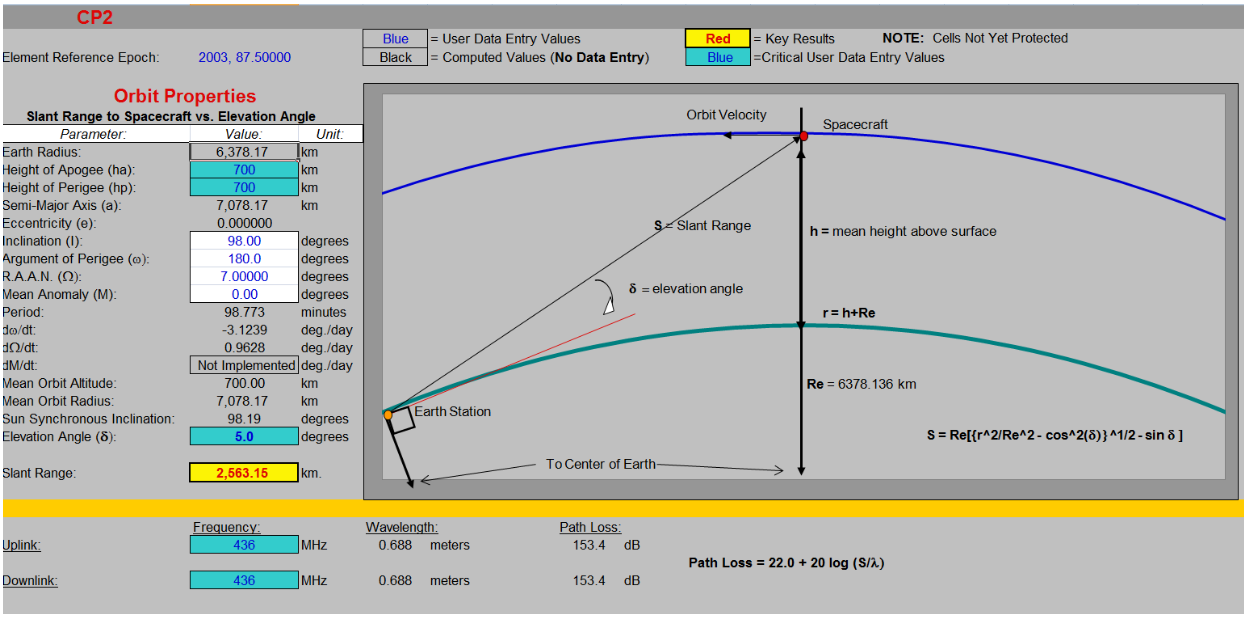

FIGURE 9: LINK BUDGET FROM JAN A. KING AND IARU

There is danger relying solely upon link budgets, no matter how complex they are. Unless every parameter is correct, they fall apart, leaving you with a poorly functioning satellite. We have run into this over and over: our downlink capabilities have been acceptable on all launched satellites, but the uplink has been extremely patchy. The link budget above is deceptively forgiving due to user error, in the wrong hands. For a historical example, CP2/4 had horrendous uplink problems while the downlink capabilities were reliable [6,7,8,9, 10]. The link budget, summarized in table 3, indicates otherwise, implying a failure in analysis.

CP2 Link Budget	Downlink	Uplink
System Link Margin	**4.5dB**	**25.5dB**

TABLE 3: HISTORICAL CP2 LINK BUDGET CONCLUSION

The point is that no matter the complexity and thoroughness of a link budget, both the ground station and satellite must be tested in the field to ensure actualized performance.

4.2 Long Range Tests

Long range testing of bidirectional links are the best method to verify link budgets and assure success, but care must be taken to properly assemble the setup. Recent experiments prove this point exceptionally well; some older experiments were not as meticulous, causing harm in their false success. The recent long range tests performed by Austin Williams' in his Thesis work were pivotal in finding test setup issues, and lessons from his testing were applied to the final test setup used in this project. His results are summarized below.

Completion of the UHF Daughterboard prompted strenuous sensitivity testing, both indoors and long range. Sensitivity in a faraday cage was exceptional, reaching -118dBm at 9.6kbps. Increasing the data rate decreased sensitivity, as seen in Table 4 and Figure 11.

	9.6kbps	19.2kbps	38.4kbps	100kbps
Cutoff Sensitivity (dBm):	-118	-116	-114	-107
Delta from Baseline @9.6kbps (dB):	0	-2	-4	-11

TABLE 4: RESULTS OF AUSTIN WILLIAMS' NB SENSITIVITY TESTING [11]

The faster the data rate, the larger the penalty to the link margin. Results in a faraday cage matched later long range testing from Bishops.

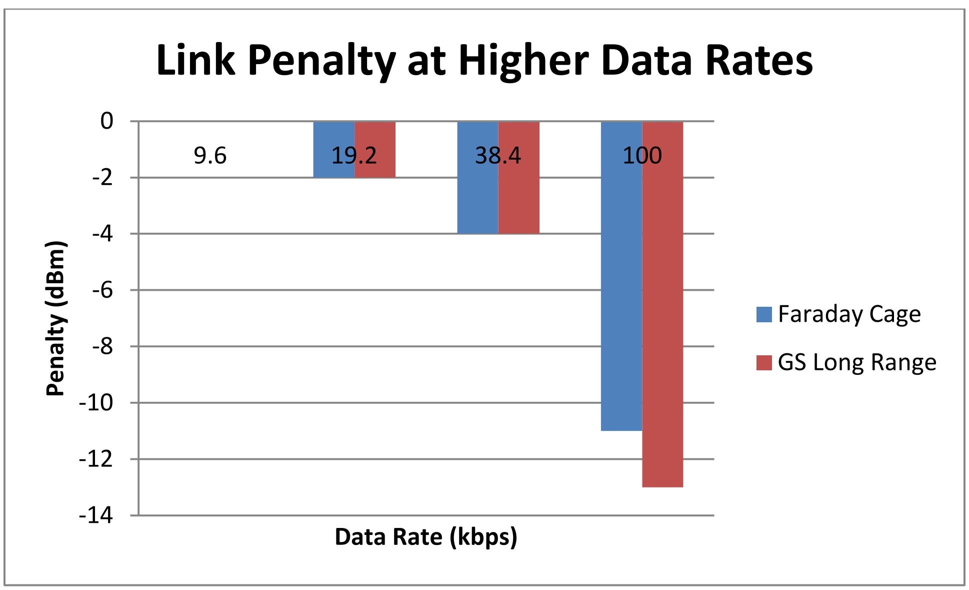

FIGURE 10: PENALTY OF HIGHER DATA RATE COMMUNICATION

Austin's tests provided the best case sensitivity to expect at 9.6kbps. There is the desire to stop here, and use this number in simplistic link budgets, but that neglects one important factor in long range links: ambient or self-generated noise. The link attenuation was simulated with the device under test (DUT) within a faraday cage, and the transmitted signal passing directly through a variable attenuator. The test setup is detailed in Figure 12.

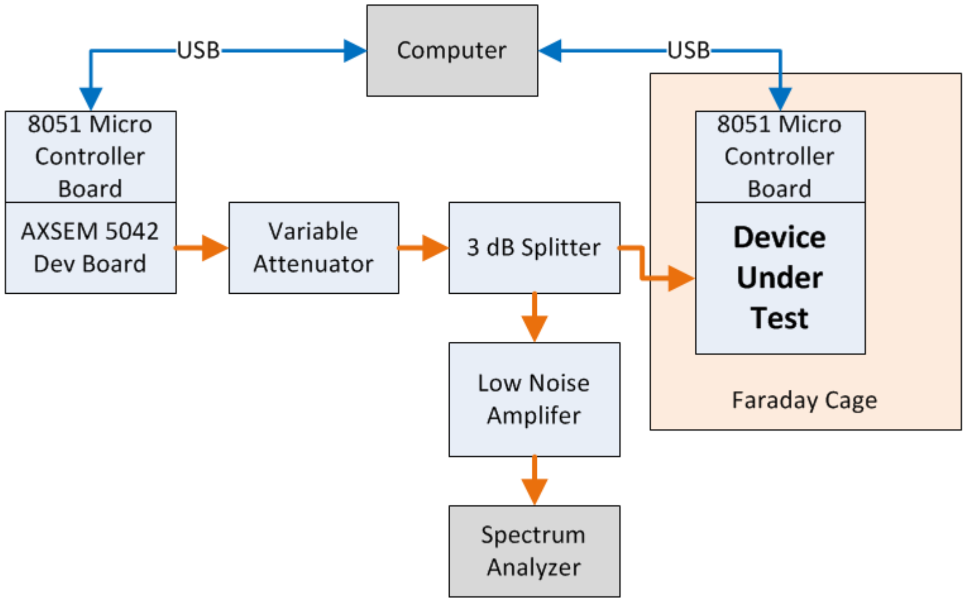

FIGURE 11: FARADAY CAGE TEST SETUP OF NB [11]

The problem is that all noise, both self-radiated and ambient, are attenuated along with the test signal. This results in an artificially low noise floor, an unrealistic situation considering that the ground station is on Cal Poly campus. This test still proved extremely useful, but the caveats must be known before assuming it applies in all situations. This was learned the hard way during preparation for a high altitude balloon launch for CP8 (IPEX).

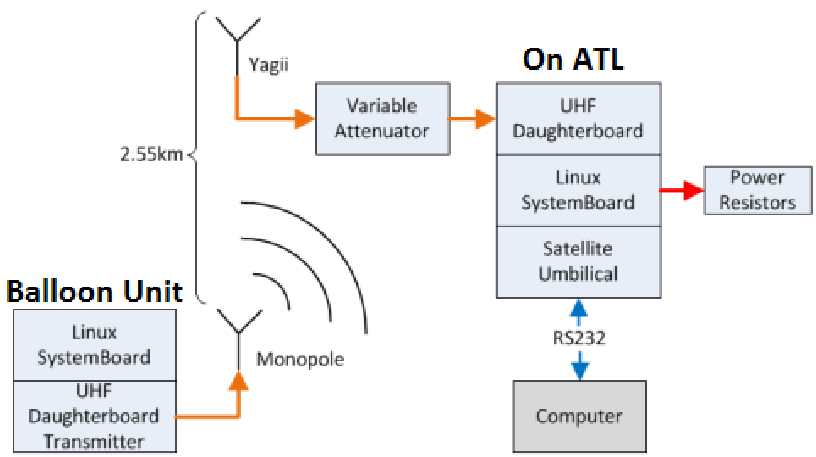

FIGURE 12: IPEX BALLOON UNIT TEST SETUP

The Balloon Unit was at the base of Bishops, while the team on the ATL used a handheld Yagi. Beacons from the Balloon Unit were attenuated using the Variable Attenuator on the receiving end. Cutoff power levels were found to be somewhat comparable to my more strenuous ground station testing detailed in the following sections.

VariableAttenuator(dB)	Regulators?	DropRate(%)
40	Off	0
50	Off	0
54	Off	20
54	On	20

TABLE 5: 'DOWNLINK' ATTENUATION CUTOFF FOR IPEX BALLOON UNIT [11]

Assuming that the Free Space Path Loss calculation is correct, at 93.4dB loss, the 'downlink' in this test cut off at ~147.4dB simulated path loss. This makes many rough assumptions, but is a decent sanity check that the link will hold during the planned balloon launch, which eventually reached 102,000 feet (115dB FSPL). The problems occurred when attempting to uplink back to the Balloon Unit.

VariableAttenuator(dB)	Regulators?	DropRate(%)
0	Off	0
10	Off	0
20	Off	2
25	Off	25

TABLE 6: 'UPLINK' ATTENUATION PROBLEMS FOR IPEX BALLOON UNIT [11]

Theoretically, there shouldn't be a difference between uplink and downlink. The radios are identical and transmit powers identical. Only difference is the choice of antennas between tests, which shouldn't make a difference, assuming Antenna Reciprocity is true. Antenna Reciprocity is a theory that essentially states that the gain of an antenna should be the same in both transmit and receive directions, so they *shouldn't* be the problem. So where is the problem? Are one of the radios broken, or was there an issue elsewhere?

Further troubleshooting narrowed down the culprit: monopole antennas depend heavily on a good ground plane, and ours was using the side panels for RF ground. A mixture of common mode current and radiated noise from the SystemBoard increased the noise floor on the Balloon Unit, crippling its receive sensitivity by 30dB. The system on the ATL used a Yagi, which has a separate RF ground and strong directionality, limiting the impact of its own self-radiated RF noise. Past testing had never discovered these issues, as sensitivity tests had isolated the NB within a faraday cage, or long range tests had only been performed with Yagi antennas. The only situation where we had a problem was during this very specific, somewhat flight hardware indicative balloon launch. No link budget nor poor test setup would have revealed the monopole issue, highlighting the importance of a proper test setup.

4.3 Past Issues and Lessons Learned

The first long range test performed in evaluating the New Bus ground station also showed the importance of a proper test setup. I used lessons learned from past long range tests in preparation:

1. No attenuation should be used on the receive side: it artificially lowers the receivers noise floor
2. Antenna Reciprocity should not be depended upon when testing receive capabilities. Only use flight antennas to test receive sensitivity.
3. Test only 1 direction at a time, instead of bidirectional 'ping' tests. Simplify test setups to simplify troubleshooting
4. Characterize ALL equipment before AND after long range testing
5. Move equipment as little as possible during testing. Small changes to the test setup can have large impacts
6. Test the same portion of the link using multiple methods, both in forward (transmit) and back (receive), before assuming calculated values are correct. Broken links or exceptionally complicated setups tend to become oversimplified assumptions

However, I had forgotten one important factor in this analysis: simulating an orbital link requires decreasing transmitted power by more than 140dB (500km, directly overhead is 139.25dB), or approximately 10^{-14} Watts on the receive side. The first long range bishops test assumed all RF power from the satellite is emitted by the antenna, and an attenuator would be enough to isolate the system. Interestingly, the variable attenuator had little effect when measured by the spectrum analyzer on the ground station side, as seen in table 7.

Variable Attenuator Setting	30dB	40dB	50dB	60dB
Theoretical Signal Strength (dBm)	-77.2	-87.2	-97.2	-107.2
Experimental Signal Strength (dBm)	-77.7	-88.2	-91.2	-93.2
Delta (dB):	***0.5***	***1***	***6***	***14***

TABLE 7: FAILED TRANSMISSION ATTENUATION

The max attenuation the variable attenuator provided was 46dB. At first, it was thought the VA was broken, but later characterization proved the VA capable of 110dB (+/-1dB) attenuation in 1dB steps. The real problem was that the ground station was able to pick up unintentionally radiated noise which was coming elsewhere than the antenna. Placement in a faraday cage resolved the issue. This leads to the final lesson learned:

7. Long Range tests require the use of a faraday cage on the transmit side in order to simulate a real orbital power level

5 Ground Station Experimental Testing

5.1 Noise Floor

The ultimate limit in long range communications is the noise floor, and is often neglected by inexperienced Electrical Engineers. To complicate matters further, the noise floor is not a simple, single measurement using the spectrum analyzer. Spectrum Analyzers integrate the spectral power over their 'Resolution Bandwidth', or RBW. Essentially, the spectrum analyzer has a filter of a specific bandwidth that is set by the user, then this filter is swept across the spectrum. At each frequency, the power is integrated and displayed, then the SA moves to the portion of bandwidth. The result is that, the higher the RBW on a SA, the higher the *apparent* noise floor. This is evident in the apparent noise floors at different spectrum analyzer RBWs, measured outside of Engineering 4 pointing towards the sky.

BW:	300kHz	100kHz	30kHz	10kHz	1kHz	10Hz
Signal Strength: (dBm)	-65.7	-71.1	-76.8	-80	-89.3	-112.9
Noise Floor (dBm):	-108.9	-114.3	-120	-123.2	-132.5	-156.1

TABLE 8: NOISE FLOOR MEASURED OUTSIDE ENGINEERING 4

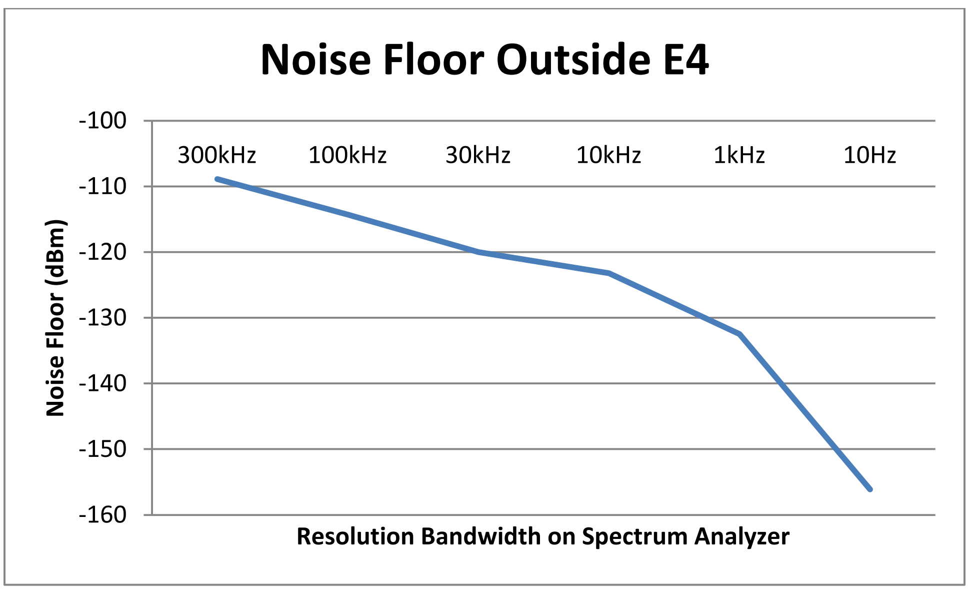

FIGURE 13: NOISE FLOOR MEASURED OUTSIDE ENGINEERING 4

It is not a problem that the SA isn't perfectly measuring the 'real' noise floor. The front end filter on the satellite radio transceiver has a specific bandwidth that is set depending on the data rate (and thus bandwidth) of the incoming signal. Effectively, the noise floors measured at different RBWs are the noise floor at different downlink data rates. To simplify the measurements, I assume a filter bandwidth is the same as the data rate. The real transceiver bandwidth will be higher than the data rate by approximately 50%, depending on manufacturer, implying a slightly higher Noise Floor.

Measuring the noise floor on Marconi is relatively simple, and will be close to the same noise floor as the NB ground station, as the cables and Pre-Amp are largely the same. To measure the noise floor, the coax from the roof is split between the Yaesu and Spectrum Analyzer by a 3dB splitter, and amplified using a 43.2dB LNA. The coax must still be connected to the Yaesu, as it powers the Pre-Amp.

Noise Floor (10kHz RBW) of GS Pointing Towards Bishops		
Reading on SA:	-70	dBm
Gain on LNA:	43.2	dB
Pre-Amp:	19*	dB
3dB Splitter:	-3	dB
Cable Losses:	-2	dB
Noise Floor:	**-127.2**	**dBm**

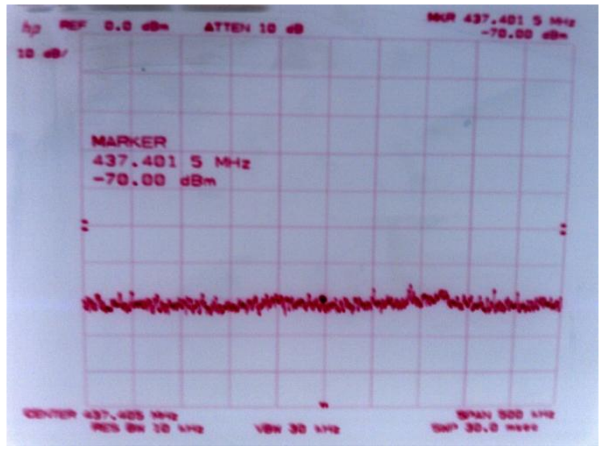

FIGURE 14: NOISE FLOOR OF MARCONI

**Exact gain determined during test equipment characterization*

The Spectrum Analyzer is only sensitive to approximately -100dBm at a resolution bandwidth of 10kHz, so the 43.2dB LNA is necessary to boost the noise floor. The LNA and Pre-Amp increase the noise floor, just as they increase any signal, and are factored into the noise floor calculation. Cable losses and the 3dB splitter decrease the noise floor in the same fashion. The noise floor of the ground station is -127.2dBm, ignoring LNA white noise. We will not be able to decode any signals below this power level, no matter how sensitive our receiving equipment.

5.2 Long Range Test Setup

Two separate, but comparable, configurations were tested. First, I evaluate downlink performance of TestSat and Marconi. This sets the baseline capability we expect in a ground station. Using this configuration, we will also experimentally infer the path loss, and compare to Free Space Path Loss equations commonly used in link budgets. Second, TestSat will be replaced by the New Bus, acting as a stand-in for CP7, CP8, CP9, and CP10 satellites. Likewise, the UHF feed from Marconi will be disconnected from the Yaesu radio and connected directly to a SystemBoard + UHF daughterboard combination, acting as the New Bus ground station. In both cases, a 3dB splitter on the ground station side splices the UHF signal at the radio terminal into the Spectrum Analyzer. The Spectrum Analyzer is used to measure signal strength throughout testing.

FIGURE 15: LONG RANGE BISHOPS TEST SETUP

The simulated satellite is placed in a faraday cage, with a coax line fed out to the 'rubber ducky' antenna. A variable attenuator is right before the antenna, and used to adjust the output power level. At first, the attenuator is set to 0dB attenuation to verify proper a successful link, then continually increased until the signal cannot be decoded by the ground station over 90% of the time. TestSat is only tested at 1200bps, while the NB changes modulation and data rates, adjusting attenuation for each. Both radios operate at 437.405MHz.

It bears mentioning that a large amount of amplification is used to be able to see signals at such low power levels. Each amplifier introduces its own noise (called the Noise Figure) to the spectrum. By far the most important amplifier is the Pre-Amp on the roof, which influences the signal to noise ratio (SNR) more than any other in the receive chain. The Pre-Amp we use has a rated NF of 0.9dB. An LNA is also placed in front of the SA, with a gain of 43.2dB; this LNA is required to boost the received signal within the SA's sensitivity/visual range. Figure 19 shows the real test setup, while Figure 20 simplifies the test configuration into a block diagram.

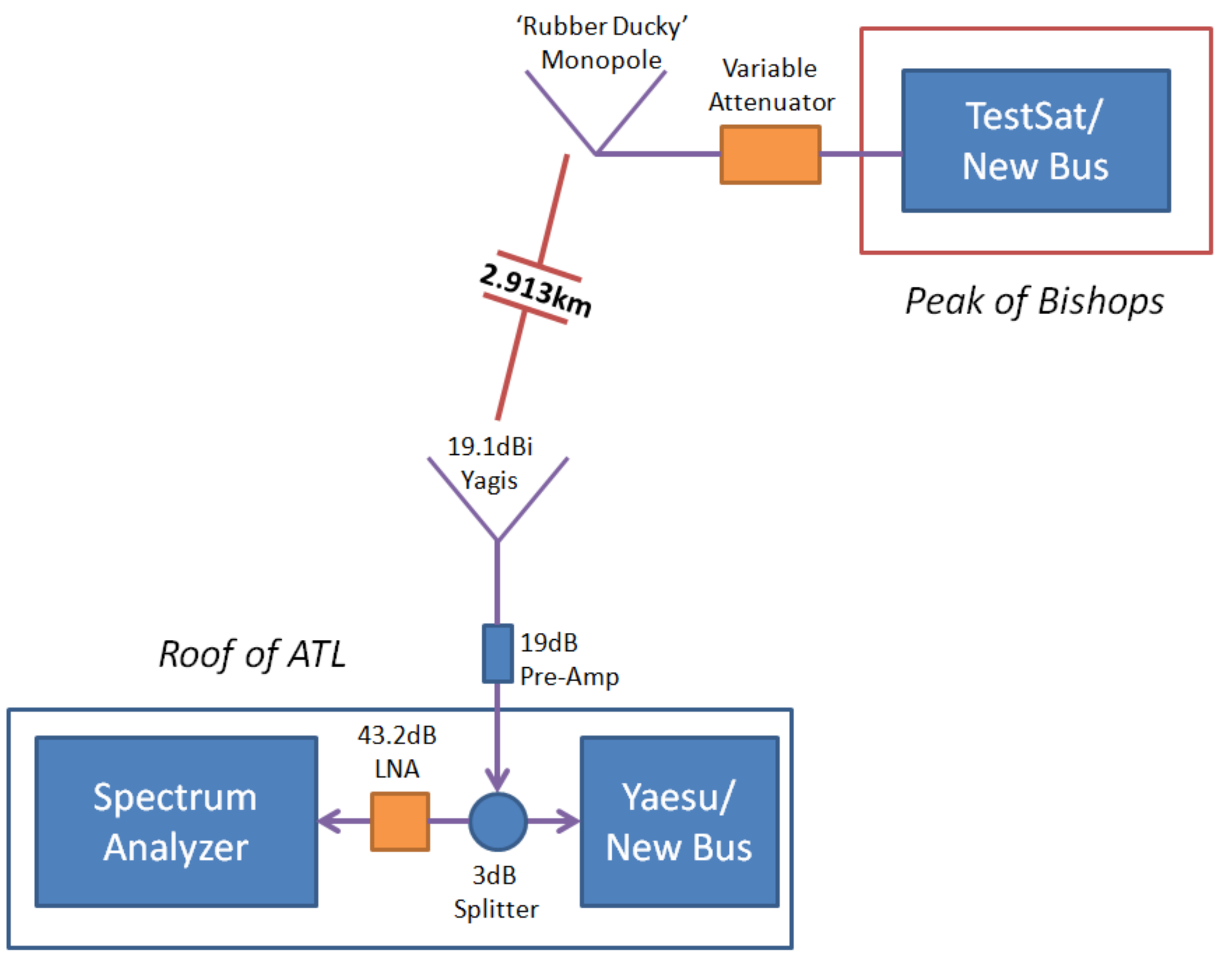

FIGURE 16: LONG DISTANCE TEST SETUP

5.2.1 TestSat

The signal was first acquired at 0dB attenuation. TestSat was plugged in, and began beaconing every two minutes. The signal power is captured on the spectrum analyzer, as seen in Figure 21.

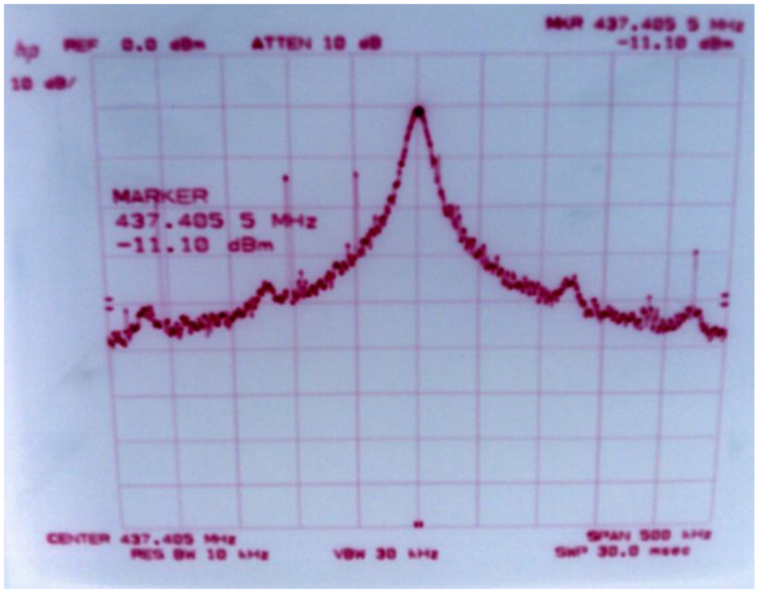

FIGURE 17: TESTSAT'S FULL POWER TRANSMISSION FROM BISHOPS

The peak power is used to determine the path loss from Bishops. Gains and losses on the receiving ground station are factored out, and the final path loss determined in Table 9.

Reading on SA:	-11.1	dBm
Test Sat Tx power @ U.FL:	26.3	dBm
Gains and Losses:		
Yagi (Marconi):	19.1	dB
Polarization Losses:	-3	dB
LNA:	43.2	dB
Pre-Amp:	19	dB
3dB Splitter:	-3	dB
Cable Losses (from roof):	-2	dB
Path Loss:	**-110.7**	**dB**

TABLE 9: EXPERIMENTAL PATH LOSS FROM BISHOPS LONG RANGE TESTING

This path loss assumes a perfectly isotropic radiator (0dB) on TestSat. This is a poor assumption, although the exact gain from the antenna used is unknown at this time. However, the same antenna is used for testing both TestSat and the NB, so it is suitable for comparing the two setups.

Theoretical Path Loss = 22.0 + 20 log (S/λ)

S is the 'Slant Range', or distance in this situation.

λ is the wavelength, or 0.686 meters

Or **-94.5dB** at 2.913km.

There is a 16.2dB difference between theory and experiment. The cause is an unknown at this point. I suspect the monopole is not nearly an isotropic radiator, so the test should be recreated using a characterized Yagi as a replacement.

TestSat failed to decode beyond 55dB attenuation. Backing out the receive sensitivity of the ground station, this mean we can receive signals down to **-122.2dBm** at the input to the Pre-Amp. This is an important factor in planning link budgets, and neglected in past budgets. If Pre-amp gain is removed, this power level is -108.2dBm. The New Bus is 10dB more sensitive than this power level, indicating that the poor SNR is the reason we cannot decode the signal.

Ground Station, Antenna or Sky Noise Temperature Calculation Tool:		
Galactic Noise Component:		
Receiver Frequency:	437.5	MHz
Coldest Galactic Noise Temp.:	20	K
Warmest Galactic Noise Temp:	84	K
Terrestrial Noise Component:		
Receiver Bandwidth:	10.0	KHz
NOTE: Estimated or Measured Noise Level:	-122.2	dBm
Noise Source Effective Temperature:	4365	K
Minimum Sky Noise Temp:	4385	K
Maximum Sky Noise Temp:	4449	K

FIGURE 18: CAMPUS NOISE IMPACT ON GROUND STATION SENSITIVITY

This is the **Noise Source Effective Temperature**, the largest issue with the current ground station. Using this signal power, the effective terrestrial noise temperature of our ground station can be determined and used in Jan King's link budget in the 'Receivers' section, partially copied in Figure 22. To do so, we can use this equation [14]:

$$T_s = \frac{10^{\frac{P_n - k}{10}}}{BW}$$

Where *k* is Boltzman's Constant, or -228.6 dBW/K/Hz
P_n is the noise power at the at the antenna terminal (dBm)
and BW is bandwidth of the Receiver (RBW in this case)

The result is a Noise Source Effective Temperature of 4365K for a 10kHz RBW. Defaults from Jan King's link budget specify this as 417K, while internal link budgets have this set to as low as 21K. Fixing this in the CP10 link budget resulted in staggering changes to the downlink margin.

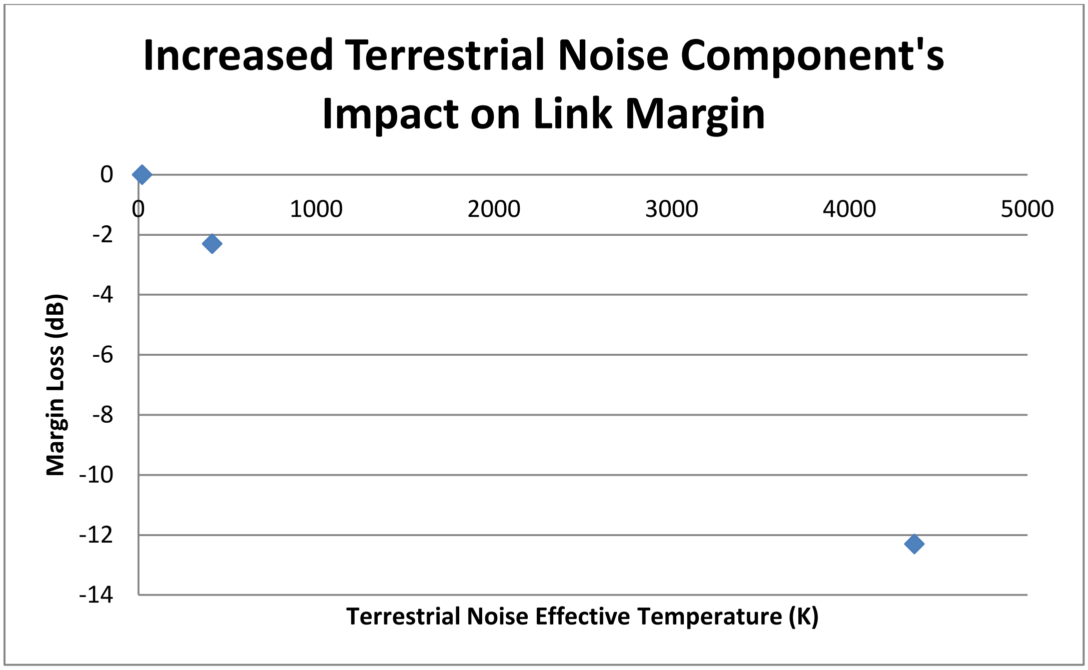

FIGURE 19: INCREASED TERRESTRIAL NOISE COMPONENT'S IMPACT ON LINK MARGIN

If the ground station were only limited by the antenna, Figure 23 indicates that we are losing 12.2dB of margin on the downlink. Realistically, the receivers would the limit, with the NB capable of only another 10dB. Likely, the side lobes of the ground station antenna are picking up nearby noise, although further testing is necessary. The good news is that there is a large amount of lost potential in our current station, with a very large reward if fixes are implemented.

5.2.2 New Bus

The New Bus' replaced both TestSat and the Yaesu, and testing at 0dB attenuation reconfirmed a properly working ground station. The baseline was compared to TestSat, then data rates and modulation schemes were modified and sensitivity recorded. Baseline was virtually identical, as we are limited by the noise floor, while increasing data rates incurred large sensitivity penalties. GMSK also resulted in a loss of sensitivity. Figure 24 summarizes tradeoffs inherent in moving from baseline.

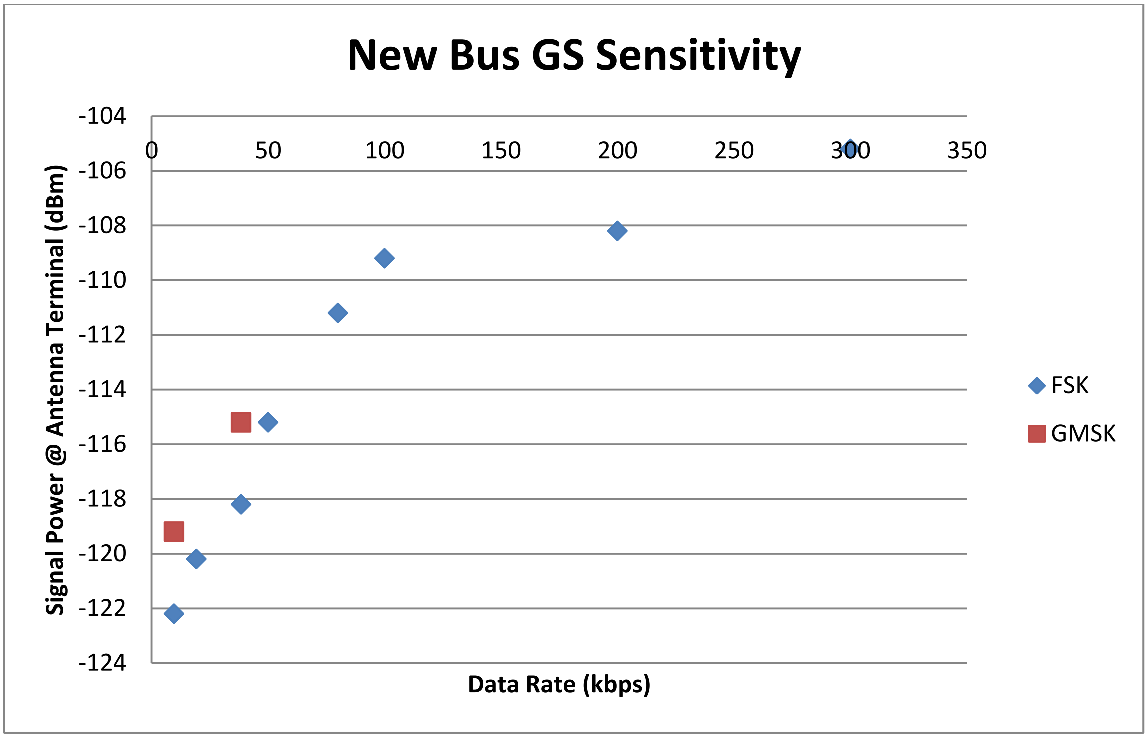

FIGURE 20: NEW BUS GROUND STATION SENSITIVITY AT VARYING DATA RATES AND MODULATIONS

		9.6kbps	19.2kbps	38.4kbps	50kbps	80kbps	100kbps	200kbps	300kbps
Power Level @ Yagi	FSK	-122.2	-120.2	-118.2	-115.2	-111.2	-109.2	-108.2	-105.2
term. (dBm):	GMSK	-119.2		-115.2					

TABLE 10: NEW BUS GROUND STATION SENSITIVITY AT VARYING DATA RATES AND MODULATIONS

A system receive sensitivity of -122.2dBm is very good. Assuming a satellite transmission power of 30dBm and a perfectly isotropic antenna, the ground station would close the link at a 800km altitude, horizon to horizon. Past satellites did not perform as well: transmission power was closer to 27dBm while the dipole antenna had a gain of ~-10dBi for much of its radiation pattern [15]. In this situation, the ground station would struggle to decode beacons when the satellite is at 700km and 10° Elevation. My personal experience with CP5 operations matches the non-ideal situation.

6 Performance Analysis

6.1 Orbital Performance

To predict the performance of the New Bus Ground Station in its current iteration, certain assumptions are made about the orbiting satellite. These assumptions are realistically achievable with current hardware.

Transmit Power:	30dBm
Antenna:	Dipole (2.15dBi)
Satellite Pointing Losses:	-10dB
Polarization Loss:	-3dB
Link Margin:	6dB

TABLE 11: SPACECRAFT TRANSMISSION ASSUMPTIONS

Assuming Free Space Path Loss as the only signal attenuator, a list of distances are generated in Table 12 corresponding to the path loss that could be overcome. For reference, a 700km altitude and 10° elevation is a slant range of 2,155km.

	9.6kbps	**19.2kbps**	**38.4kbps**	**50kbps**	**80kbps**	**100kbps**	**200kbps**	**300kbps**
Cutoff Path Loss (dB):	-153.4	-151.4	-149.4	-146.4	-142.4	-140.4	-139.4	-136.4
Distance (km):	2534	2013	1599	1132	714	567	506	358

TABLE 12: NEW BUS GROUND STATION BASELINE CAPABILITIES

The system is capable of a great deal better, but the transmitted signal has fallen below the ground station's noise floor. To do any better, the satellite would need to increase transmit power or use a directional antenna with pointing capabilities. If the noise floor could be decreased by 10dB, the ground station can reach its optimized sensitivity capabilities.

	9.6kbps	**19.2kbps**	**38.4kbps**	**50kbps**	**80kbps**	**100kbps**	**200kbps**	**300kbps**
Cutoff Path Loss (dB):	-163.4	-161.4	-159.4	-156.4	-151.4	-150.4	-149.4	-146.4
Distance (km):	8014	6366	5057	3580	2259	1794	1599	1132

TABLE 13: GROWTH POTENTIAL FOR NEW BUS GROUND STATION

Where before the 9.6kbps link was possible, a 80kbps link could be used. The baseline data rate of 9.6kbps would now be useable at 800km at 0° elevation, providing a much more reliable link.

6.2 Data rate and Modulation Trade-Offs

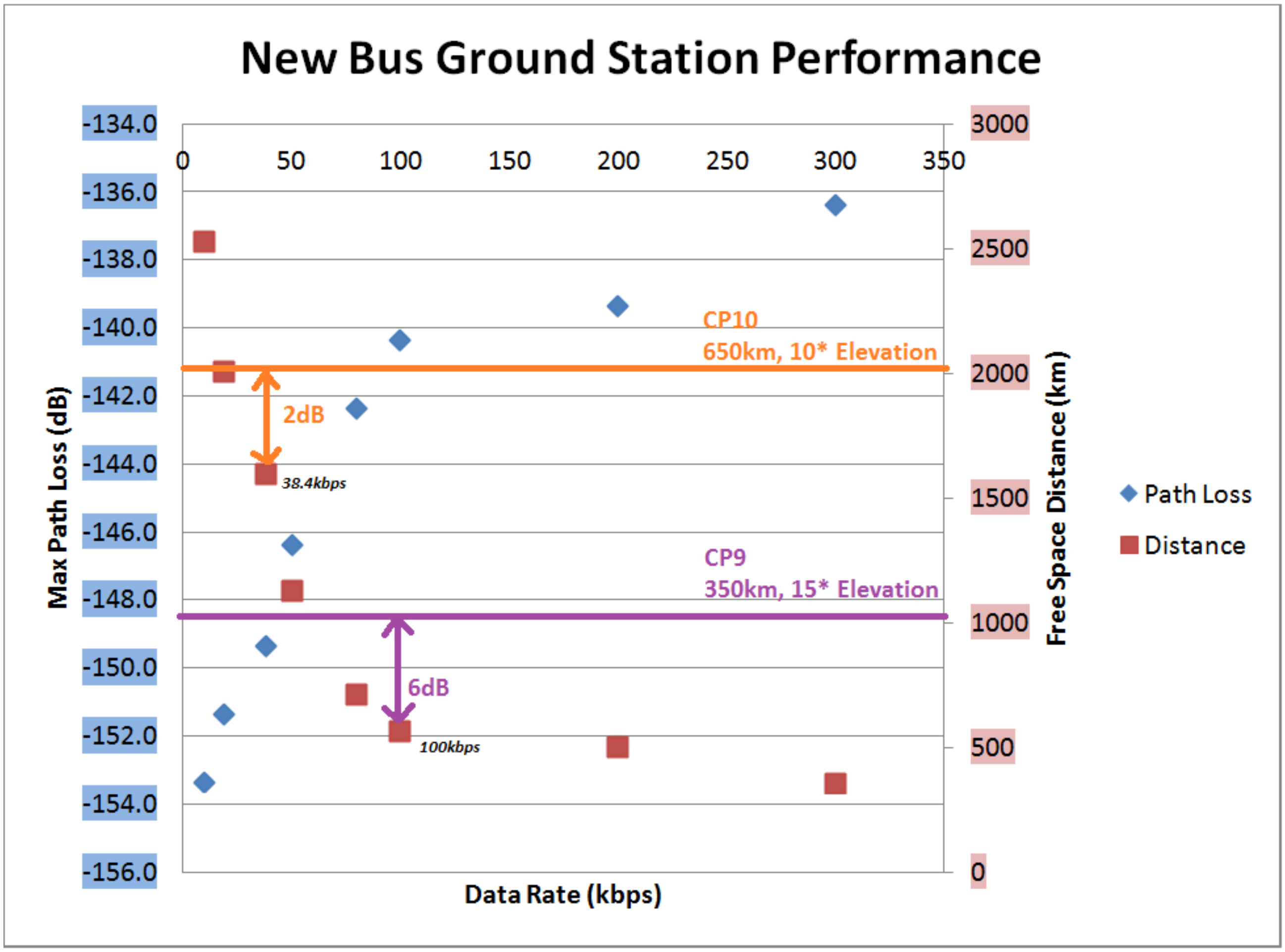

FIGURE 21: BASELINE NEW BUS GROUND STATION PERFORMANCE

Figure 25 graphs the experimentally determined path losses at which decoding failed, and converts these to orbital distances. In its current configuration, the New Bus Ground Station could not adequately support CP9 or CP10, which require much higher data rates than any past mission. Further, moving to the faster data rates may require a change to GMSK for bandwidth reasons, which decreases link integrity by a further 3dB. There are fixes that can be implemented, and testing was successful in determining where improvement can be made.

7 Future Work

The New Bus Ground Station performs adequately at baseline data rates, so development can proceed as planned. Originally scheduled work is as follows in Table 14:

Electrical/Mechanical Tasks		Completed
Procure Equipment	*Weatherproof enclosure*	X
	100W RF Amp and Rotor+Controller	X
	Pre-Amp	
	DC Power Supply (4.2V @ 1A)	
	Pre-Amp and RF Amp power supplies	
	Yagis (or other antennas)	
Convert Weatherproof Enclosure to Faraday Cage (Optional)		
Integrate Ground Station Equipment into Enclosure		
Mount Enclosure on Roof		
Verify Performance through Long Range testing		

TABLE 14: LIST OF FUTURE GROUND STATION WORK

Software integration will be a large effort. Currently, most programs do not care whether they are run on a ground station instead of a satellite, although the system's reference frame changes. Radio and rotor drivers are complete, as is an orbit propagator. The most radical departure will be pulling each software component together into a user-friendly, somewhat automated system. Uploading TLEs, setting the command queue, and other extremely helpful tools will need to be designed and implement for actual satellite operations. For now, software is far enough along for system performance testing.

The discovery of the disruptive noise floor on our system prompts further investigation. Resolution means a robust ground station that is capable of downlink rates upwards of 100kbps, a requirement for time-critical, low orbit missions such as CP9. Decreasing the noise floor is a difficult, lengthy task, likely involving a move to different antenna types such as helicals or shielding the side lobes on the current Yagi configuration.

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A. Hertz and Marconi Block Diagrams

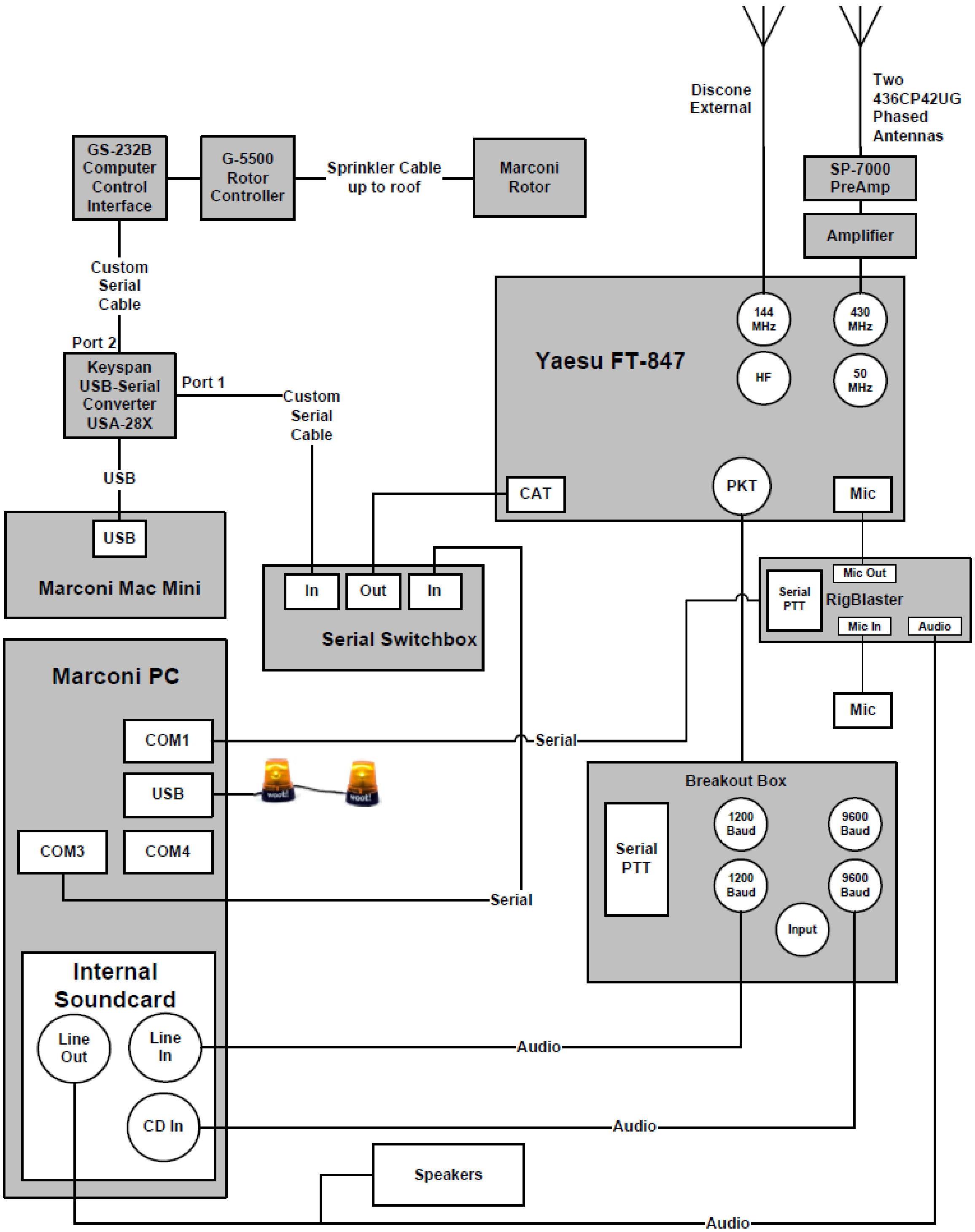

FIGURE 22: BLOCK DIAGRAM OF MARCONI [16]

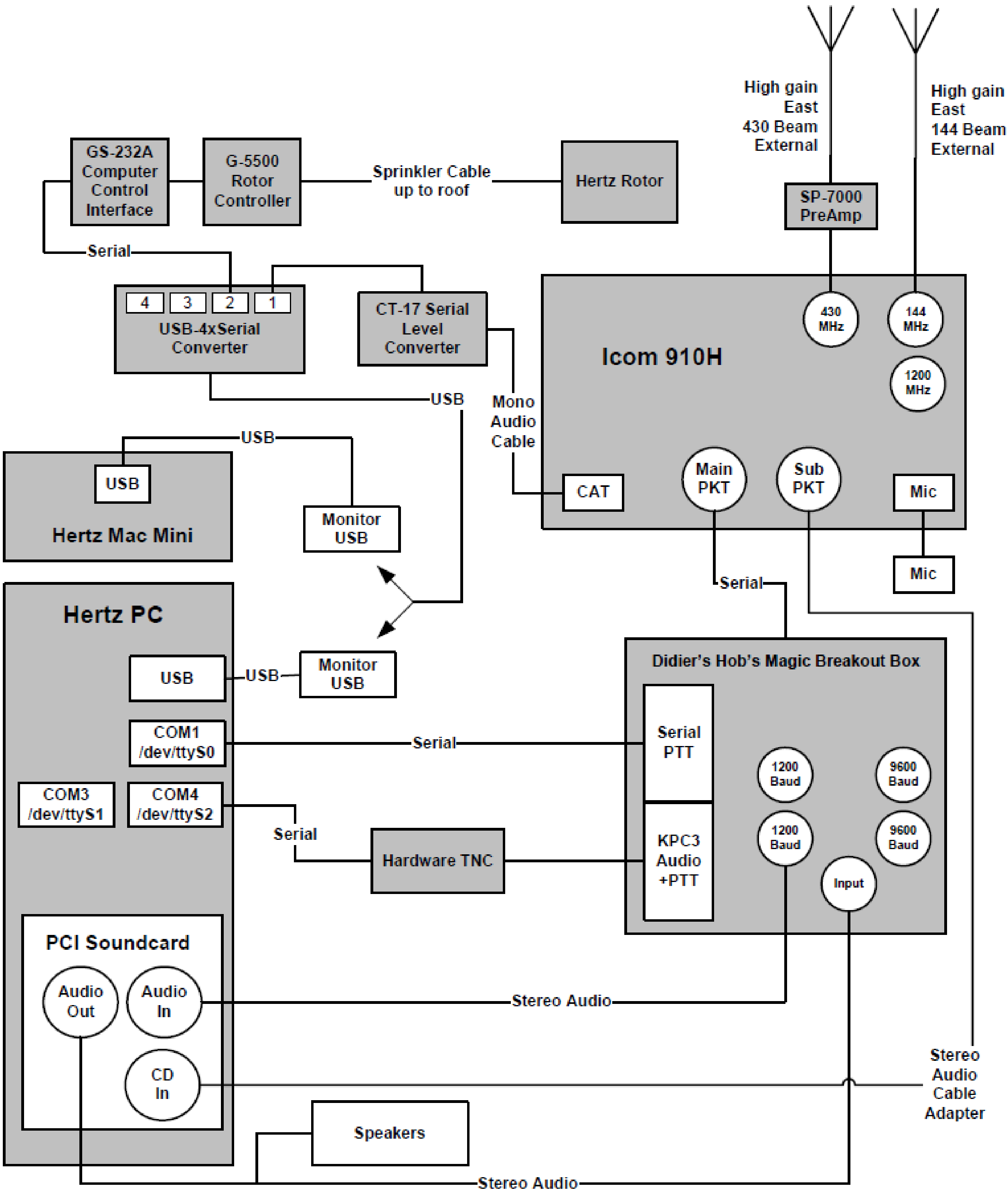

FIGURE 23: BLOCK DIAGRAM OF HERTZ [17]

B. Senior Project Analysis

Summary of Functional Requirements

The project defines requirements for a new ground station with the capability to find and track nanosatellites. The design requires specific minimum downlink data rates for a satellite at specific orbits. Link budget parameters are fixed, and a long range test setup is defined for proper testing.

Primary Constraints

Tremendously low power orbital links are difficult to simulate, so noise must factor into any test plan. Hardware under test had significantly better sensitivities than test equipment, so absolute measurements proved difficult to gather. Proper test setups proved pivotal to success.

Economic

Creation of the ground station requires several students to assist in development of the design and manufacturing, providing practical design experience which increase their productivity in the workforce. With a ground station at Cal Poly, CubeSats can increase in complexity towards more robust, higher frequency radios allowing higher communication rates. As data rates increase on CubeSats, payloads can increase in complexity, removing a barrier scientific institutions in the creation of their payloads. With increasingly robust payloads comes better understanding of the world, continuing the exponential increase in technological improvement and the following trickle-down benefits.

Estimates place the total system cost at $6,817.

Figure 28 shows the original development timeline, and Table 15 analyzes estimated costs.

	Labor (Integration, Testing, Software)				Materials			
	t(a)	t(m)	t(b)	*t(e)*	t(a)	t(m)	t(b)	*t(e)*
Subsystem Costs								
Antennas	$100	$150	$200	*$150*	$200	$800	$2,000	*$900*
Rotor + Controller	$300	$500	$700	*$500*	$500	$800	$1,000	*$783*
System Mount	$100	$200	$300	*$200*	$100	$200	$300	*$200*
Weatherproof Box	$50	$150	$200	*$142*	$50	$150	$200	*$142*
New Bus Electronics	$600	$800	$1,000	*$800*	$2,000	$3,000	$4,000	*$3,000*
		Labor Total:		**$1,792**		Materials Total:		**$5,025**
						System Total:		$6,817

TABLE 15: TENTATIVE COST ESTIMATE

Tentative cost analysis computations use the following equation:

$$C_e = \frac{(C_a + 4C_m + C_b)}{6}$$

Where C_e is the estimated cost, C_a is the most optimistic excepted cost, C_m is the most realistic expectation, and C_b is the worst case scenario.

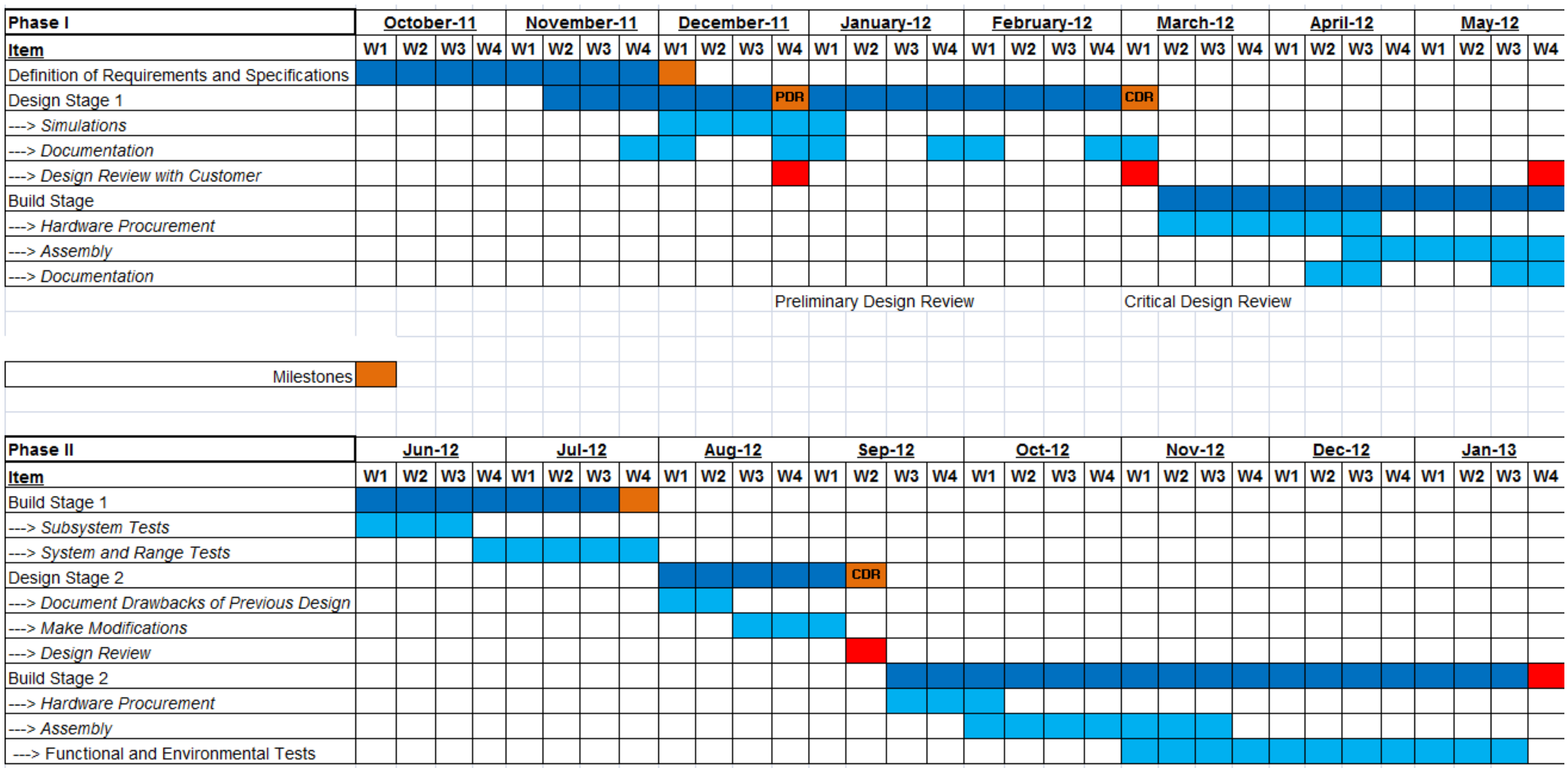

FIGURE 24: GANTT CHART OF ORIGINAL PROJECT SCHEDULE

Commercial Manufacturing

There are no plans for large scale manufacturing. The budget would not be dramatically increased if manufacturing on a large scale.

Environmental

The system relies largely on metal structural hardware and some fiberglass used in the electrical subsystem. Hardware must not biodegrade, since it sees continual use. Environmental impacts come indirectly:

The ground station requires unimpeded views of the sky, so cannot be in a forest or city with tall buildings. Its mounting location depends on a stable surface, so concrete may be used in mounting. The system requires constant power and cannot turn off entirely. The current design does not rely on renewable energy sources, so long lengths of wire supply power from campus, incurring extra losses due to distance.

Manufacturability

The system depends as much as possible on standard sizes in construction. The design depends heavily on the dish, decreasing manufacturability unless a constant source of identical dishes are found. Subsystems use COTS components exclusively, but the antenna mount must be individually fashioned.

Sustainability

Power consumption on average is lower than a 100 watt light bulb. To improve the system in the future, a solar panel and battery could supply power, removing all operation costs besides maintenance. As long as the hardware suffers no damage, upgrading the design will be easy due to the dependence on off-the-shelf consumer hardware.

Ethical

Safe construction and hardware limited mobility prevent misuse outside of destructive communication interference. Automated software controls the tracking of Cal Poly CubeSats, which do not perform ethically violating missions. This software is certainly fallible, so mission specific data may be intercepted and disseminated without the customer's consent. Cal Poly's space is at a premium, despite holding the second most land in California, and this system requires unimpeded view of the sky. This prevents future growth upwards, but should not be an issue as long as San Luis Obispo continues to prevent massive buildings.

Health and Safety

It must be ensured that the antennas don't point at buildings, as the transmitter which will be implemented later may use high powered radios. Studies into high powered radio transmitters show a weak support to cancer correlation, however the dish stands hundreds of meters away from the nearest buildings and physically cannot point towards them. Future development may change the latter, but software updates and maintenance can ensure proper health precautions. Even with a

person standing near the dish, very little power radiates from the side lobes (in the milliwatt range), and the dish is too tall to stand in front of the main beam.

Social and Political

Space on Cal Poly campus is extremely limited, so finding a good location for mounting a large ground station proves challenging. The design decision to use the same space as the previous dish mount removes this space issue, as it was handled by the previous team. Cal Poly and PolySat both benefit from the implementation of a ground station, as it provides educational value in a convenient location. Cal Poly and PolySat share the responsibility in different ways, as Cal Poly must be careful of liabilities in the construction by students, and PolySat pays and operates the system. The increase in communications capabilities increases visibility around the world, bolstering our reputation for practical knowledge. PolySat will provide access to downlinked data to different universities, creating new avenues for growth in the academic community.

Indirectly, the ground station will prove useful to other universities hoping to track their own satellites though the use of GENSO. This provokes interest in satellite and aerospace engineering, inspiring future generations towards international problem solving.

Development

See the Bibliography section in Section IV for a list of references. I learned:

- How to use Functional Block diagrams to establish subsystems
- Proper Link Budget analysis and long range test setup configuration
- Proper documentation techniques