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Advancing Engineering Education through University Ground Stations

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Advancing Engineering Education through University Ground Stations

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Abstract

Ground stations are essential for space missions to conduct data retrieval, telemetry, tracking, and control. In the past, ground station use has been limited to government and private space sectors due to their cost. As a result, this has led to few laboratory activities that employ ground station technologies in engineering programs. More recently, the cost of ground station components has decreased, along with an increase in publicly available designs, making ground stations more accessible to universities. In this paper, the integration of ground stations into university curricula is investigated and an approach to leverage ground stations to improve educational outcomes for aerospace engineering students is outlined. An overview of foundational information on ground stations, their components, and use in government and industry is provided. A review of the current integration of ground stations into university activities and curricula is presented, with an emphasis on the approaches for integration and alignment with curriculum. Learning objectives were developed by using the Accreditation Board for Engineering and Technology's (ABET) requirements for aerospace engineering programs alongside Bloom's Taxonomy to leverage university ground stations. The specific ground station requirements and design considerations that are necessary to achieve the desired functionality for execution of the learning objectives are outlined. The framework for laboratory activities designed to fulfill the learning objectives and integrations into aerospace curricula were examined to connect the developed laboratory activities to undergraduate courses and academic projects.

1. Introduction

The collection of Earth observation data relies on ground stations. In order to prepare aerospace students to work with satellites and space systems, they need to be aware of ground stations and their key functions. In the past, the cost of ground stations has limited their use to government and private space sectors, but with the decreasing cost of ground station components, ground stations are becoming more accessible to university aerospace programs. The next class of aerospace engineers will need to be proficient with ground stations to lead and manage the new wave of space endeavors.

Ground stations are systems that send and receive data to and from satellites [1]. Ground stations themselves rely on and use several different astronautical topics, all of which could or should be taught in an aerospace engineering curriculum [1]. Along with being a useful learning tool in aerospace education, ground stations are also readily used in industry and government work. This emphasizes that ground stations should be a common tool used in university aerospace engineering programs, but currently, they are not. The absence of ground stations in undergraduate education is due to several factors from cost to integration into lab curriculum challenges [2]. As technology advances, the cost constraint is becoming less critical with low-cost ground stations becoming more common, allowing for universities to begin introducing ground stations into aerospace curriculum [3]. Specifically, aerospace engineers will be working on more space-oriented missions, such as the Artemis missions and future Mars missions, alongside expected missions from the private spaceflight sector led by Space-X, Blue Origin, and Virgin Galactic [4].

The goal of this paper is to investigate an approach for the integration of ground stations into undergraduate aerospace engineering education. Section 2 provides background on ground stations, their components, and their utilization in government and industry. Section 3 outlines the current state of ground station education, focusing on university ground station projects and pedagogical tools for aerospace education. Section 4 integrates the Accreditation Board for Engineering and Technology's (ABET) requirements and Bloom's Taxonomy to develop a strategy for integrating ground stations into aerospace engineering curricula, i.e., the selection of a low-cost ground station along with the development of learning objectives and laboratory activities. Section 4 also provides examples of courses and university projects that a ground station could enhance, and some concluding remarks and future work are presented in Section 5.

2. Background

In order to effectively discuss the development of pedagogy related to ground stations, a review of ground station design, major components, and utilization in government and industry is provided.

2.1 Ground Station Components

The design and construction of a ground station requires many components and systems such as a computer system, orientation system, and antennas. The main system that controls and manages all other components, subsystems, and software is a computer system. This system collects data sent from the satellite and transmits commands. Another aspect of this system is that it orients the azimuth and elevation (Az/El) motors and aims the antenna to obtain and maintain radio connections. Although not used in all ground station designs, Software Defined Radio (SDR) has become more common due to its flexibility and ease of adaptation with different frequencies [5]. SDR is a computer system component that is used to operate the transmission and collection of radio frequency (RF) signals [1]. If an SDR is not used, it can be replaced by transmitters and receivers, or transceivers that send and receive radio transmissions through an antenna [6]. SDR is discussed in further detail in Section 2.3. In general, once signals are collected, they must be demodulated using software, like Sigmira [7], when signals are transmitted, they must then be modulated for the satellite to receive them [8]. Another essential component for ground station operations is the tracking system. The purpose of the tracking system is to control the antenna's direction and to orient it to align with the target satellites. To align the antenna, the ground station uses the Az/El motors, which are oriented by software that collects satellite orbits, like Gpredict [1]. The main component of a ground station is its antenna. The antenna of a ground station collects RF waves, and the antenna feed converts the electromagnetic waves into conducted RF electrical signals [1]. The antenna feed connects the RF electrical signals to the computer system to collect and demodulate the signal. Depending on the computer system other components of the antenna system could be used such as a low-noise amplifier (LNA) [9]. An LNA is meant to boost the strength of the RF signal that is intended to be heard that is meant to limit unintended noise [9].

2.2 Antennas

The most common university-based ground stations are RF ground stations and use either a parabolic dish antenna or a Yagi antenna [1]. Parabolic dish antennas are shaped as concave shell, while Yagi antennas have small perpendicular rods that run along a long main rod. The benefits of parabolic dish antennas are that they are less complex, inexpensive, and highly directional [10]. The detriment of parabolic dish antennas is that their size depends heavily on gain and desired frequency [10]. The benefits of a Yagi antenna are that they are highly directional and relatively inexpensive [10]. The detriments are that they have low gains if small, and high gains if large, therefore, large bandwidth results in a larger design [10]. Parabolic dish antennas tend to be used in the S-band, while Yagi antennas tend to be used in the very high frequency (VHF) and ultra-high frequency (UHF) ranges [11]. To properly orient themselves, these antennas have azimuth and elevation motors to align with satellites with which they are trying to communicate [12] [13]. Most university-based antennas receive and transmit data over VHF, UHF, and/or S-Band frequency ranges to communicate with satellites in low Earth orbit (LEO) [1]. These bands of radio frequencies are categorized by several different standards: Institute of Electrical and Electronics Engineers (IEEE), European Union (EU) and North Atlantic Treaty Organization (NATO), and International Telecommunication Union (ITU) [14]. For this paper, the frequency range from the IEEE is used [14]. The range for VHF is 30-300 MHz, UHF is 0.3-1 GHz, and S-band is 2-4 GHz [14]. These ranges are used by many different organizations to collect and transmit their data. The higher the frequency, the more data the radio waves can carry, and the larger the antenna needed to produce the radio waves. The ideal location for a ground station is a location with a high elevation and a clear view of the sky [8]. For many universities, a roof location allows the antenna to maintain an unobstructed view of the sky, and the azimuth and elevation motors can properly align with the satellite to send and receive data for the longest amount of time as the satellite orbits overhead.

2.3 Radio Frequency Communication

This section explains ground station communication and the types of tools and strategies that are used to make sure these methods of communication are operational. For radio communication to occur there must be a transmitter and a receiver. Ground stations and satellites both have a transmitter to send radio signals and a receiver to collect them. Radio signals are electromagnetic waves in the radio spectrum with frequencies ranging from 30 Hz to 300 GHz [14]. These waves are sinusoidal and must be modified to encode data that is being transmitted. Three ways to modulate these electromagnetic waves are pulse modulation, amplitude modulation, and frequency modulation [15]. To transmit code, these modulations are used to encode data into radio waves that are then sent to the satellite via the ground station. The satellite collects the radio waves and converts them back into the code, then the satellite can process and implement the coded commands [16]. When satellites send data back, the same process is performed to obtain the data sent by the satellite to the ground station.

There are several requirements needed for a ground station's RF communication system. The first requirement is a defined frequency range for uplink and downlink. If the target satellite's uplink uses VHF, then the ground station needs to have a VHF downlink and vice versa. Antenna gain is also a requirement an organization might consider when developing a ground station. Gain is meant to show the output range of an antenna compared to a theoretical antenna [17]. Specifically, in a transmitting antenna, the gain describes how well the antenna converts input power into radio waves headed in a specified direction [18]. Gain can be measured in decibels relative to isotropic (dBi), where the isotropic dB refers to the dB of an isotropic antenna (i.e., an antenna that radiates the same intensity of radio waves in all directions) compared to an antenna focused in one direction [18]. Similarly, data rate is an important consideration for ground station antennas. Data rates of antennas are measured in bits per second (bps). To send more information in the same amount of transmission time, a greater bps is needed. Generally, the larger the frequency band used, the higher the data rates the ground station can accommodate [19]. The location of a ground station is another key requirement, i.e., to ensure the target satellite is in the ground station's horizon mask. A horizon mask is the area of the sky in which an antenna can communicate with a satellite, this area can be greatly impacted by nearby terrain.

An antenna can be controlled by an SDR to generate or define the desired modulation for the RF signal [5]. The purpose of SDR is to reduce the number of analog components to increase the efficiency and connectivity with computers. In the past, radio communication had many analog components and, with SDR, most of them have been digitalized [20]. SDR functions by collecting radio waves through an antenna and splitting them into two paths. Once split, they are sent through a mixer, and then through an analog-to-digital converter (ADC) [21]. After going through an ADC, they are converted into either in-phase (I) or quadrature (Q) data components [21], [22]. I/Q data is a representation of complex signals recorded by an antenna [20], [21]. They can then be formatted into a waterfall chart that shows the frequency spectrum of the recorded data (for example, see Figure 1).

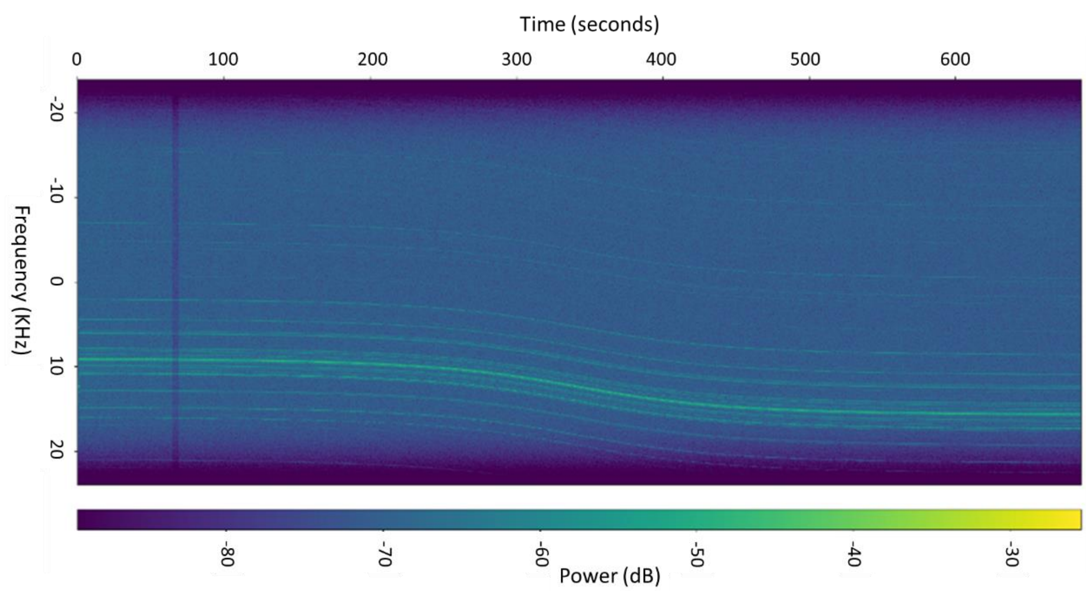


Figure 1: SatNOGS Waterfall of FOX-1A, collected by 150-OM1LD-Needronix on Feb. 5th, 2023

According to [5], the two major advantages of SDR are its flexibility and ease of adaptation. Flexible because it can be changed to suit different frequencies for different missions, and it is adaptive because most parts involving radio functions are easily edited to fit new needs [5]. This flexibility and adaptivity are the main advantages for the use of SDR on educational ground stations.

Besides collecting data from satellites, the main purpose of a ground station is to monitor the tracking, telemetry, and control (TT&C) of satellites. The purpose of a TT&C subsystem is to ensure the safety and reliability of a space mission. The three major tasks of the TT&C subsystem are monitoring the status of the satellite, monitoring the exact location of the satellite, and the control and operations of the satellite during its mission or task [23].

2.4 Industry and Governmental Ground Stations

The majority of ground stations are operated by industry and government and are used to manage their respective satellite resources. For example, SpaceX's Starlink is a satellite constellation project designed to provide worldwide internet access [24]. Starlink uses a network of ground stations to manage the constellation of satellites they have launched to connect their users to their satellites. SpaceX has already made applications to the Federal Communications Commission (FCC) for 32 ground stations in the United States [24]. Government agencies, such as NASA, ESA, and DLR, use their ground stations to manage their space-related projects. Also, these government agencies, along with their respective weather agencies, use their ground stations to manage weather satellites. For example, the NASA Advanced Composition Explorer (ACE) satellite is tracked by NICT, KSWC, DLR, NASA, and NOAA (WCDA, BOU) because the satellite needs to have constant contact to transmit the data it is collecting [25].

Another program developed to increase the accessibility of ground stations is the Satellite Networked Open Ground Station (SatNOGS). Since ground stations have historically been fairly expensive and difficult to set up, the SatNOGS was formed as an open-source ground station network, composed of ground stations built from affordable tools and resources [26]. SatNOGS was started at the NASA Space Apps Challenge in 2014 and came in first place [27]. Now, SatNOGS is a part of Libre Space Foundation (LSF), where it is building a network of crowdsourced ground stations.

3. Current State of Ground Station Education

This section introduces the current state of ground station education at the university level. In particular, the following subsections discuss ground station projects as well as adjacent pedagogical tools used in university aerospace departments.

3.1 University Ground Station Projects

With the advent of the small satellite industry, many universities have embraced ground station projects in conjunction with the development of small space missions, such as CubeSat projects. For example, between 2017-2019, Georgia Institute of Technology (Georgia Tech) supported five different small satellite missions: RANGE, Prox-1, ARMADILLO, RECONSO, and

USIP [28]. All five of these missions used various ground stations on Georgia Tech's campus, with frequencies ranging from VHF to S-band [28]. Another ground station project developed for university education was the Microsatellite Ground Station created by the National Cheng Kung University (NCKU) [3]. This ground station uses amateur microsatellites to operate as an education mission aimed at orbit tracking and signal reception [3]. This ground station was designed to be a hands-on outlet for aerospace students to test their in-class knowledge [3]. Another university with a large 21 m ground station is Morehead State University (MSU) in Kentucky. The MSU 21 m antenna is used in different research programs, such as in radio astronomy and satellite missions, and supports the small satellite community, in particular, CubeSat programs [29].

3.2 Pedagogical Tools

A related educational tool to ground stations are CubeSat simulators [30]. For instance, the AMSAT CubeSat Simulator was designed specifically to be an educational tool for systems design, electrical subsystem management, and telecommunications. The AMSAT simulator is a hardware-in-the-loop setup [31]. The AMSAT CubeSat Simulator has four layers: solar power management, control, battery management, and transmitter [30]. In [32], various lessons that can be taught with a CubeSat simulator are discussed. One of the subsections of lessons described is "Basic Electronics, System Calibration, and Parameters," where students are introduced to lessons about current, batteries and voltage, and ADC [32]. Another subsection, "Satellite Operation Activities" teaches about the limitations of the CubeSat and the ways various subsystems of the CubeSat function [32]. Alternatively, another commonly used pedagogical tool is developing flight-ready CubeSats, such as UNISAT (University Satellite), EduSAT (Educational Satellite), and UniCubeSAT (University Cube Satellite) [33]. These satellite programs were developed by the Group of Astrodynamics of the University of Rome ''La Sapienza'' (GAUSS) and were designed for classroom use with commercial off-the-shelf components [33]. The UniSAT program was a set of five 10 kg satellites each designed for different missions [33]. The EduSAT program was founded by the Italian Space Agency and has a similar purpose as UNISAT, but is directed toward high school students [33]. The UniCubeSAT program's purpose was to scale down UniSAT from 10 kg to 1 kg [33]. The University of Tokyo also developed XI-IV and XI-V CubeSat projects [34]. XI-IV was a CubeSat project launched by the University of Tokyo and it had five objectives, including space engineering education. Overall, these pedagogical tools can be enhanced when used in conjunction with a ground station.

4. Educational Ground Station Development

This section describes the process used to develop learning objectives and laboratory activities and their integration into aerospace engineering courses. The learning objectives were developed using the aerospace curriculum requirements established by ABET alongside Bloom's Taxonomy. ABET guided the topic areas for the learning objectives and Bloom's Taxonomy provided the framework to categorize and construct the objectives systematically. Specifically, the process focused on the six major categories of Bloom's Taxonomy, and action verbs were used to describe the objectives the students would need to complete or learn. Lastly, this section discusses design considerations for building a ground station to meet the learning objectives.

4.1 Aerospace Curriculum Requirements

The curriculum guidelines for engineering curricula are established by ABET to ensure all engineers receive appropriate discipline-specific depth and breadth in their education. Aerospace engineering is a field with a wide scope of content. According to ABET, an aerospace engineering program must combine aeronautical engineering and astronautical engineering topics [35]. According to ABET, students must have sufficient depth of knowledge for engineering practice in all topics of either aeronautical engineering or astronautical engineering, along with having comparable depth in at least two topics from the other area [35]. In the context of ground stations, the astronautical topics are the most relevant for this work. According to ABET, an astronautical engineering curriculum must include the following topics: "orbital mechanics, space environment, attitude determination and control, telecommunications, space structures, and rocket propulsion" [35].

4.2 Learning Objectives

Using the ABET astronautical engineering topics previously mentioned, learning objectives were developed. The learning objectives were designed to fit within the telecommunications and orbital mechanics topic areas of astronautical engineering [35]. The telecommunications topic is based around the processing and transfer of information [36]. Within the scope of aerospace engineering, it is primarily focused on the transfer of data to and from satellites and space missions. The orbital mechanics topic often includes fundamentals such as the two-body problem, orbital elements, and on-orbit maneuvers [37].

To produce these learning objectives that fulfill these ABET topics, Bloom's Taxonomy framework was used. The framework has six major categories: remember, understand, apply, analyze, evaluate, and create [38]—all of which are important to a well-rounded understanding of a topic. These six categories are hierarchical with each progressive category previously listed demonstrating an increase in complexity and abstractness [39]. Though understanding, applying, and analyzing are more applicable to a laboratory experiment, all of the categories are applicable to the use of ground stations in education. The foundation of all these categories is knowledge, and according to the revised edition of Bloom's Taxonomy, there are four different types of knowledge: factual, conceptual, procedural, and metacognitive [39]. Within the scope of these laboratory activities, only factual, conceptual, and procedural knowledge will be utilized. This can be seen in the learning objectives that focus on knowledge about the current state of ground station operations. Conceptual knowledge is needed to organize the functions of a ground station and procedural knowledge on how to operate a ground station is required. One of the key tools used in the construction of these learning objectives is action verbs. The action verbs are aligned to each of the categories of Bloom's Taxonomy. In [39], several lists of action verbs are included and have been leveraged to form the learning objectives found in Tables 1, 2, and 3.

Using Bloom's Taxonomy along with the aerospace topic areas from ABET in conjunction with the functions of ground stations, these learning objectives were created to be relevant and important to the education of aerospace engineering students at the undergraduate level (see Tables 1, 2, and 3). Each of these tables have learning objectives categorized into Telecommunications, Orbital Mechanics, and Data Collection and Analysis. The

Telecommunications and Orbital Mechanics categories are based on the ABET topics previously mentioned. The Data Collection and Analysis category is based on the overlap of telecommunications and orbital mechanics, focusing on the collection of the RF signals with the ground station and the analysis of the TT&C data, respectively.

Table 1: Telecommunication Learning Objectives

No.	Module: Telecommunications	Bloom’s Taxonomy Category
1.1	Explain the different organizations and governing bodies in radio communications and their roles.	Remember
1.2	Explain the purpose and necessity of spectrum management.	Understand
1.3	Summarize the scope and purpose of uplink and downlink rates involving the collection and sending of data (in conjunction with satellite orbits).	Understand
1.4	Compare and explain the different methods and uses of radio communication.	Analyze
1.5	Compare and contrast the benefits and uses of the different types of radio antennas.	Analyze
1.6	Operate the ground station to receive satellite data.	Apply (procedural knowledge)

Table 2: Orbital Mechanics Learning Objectives

No.	Module: Orbital Mechanics	Bloom’s Taxonomy Category
2.1	Describe how and why ground tracks are used.	Understand
2.2	Calculate the orbit of a chosen satellite.	Apply
2.3	Determine the alignment of the satellite in the chosen orbit.	Apply
2.4	Use TT&C data (or TLE data) to orient and program a ground station’s orientation system to collect data.	Apply
2.5	Obtain and analyze satellite TT&C data collected.	Analyze

Table 3: Data Collection and Analysis Learning Objectives

No.	Module: Data Collection and Analysis	Bloom's Taxonomy Category
3.1	Explain the different types of data that are transmitted by satellites and their purposes.	Understand
3.2	Orient, set up, and collect data using a ground station.	Apply
3.3	Process collected data from a satellite.	Analyze
3.4	Examine and explain the data collected.	Analyze

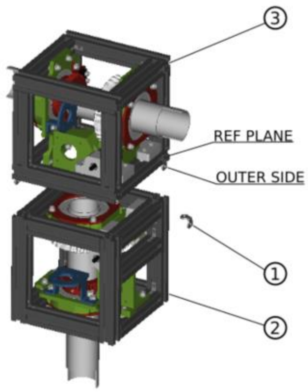
4.3 Ground Station Design

This section discusses the design considerations for selecting a ground station along with the selection of the components used in the construction of the ground station that was designed to be low-cost and able to fulfill the learning objectives. Specifically, this section focuses on the selection of the rotator, antenna, and software used in the operation of the ground station.

4.3.1 Design Considerations

For a ground station design to be accepted and ubiquitous in aerospace education, the ground station design must satisfy the following design considerations: low-cost and reliable. In this section, the development of the ground station was conducted to meet those criteria while allowing it to accomplish the learning objectives. Specifically, the ground station must be low-cost and easily acquired, and it needs to be a tested design that can be operated by students. The key features needed in a ground station to satisfy the learning objectives are that the ground station must collect RF transmissions from satellites and orient itself to point at the orbiting satellite to receive the data.

These design considerations along with the information discussed in Section 2, show that SatNOGS has an established, low-cost ground station that could easily be leveraged. Their documentation on the design, assembly, and operation of their ground station design is a valuable resource. SatNOGS also has an online forum that allows ground station operators to communicate and ask questions about the system. SatNOGS developed a network of ground stations where operators are able to schedule and collect data from many satellites orbiting all around the world. Using their network allows for laboratory activities to be run remotely or when weather or other extenuating circumstances may not permit data collection. The resources that SatNOGS has publicly available, namely, their several websites and forums, allow for a simple setup and easy methods of troubleshooting if problems arise. These are key aspects to allowing universities to easily purchase and assemble a ground station on campus.



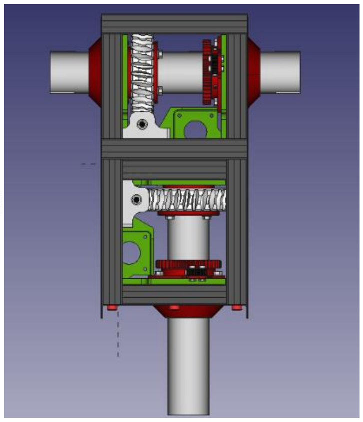


Figure 3: SatNOGS V3 Rotator Assembly (Left) [40], FreeCAD SatNOGS V3 Rotator (Right) [40]

4.3.2 Rotator Design

The rotator that was selected was the SATNOGS V3 rotator [40]. This rotator, shown in Figure 3, is the current model of SatNOGS rotators. It orients the antenna by rotating the horizonal and vertical masts using two NEMA 17 stepper motors to ensure accurate orientation. The motors are attached to a worm gear that rotates the masts. The worm gear is set at an angle so that the masts are locked in place when assembled and can only be rotated by the worm gear.

4.3.3 Antenna Selection

First, for the design of any ground station, the purpose of the ground station must be determined. This will dictate the target type of satellites and the capabilities and sophistication of the ground station. For the design of this ground station, the purpose is the education of undergraduate students. Specifically, to provide them the opportunity to operate and use skills involving telecommunications and orbital mechanics. These opportunities would involve the collection of data transmitted from satellites to Earth. To fulfill these goals, a survey of satellites was collected to determine the optimal frequency for the ground station antenna to receive and transmit. The satellites analyzed were taken from the active satellites list maintained by Radio Amateur Satellite Corporation, AMSAT [41]. From this survey of amateur radio satellites, it was determined that a significant portion of the Orbiting Satellite Carrying Amateur Radio, OSCAR, satellites are transmitting and receiving in the VHF and UHF bands. Also, the International Space Station (ISS), amateur radio frequencies are 145.825 MHz for uplink and 145.825 MHz for downlink [48]. Therefore, with a 145.825 MHz antenna, a receiver on a ground station would be able to connect to the ISS and receive their radio transmissions. These frequencies are for the mode V Automatic Packet Reporting System (APRS), which, according to AMSAT, is the most common operating configuration for the ISS [42]. Another configuration for amateur radio onboard the ISS is the V/U FM Voice Repeater Worldwide that has an uplink of 145.990 MHz and a downlink of 437.800 MHz [42]. Therefore, the chosen antennas are designed to fit within these two ranges of approximately 145 MHz and 437 MHz. Besides the desired frequencies, the type of antenna also restricts some of the component selection. The type of antenna that was chosen was a Yagi antenna. This type of antenna was chosen over the turnstile, parabolic dish, and helical antennas because the Yagi antenna is more applicable to the learning objectives. The primary reason that the Turnstile antenna was not chosen is due to its omnidirectional functionality, which would not give students the opportunity to orient the antenna to the incoming satellite (a key learning objective). The next two antennas were ruled out due to practicality: parabolic dish antennas tend to operate at higher frequencies than Yagi antennas, and for helical antennas, they tend to weigh more than the Yagi antennas, which would make orientation more difficult for the rotators [43], [44], [45]. The two antennas that were selected were 2MCP8A and 436CP16, which have operating frequencies of 143-147 MHz and 432-438 MHz, respectively [43], [44]. Both antennas are designed for low Earth orbit communication [43], [44] and they were also recommended by SatNOGS as commercial antennas that are compatible with their design [46]. The SDR selected for this ground station was the RTL-SDR.COM that is a commonly used, relatively inexpensive SDR that has been previously used in conjunction with the rest of the SatNOGS ground station design.

4.3.4 Software

There are several software that are used in the operation of the ground station. The first is the SatNOGS OS for Raspberry Pi used to connect the incoming data to the SatNOGS network. Arduino IDE is used to program the SatNOGS Arduino Uno/CNC Shield-Based Rotator Controller [47]. GPredict is a real-time satellite tracking and orbit prediction software [47]. The last main software for the rotator is Ham Radio Control Libraries (Hamlib) that is an API used to control radio equipment via a computer interface [47]. These software are controlled by the SatNOGS network through a terminal-based boot on the Raspberry Pi. There are other software incorporated into the network to demodulate some of the different types of data collected by ground stations. The software can also be used to demodulate data on the student end. The SatNOGS OS allows it to be remotely accessed, using the Raspberry Pi’s IP address, to manually set observations.

4.4 Laboratory Activities

The laboratory activities were designed to fulfill all the learning objectives previously mentioned. There are five planned laboratory activities with each activity building upon the next and becoming more open-ended. Specifically, the first two activities focus on tutorials and introductory instruction on ground stations, while activities three, four, and five provide students with opportunities to use the skills and knowledge generated from the previous activities to choose what they would like to investigate. The first laboratory activity (Lab 1) shown in Table 4 is “Ground Station and Software Tutorials”. This activity introduces students to the primary software used in the later activities focusing on the SatNOGS Network and AGI Systems Tool Kit (STK). Although Lab 1 does not fulfill as many LOs as the other labs, it is critical for student success by establishing ground station basics. The second lab is focused on telecommunications and allows students to learn and explore within the field of RF communications as well as gain an understanding of how RF communication works and how it is used in space missions. Lab 3 teaches students to implement their knowledge of orbits and telecommunication to determine a suitable location for a ground station for a chosen satellite. This lab uses STK as a visual aid and data provider on the telecommunication accessibility of the chosen ground station. The fourth lab is an analysis of two-line element (TLE) data, what it stores, and how it can be used by ground

Table 4: Laboratory Activities and their Learning Objectives

Lab No.	List of Experiments	LOs
1	Ground Station and Software Tutorials	2.1
2	Telecommunications	1.1, 1.2, 1.3, 1.4, 3.1
3	Ground Station Selection	1.3, 1.5, 2.1
4	Two-line Element (TLE) Analysis	2.2, 2.3 2.4
5	Operation and Data Collection of University Ground Station	1.6, 2.5, 3.2, 3.3, 3.4

Table 5: Laboratory Activity Attributes [48]

No.	Title of Experiment	Relationship to Courses	Content Level	Activity Type
1	Ground Station and Software Tutorials	Complete Independence	Least Sophisticated	Tutorial
2	Telecommunications	Complete Independence	Middle Sophisticated	Exploration
3	Ground Station Selection	Loose Coupling	Most Sophisticated	Exploration
4	Two-line Element (TLE) Analysis	Loose Coupling	Most Sophisticated	Exploration
5	Operation and Data Collection of University Ground Station	Loose Coupling	Most Sophisticated	Experimentation and Analysis

station operators. This lab uses STK's TLE input option to provide students exposure to STK while connecting the two lines of data to visualize an orbit. The last laboratory activity (Lab 5) is focused on the operation and use of the SatNOGS network through the ground station previously mentioned. This lab has students pick a satellite and, using the SatNOGS network, schedule observations and collect and demodulate the collected data into images, TLE, TT&C, or other user-readable data.

The laboratory activities created were categorized into several lab-based attributes from [48]. The attributes used are the relationship between the lab and courses, content level of the activity, and activity type, which are shown in Table 5. The relationships between the lab and courses described in Table 5 are complete independence and loose coupling. Complete independence means the laboratory activity does not rely on theory from lectures for completion. Specifically, that the activity teaches all the content related to astronautics that is required to complete the lab [48]. Loose coupling is when the content in the laboratory activity may or may not depend on theory from lectures, meaning that the content taught within the labs can be augmented by content from a lecture [48]. To clarify, complete independence and loose coupling do not mean that the content taught in the activities are unrelated to course content, it is referring to the level of reliance on content taught in lecture. The rationale for the categorization of Labs 1 and 2, as complete independence with regards to their relationship to courses, is that they are more tutorial focused laboratory activities. Labs 3, 4, and 5 are categorized as loose coupling because they are not reliant on course instruction to provide the baseline knowledge for completion. Although Labs 3, 4, and 5 do rely on the tutorial aspects of Labs 1 and 2.

4.5 Curriculum Integrations

This section focuses on how ground stations can be used in aerospace courses and projects. Specifically, these learning objectives and laboratory activities are applicable to several key courses in aerospace engineering and can be used to further develop aerospace engineering projects.

4.5.1 Course Integrations

There are several university courses that would benefit from the use of a ground station. For example, from Purdue University: Spacecraft Design, Space Flight Operations, Introduction to Satellite Navigation and Positioning, Orbit Mechanics, RF System Design, Digital Signal Processing, and Electromagnetic Field Theory all have connections to ground station operations [49]. Along with these courses, other aerospace engineering schools such as Virginia Tech, MIT, and the University of Maryland offer similarly names courses [50], [51], [52]. Specifically, Virginia Tech offers Spacecraft Position/Navigation/Timing and Orbit Determination. MIT's undergraduate aerospace curriculum includes Space Systems Engineering, and Communication Systems and Networks [51]. The University of Maryland teaches space track aerospace engineering students Space Navigation [52]. The overarching subcomponents of these courses are all capable of connecting to critical aspects of ground stations and how they function. For instance, in the second segment of Space Flight Operations, they learn tracking station operation and spacecraft telemetry [53]. In Space Flight Operations, there are course objectives (COs) that relate to ground stations: "space communications, spacecraft commanding, and telemetry, and spacecraft technical resources" [53]. These COs were established to accomplish the following student learning outcomes (SLOs): "evaluate the viability of a space mission design based upon technical resource budgets" and "understand the basics of launch operations" [53]. In RF System Design, the concepts of RF waves and transmission are discussed. One of RF System Design's learning objectives is understanding basic design principles of RF modules and transceivers [54]. All of these courses teach content relevant to how ground stations communicate with satellites and could benefit from ground station lab activities. Integrating a ground station within these courses can provide students with experience with ground stations and their operation. Further, as an example, in Table 6 the similarly named courses previously mentioned are shown with their corresponding ABET Topic and the laboratory activity that connects with their content.

Table 6: Aerospace Courses with Respective ABET Topics and Learning Objectives [35]

Courses	ABET Topic	Labs
Spacecraft Design	Telecommunications and Orbital Mechanics	3, 4
Space Flight Operations	Telecommunications and Orbital Mechanics	3
Space Systems Engineering	Orbital Mechanics	3,4
Introduction to Satellite Navigation and Positioning	Orbital Mechanics	4
Orbital Mechanics	Orbital Mechanics	4, 5
RF System Design	Telecommunications	2, 3
Digital Signal Processing	Telecommunications	5
Electromagnetic Field Theory	Telecommunications	2

4.5.2 Project Integrations

Along with the courses mentioned in the previous section, there are a couple of specific ways in which ground station use and ground station component systems can be taught in conjunction with other aerospace activities. One of the most common methods to introduce ground stations into curricula is through a senior design project. For example, within the San Jose State University Astronautics program, students are required to take a two-semester course on spacecraft design projects [55]. These design projects consist of written reports and presented briefings, that are meant to help students learn to organize and condense their work, and to focus on the key aspects of their topic [55]. Similarly, at Saint Louis University, they have a senior capstone design class, where students work interdisciplinarily to solve open-ended problems that are meant to encourage teamwork, and good project management skills, along with written and oral communication skills [6]. These space design courses could leverage a ground station in unique ways to support design and mission-related projects.

5. Conclusion

This paper developed an approach for the use of ground stations in undergraduate aerospace curriculum by providing a background on ground stations, their components, and current uses, as well as an overview of the current state of ground stations in education. The use of ground station projects and pedagogical tools in university settings was presented. Learning objectives leveraging ground stations were developed using the ABET topics for astronautical engineering in conjunction with Bloom's Taxonomy. The design considerations for a low-cost ground station tailored towards engineering education were discussed and an outline of laboratory activities, designed to work with the SatNOGS ground station and network, that fulfill the learning objectives, were developed. Lastly, the laboratory activities were discussed in light of current aerospace courses and projects to demonstrate the usefulness of a ground station in teaching aerospace engineering topics. Overall, the integration of a ground station into aerospace engineering curriculum as an educational tool has great potential to add pedagogical value to undergraduate aerospace engineering curricula. Future work should focus on conducting the laboratory activities with students to evaluate student knowledge acquisition in the targeted ABET astronautical topic areas.

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