AMATEUR GROUND STATION FOR CUBESATELLITE PROGRAM

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ABSTRACT

KUbeSat is a student led satellite program at the University of Kansas (KU). KUbeSat-1 is intended to operate in a Sun-Synchronous orbit at 550 km, with an inclination between 85-95°. KUbeSat-1 is slated to be launched in April 2022 as part of NASA's CubeSat Launch Initiative. It features two payloads: Primary Cosmic Ray Detector and High-Altitude Calibration KUbeSat. To support KUbeSat-1 and future missions, an amateur ground station is currently being built to operate in the UHF range of 435-438 MHz with half-duplex capability. This paper presents the mission concept, ground station architecture, testing outcomes, and future improvements.

INTRODUCTION

Since 2016, students at the University of Kansas have been working to build and launch a small satellite through a program known as KUbeSat. The first satellite to launch through this program is called KUbeSat-1 and is set to launch in Spring 2022 through the NASA CubeSat Launch Initiative (CSLI). NASA CSLI selects missions from different academic institutions and provides them with a launch opportunity if the applicant can provide a built and tested satellite to be launched. NASA CSLI seeks to have every state in the United States launch a small satellite through their program. To support KUbeSat-1 and future missions, the program chose to design and build a ground station (GS) architecture. This design is based on the goals of the KUbeSat-1 mission and its' payloads, as well as providing infrastructure for communications with satellites for several missions after. The primary goals of the KUbeSat program are to 1.) successfully build and launch a small spacecraft into orbit that can perform payload research, and 2.) to build a functioning ground station to design requirements that can provide communications with the KUbeSat-1 satellite.

The ground station design is based on needs of the mission, as well as cost. Ground stations that other universities built to assist in their CSLI projects are also taken into consideration for this design, as they have proven success in communicating with a satellite [1], [2]. Requirements that are used to guide design and testing for the ground station, also known as Hawksnest, are as follows: 1.) To build an economical and reliable ground station using COTS components, 2.) To establish an amateur ground station in the UHF frequency range to contribute to the amateur radio community through communities like SATNOGS, and 3.) To design a half-duplex ground station with capability to expand into full duplex. The ground station will be run by certified members of the KUbeSat program who have obtained a minimum of a Technician's License from the Amateur Radio Relay League (ARRL), which is the national association for Amateur Radio in the United States.

MISSION BACKGROUND

KUbeSat-1 has taken the shape of a 3U cube satellite with dimensions approximately 10 x 10 x 34 cm and about 4.5 kg. The CubeSat frame is made of Aluminum 6061-T6 from small satellite company, Endurosat. KUbeSat1 also uses Endurosat's Solar Panels, UHF transceiver, UHF antenna, and Onboard Computer (OBC). The attitude and determination system is built by CubeSpace and includes several vital components needed for maneuvering in space. It contains all standard commercial off-the-shelf (COTS) materials, electrical components, PCBs, and solar cells. The Earth-facing side of the 3U is covered by a flame retardant (FR4) panel to allow for cameras and Earth sensors to be easily mounted. The electrical power consists of commercially available systems such as the Clyde Space Starbuck Nano EPS and Optimus Lithium-Ion battery.

KUbeSat-1 will be launched into a 550 km orbit into a near-circular Sun-synchronous orbit. At this altitude, the satellite will have an orbital period of about 95.5 minutes and will pass over the custom-built ground station in Lawrence, KS approximately five times a day. Figure 1 shows the ground track that KUbeSat-1 will follow at a 550 km orbit. The red circle shows the location of our ground station, which is located on campus at the University of Kansas in Lawrence, KS. The ground track verifies that the satellite will pass over the ground station when orbiting, as it passes through the red circle. The pink circle at the bottom shows the location of the ground experiments that will eventually be calibrated by future iterations of HiCal payloads, which is near McMurdo Station in Antarctica.

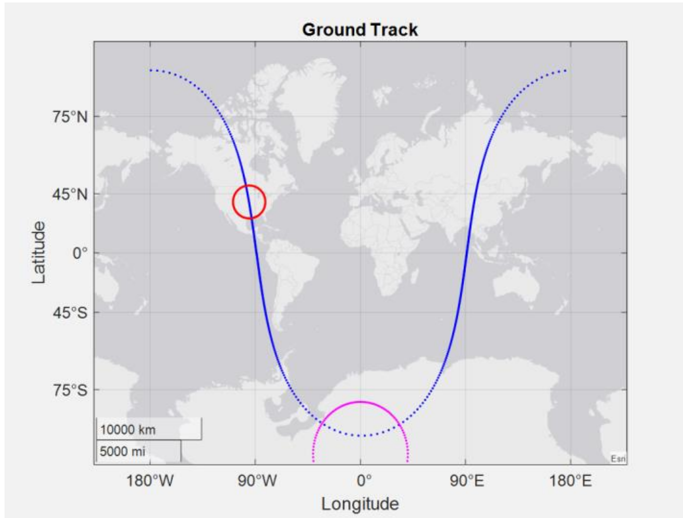

Figure 1 KUbeSat-1 Ground Track for 1 Orbit at 550 km Altitude.

KUbeSat-1 is equipped with two payloads, the primary cosmic ray detector (PCRD) and the High-Altitude Calibration KUbeSat (HiCalK). The cubesat is planning to survey and collect cosmic rays intercepting Earth with its primary payload, the PCRD. It also includes a demonstration payload, the HiCalK, to prove the technology for future missions. The PCRD uses an innovative pulse shape discrimination (PSD) calorimetry method to measure the energy and species of primary cosmic rays in a CubeSat-accessible manner. Traditionally, particle astrophysics is conducted on Earth using large scintillators and radio arrays. The PCRD will bring astrophysics to a small space-based platform for the first time. In addition to the system being a first for CubeSat's, highly accurate results are anticipated as moving beyond Earth's atmosphere eliminates the influence of weather and allows lower-energy cosmic rays to also be studied. KUbeSat's other payload, HiCalK, emits a terminated signal for ultra-high energy cosmic ray ground experiments sensitive to very-high-frequency radio. The HiCalK is the successor of past High-Altitude Calibration (HiCal) instruments, which provided calibration pulses for the Antarctic Impulsive Transient Antenna (ANITA) experiments. Ultimately, the goal for these High-Altitude Calibrations (HiCal) payloads is to emit radio pulses to mimic Askaryan radiation, generating a calibration signal for ultra-high-energy cosmic ray ground experiments sensitive to very-high-frequency radio. Using the calibration signal generated by this series of payloads, these ground experiments can be compared and synchronized, which can provide additional sensitivity to astrophysical radio events. The satellite will be downlinking all collected payload data to the ground station in Lawrence, KS.

GROUND STATION DESIGN

The ground station is divided into three main areas, as shown in Figure 2. The sections are 1.) hardware that remains in a technology rack in a lab, 2.) equipment that is required to be on the roof, and 3.) the operations center. The technology rack is equipped with a transceiver, modem, and Raspberry Pi. The Raspberry Pi serves as the main computing element in the ground station, backs up downlink data on a memory card, and sends downlink data to the ground station computer to be displayed and analyzed. The equipment that is required to be on the roof is the antenna, rotator, controller, and pre-amplifier. This equipment is connected to devices in the technology rack via radio frequency (RF) cabling from the roof to the lab with the technology rack. There is one long RF cable that is connected from the transceiver to the pre-amplifier and there is also one short RF cable that is connected from the pre-amplifier to the antenna. The controller is connected to the ground station computer or the Raspberry Pi through the KU network via an ethernet cable. Finally, there is the operations center that houses the main ground station computer, which will be equipped with a user interface to display downlink data and spacecraft health parameters. The ground station computer also contains software to assist in transmit and receive of data to and from the UHF radio module on the satellite. Each piece of hardware shown in Figure 2 is discussed in further detail in later sections.

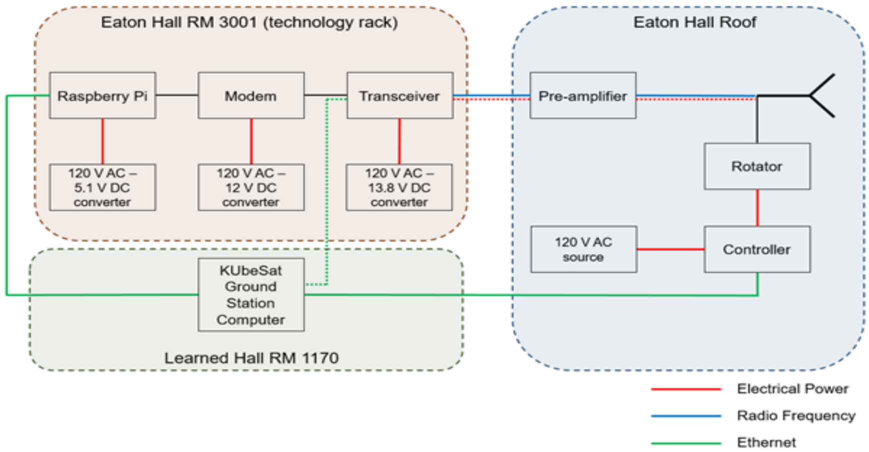

Figure 2 Ground Station Block Diagram.

Figure 3 shows an example of the fully assembled Hawksnest for components on the roof. There is a support structure, weighted down by cement blocks. The rotator sits atop the center mast, while the controller is attached via connection clamps to the mast. There are four guy wires for extra stability that are attached from the center mast to attachment points on the roof. The antenna is connected on one end of the cross-boom and a counterweight is connected on the opposing boom end to balance the weight of the antenna.

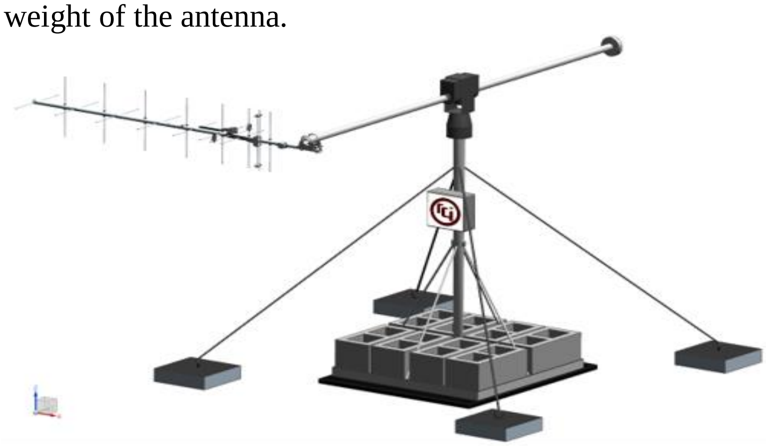

Figure 3 CAD Rendering of Fully Assembled Ground Station.

ROTATOR AND CONTROLLER

The controller used in the ground station is the RC4000 by Research Concept Inc (RCI). The controller uses the input of the NORAD two-line element (TLE) set of KUbeSat-1, which is supplied autonomously from ground station software built in-house. The NORAD TLE data provides orbital elements for Earth orbiting satellites and is updated on a regular basis and is published on easily accessible sites. The controller's software utilizes this input to track the satellite throughout the satellite's life. The controller supplies a voltage to the rotator motors and position sensors. The controller then receives feedback from the rotator sensors as an input. The controller for this ground station was chosen because RCI provided the ability to customize it to meet the needs of our ground station.

The rotator for the ground station is the Yaesu G-5500. This system has two motors, to control both elevation and azimuth respectfully. These motors are supplied power from the controller. Then, the voltage output of the potentiometers in the motors is sent to the controller software to calculate current angles for azimuth and elevation. The cross boom is routed through the rotator with the antenna attached on the end, which allows for the elevation angle to be changed. The Yaesu G-5500 is successfully used by other amateur ground stations and provides enough rotation and braking torque for the size and weight of the UHF Yagi antenna to move it elevation and azimuth. The rotator's pointing accuracy of one degree also provided enough accuracy to meet mission requirements.

Tests that were performed were manually controlling the rotator with the RC4000 controller to verify the correct wiring. This resulted in the rotator rotating in the correct direction but the RC4000 is going into runaway mode. This is currently being worked on. Once this test is done, the next test will be to attach an ethernet wire into the RC4000 and supply the controller with TLE of a known satellite and verify that the controller is tracking the satellite by receiving the beacon from the satellite.

MODEM

The modem used in the ground station is the Kantronics KPC 9612 plus. The modem transfers data between the computer and the transceiver. Commands sent from the computer are encapsulated into packets with AX.25 protocol and modulated using Gaussian Minimum Shift Keying (GMSK) before being sent to the transceiver. Packets received from the transceiver undergo the same process in reverse. GMSK is often used in radio communications because of its ability to reduce the sideband outputs which can interfere with signal carriers in adjacent frequency channels. The Kantronics modem is included in the GS design because it supports the desired modulation, packet protocol, and baud rate utilized throughout the satellite and ground station.

The KPC 9612 unit utilized by KUbeSat participated in a spectrum analyzer test to ensure the produced sidebands stay within the frequency band allotted by the FCC. The results of this test show expected GMSK spectrum shape, half power beamwidth, and side lobe levels. The modem will also undergo a full link test where data is sent from the computer to the modem to the transceiver, to another transceiver and back to the modem to test the encapsulation and decapsulation of the modem.

SOFTWARE

The three main requirements for the software are to 1) minimize loss of data packets, 2) automatically send messages to the satellite when it is overhead, and 3) log all actions and messages for documentation and troubleshooting. The ground station software program is run on the Raspberry Pi, which is directly connected to the modem. The program is responsible for handling the reception of messages sent to the ground station and transmission of messages sent to the satellite. It stores all incoming and outgoing messages in addition to logs in the filesystem. It also uses a JSON file to store configuration settings and basic information like satellite callsigns and message storage location. Figure 4 depicts the program's interactions with the surrounding ground station components.

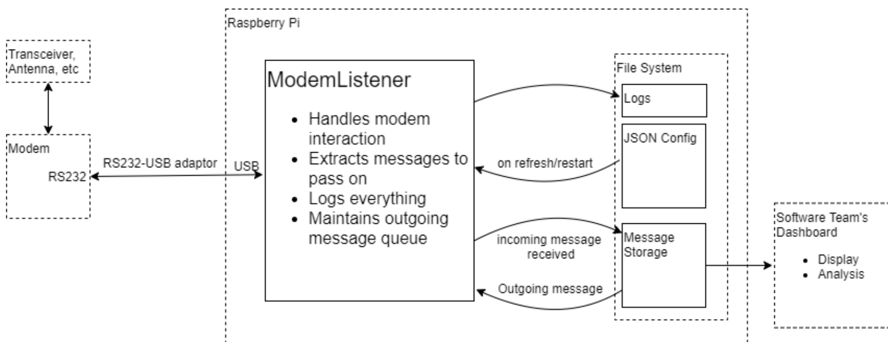

Figure 4 Ground Station Software Infrastructure.

The program maintains a queue of messages to send out to the satellite on its next pass and actively listens for the satellite's health beacon. It has two main states: idling and conversing. When idling, it listens to the modem for beacon messages from the satellite. Upon receiving one, the program transitions into the conversing state. In the conversing state the program attempts to connect to the satellite through the AX.25 protocol built into the modem. The program remains in the conversing state until the modem fails to maintain/create its connection with the satellite at which point the program transitions back to the idling mode.

On a successful connect, the program starts sending off messages in the queue. Each message on the queue is paired with some metadata that describes specific instructions for the program. The satellite and ground station send acknowledgements for the packets they receive. This allows the program to determine the status of the message queue in the event of an unexpected disconnect. The program is registered as a service in the Raspberry Pi's operating system, allowing the program to be automatically restarted by the operating system in the event of a power outage.

TRANSCEIVER

The ground station employs an ICOM IC-9700 transceiver to facilitate communications to and from the satellite. The IC-9700, when configured for KUbeSat's communication parameters, offers a transmit frequency range of 430-450 MHz, a receive frequency range of 420-480 MHz, and multiple transmitter modulation options, including single-sideband, continuous wave, radioteletype, AM, FM, digital voice, and direct detection. The IC-9700 operates with a transmitter output power of 0.5-75 W at 430/440 MHz and is capable of remote operation using ICOM's RS-BA1 Remote Control Software.

The transceiver is mounted in a technology rack and placed in one of the labs since it offers the closest access point to cable routing from the roof. Hence, it is remotely operated by the ground station computer, located in another lab in the adjacent building. This remote feature makes the transceiver a particularly good fit for the design. Current remote operation tests involve the transceiver connected through a local area network to the ground station computer. The latency in the remote connection is negligible, even when the transceiver is actively transmitting at a high-power level.

In the spectrum analyzer test, the transceiver is directly connected to a spectrum analyzer unit, and the transmit function is tested at various RF power levels and in different modulation modes. A 30 dB, 100 W attenuator is included in the test to attenuate the signal power and protect the spectrum analyzer. Important parameters like output power, side-lobe level, and half-power beamwidth are verified.

ANTENNA

The ground station antenna chosen for KUbeSat-1 is a circularly polarized, high-gain Yagi antenna by M2 Antenna Systems, Inc. Circular polarization is preferred for cubesat applications to minimize the effects of Faraday rotation as the signal propagates through the atmosphere and reduce the effects of satellite spinning or tumbling. For long distance communication, it is vital to ensure the depolarization effects are minimal since polarization misalignment can cause significant signal degradation [3]. A high-gain value of 13.3 dBic eases the link budget requirements on downlink since the maximum transmit power on the satellite is limited to 1 W. The Yagi antenna by M2, Inc. is specifically for Low Earth Orbit (LEO) satellite communications. The antenna is rear mounted for easy installation on a boom and mast fixture and for convenient cable routing. The rugged build quality is meant to ensure good performance regardless of weather, while being continuously exposed to the elements.

Figure 5 and Figure 6 shows the return loss and radiation pattern of the Yagi antenna as measured in the anechoic chamber. The measured return loss indicates that the antenna operates in the 418.75 to 438.36 MHz band. Despite the differences with the return loss from the datasheet, the assembled antenna can operate in the 435 – 438 MHz amateur band. The measured radiation pattern shows a distinct main lobe with reduced sidelobes. The measured beamwidth is 39°, while the datasheet reports a beamwidth of 42°. The reduced beamwidth reduces the antenna's field of view. However, based on the margins from the link budget, this reduction is not detrimental to the overall performance of the system.

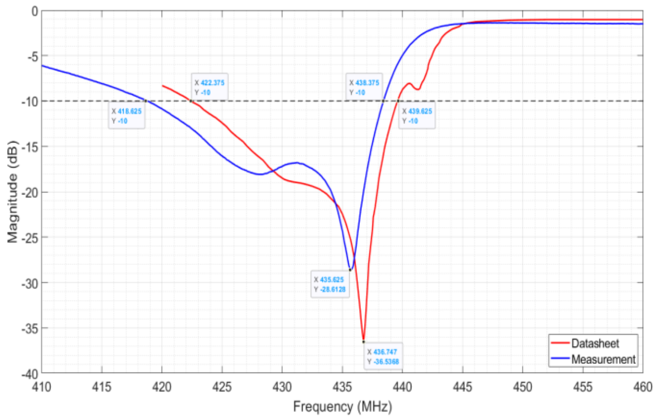

Figure 5 Simulated and Measured Return Loss.

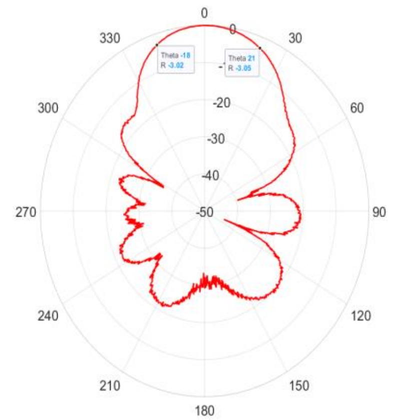

Figure 6 Measured Radiation Pattern.

PRE-AMPLIFIER

A crucial parameter that dictates the performance of any receiver system is the Noise Figure. This is especially important for space-based communication as the power level of the received signal is very low due to the high path loss. Furthermore, various noise sources like terrestrial, cosmic, and galactic can further increase the noise floor. The first stage in the receiver chain after the antenna sets the Noise Figure for the entire system. The Noise Factor of the stages that follow the first are reduced by the individual stage gains [4]. Hence, selecting an appropriate Low-Noise Amplifier (LNA) as the first component in the receiver is paramount. In addition to the Noise Figure, the LNA amplifies the signal so that the power level is within the dynamic range of the Transceiver's Analog-to-Digital Converter (ADC).

The EME221 preamplifier by MiniKits is used for the ground station. It is mounted on the mast of the antenna and is enclosed in a weatherproof box. A short 10 feet coaxial cable connects to the antenna to keep the losses low. The low-noise amplifier has a noise figure of 1 dB and a maximum gain of 29 dB, as reported in the datasheet. The transmit section of the preamplifier is just a direct bypass with an insertion loss of 0.3 dB. As the uplink budget suggests, the transceiver's maximum output power provides sufficient margin and hence additional amplification is not necessary.

This preamplifier by Minikits is designed specifically for the 70 cm, 430–450 MHz amateur band and for the masthead mount to keep the cable run small. This amplifier utilizes an on-board bias tee and hence does not require a dedicated power supply. However, only a few transceivers like the ICOM-9700 have a separate option with delay sequencing on receive mode, to power the preamplifier through the bias tee. The electrical compatibility with the transceiver, ease of physical integration, and excellent Noise Figure is why this pre-amplifier was chosen.

LINK BUDGET

Establishing radio communication with the satellite at every pass over the ground station is ideal. It is crucial to constantly check and assess the health of the craft and regularly downlink relevant data to ease on-board storage constraints. The radio link budget is a design strategy that evaluates the success of uplink and downlink communication.

The system link margin is computed by comparing the receiver Signal-to-Noise Ratio (SNR) with the SNR threshold for a particular Bit Error Rate (BER) of the signal modulation. The full link budget has been computed using the AMSAT-IARU Link Model [5]. The uplink and downlink budgets are shown in Figure 7.

On an average, only five passes can be expected each day over the ground station. Hence, it is vital to attempt a communication link for the maximum duration during each pass. Therefore, the maximum path loss is computed for the lowest elevation angle, as the satellite appears over the radio horizon. In addition to the free-space path loss, the Link Model also accommodates for the following effects as the signal propagates through the channel: antenna pointing loss, polarization loss, atmosphere loss, and ionosphere loss. The pointing loss accounts for the misalignment of either antenna's normal axis from the slant range. The polarization loss is expected to be minimal since both antennas are circularly polarized.

On uplink, the transceiver is assumed to be functioning at the maximum output power. Most COTS transceivers have sufficient transmit power capability for amateur radio operations. Based on the extra margin available for the lowest elevation angle, the transmit power on uplink is usually reduced to prevent the satellite receiver from saturating. On downlink, the system noise temperature is estimated to be 417 K, as the ground station antenna faces the sky to receive the signal from the satellite. The effective noise temperature includes antenna temperature, which accounts for galactic and terrestrial noise, system line temperature, and noise temperature of the Low-Noise Amplifier (LNA).

Uplink Budget	
Altitude	550 km
Elevation angle	10°
Slant Range	1815.7 km
Frequency	438 MHz
Ground Station	
Transceiver output power in watt	75 W
Transceiver output power in dB above one watt	18.75 dBW
Long cable loss	5.4 dB
Pre-amplifier insertion loss	0.3 dB
Short cable loss	0.33 dB
Other losses	0.38 dB
Total transmission line losses	6.41 dB
Total transmit power delivered to antenna	12.34 dBW
Antenna gain	13.3 dBi
Effective Isotropic Radiated Power	25.64 dBW
Channel	
Ground station antenna pointing loss	2.7 dB
Ground-to-Spacecraft antenna polarization loss	0.51 dB
Free space path loss	150.5 dB
Atmosphere loss	1.1 dB
Ionosphere loss	0.4 dB
Isotropic received power	-129.57 dBW
Spacecraft	
Antenna pointing loss	1 dB
Antenna gain	1.5 dBi
Total transmission line losses	1 dB
Effective noise temperature	258 K
Gain to Noise temperature	-23.3 dB/K
Received signal power at the low noise amplifier input	-130.07 dBW
Receiver bandwidth	20 kHz
Receiver noise power	-161.5 dBW
Signal-to-Noise power ratio	31.9 dB
Signal modulation	Gaussian Minimum Shift Keying (GMSK)
Data rate	9600 bps
Signal-to-Noise ratio threshold for Bit Error Rate of 10^{-5}	9.6 dB
System link margin	22.3 dB

Downlink Budget	
Altitude	550 km
Elevation angle	10°
Slant Range	1815.7 km
Frequency	438 MHz
Cubesat	
Transmit power at the antenna in watt	1 W
Transmit power at the antenna in dB above one watt	0 dBW
Antenna gain	1.5 dBi
Effective Isotropic Radiated Power	1.5 dBW
Channel	
Spacecraft antenna pointing loss	1 dB
Spacecraft -to- Ground antenna polarization loss	0.51 dB
Free space path loss	150.5 dB
Atmosphere loss	1.1 dB
Ionosphere loss	0.4 dB
Isotropic received power	-152.01 dBW
Ground Station	
Antenna pointing loss	2.7 dB
Antenna gain	13.3 dBi
Short cable loss	0.33 dB
Received signal power at the low noise amplifier input	-141.74 dBW
Low Noise Amplifier gain	25 dB
Long cable loss	5.4 dB
Other losses	0.38 dB
Received signal power at the transceiver input	-122.52 dBW
Effective noise temperature	417 K
Gain to Noise temperature	-13.3 dB/K
Receiver bandwidth	20 kHz
Receiver noise power	-159.4 dBW
Signal-to-Noise power ratio	36.88 dB
Signal modulation	Gaussian Minimum Shift Keying (GMSK)
Data rate	9600 bps
Signal-to-Noise ratio threshold for Bit Error Rate of 10^{-5}	9.6 dB
System link margin	27.28 dB

Figure 7 Uplink and Downlink Budget Calculations.

DISCUSSION AND CONCLUSIONS

From initial design of the ground station to current status, the ground station is performing as expected. All necessary hardware has been acquired and testing of the hardware is successful thus far. Antenna testing, such as return loss and radiation pattern indicate that it still performs in the expected range needed for UHF ground station communications, despite deviations from the manufacturers data sheets. The modem and transceiver tests show the expected modulation spectrum and output transmit power level.

Future work for this ground station design includes a receive-only, outdoor calibration test from current orbiting satellites. The ground station and the satellite radio module will then be tested together in a fully integrated, point-to-point system test. This will also be extended to a Day-in-the-Life test to assess the full capability of both systems.

The design intent of Hawksnest is to provide infrastructure to be built upon in future advancements of the KUbeSat program's ground station capability. The intention is to move toward full duplexing by transitioning the UHF ground station capabilities to only receiving and adding S-band capability to only transmit when the satellite is passing over. This will allow for the current design to be used on future missions, while still upgrading to having S-band transmissions. This improvement will likely not take place until KUbeSat-2 or KUbeSat-3.

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