Commercial Off The Shelf Ground Stations For Use in Rapid Testing and Innovation of Space Systems

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Abstract

Over the past 2 decades, CubeSats have revolutionised small satellite manufacturing and deployment. By reducing the overall cost of manufacturing a satellite, the technology and capabilities of satellites have been brought to educational institutions and amateur satellite enthusiasts alike. CubeSats allow for rapid iterative testing and experimental technology demonstrations which would be too expensive or time consuming to deploy on larger satellites. This has been great for educational institutions as it has reduced the cost of space research.
The problem with CubeSats however is that once a CubeSat is launched, transmitting and receiving data and commands to and from the satellite must be done through a third party ground station. To resolve this, Carleton University has built a small mobile ground station capable of interacting with CubeSats as well as Low Earth Orbit (LEO) and geostationary satellites. The groundstation uses Commercial Off The Shelf (COTS) and 3D printed parts in its construction. By using COTS and 3D printed parts, anyone can source the parts required to build their own ground station, making ground stations increasingly accessible to educational institutions and amateur satellite enthusiasts alike. On top of this, all the software used in Carleton University's ground station is open source, making the use and deployment of the ground stations readily available.

Aside from their use in CubeSat missions, these ground stations can be used on their own to interact with orbiting satellites. The ground stations at Carleton University have tracked LEO satellites and geostationary satellites alike. Seeing as CubeSats are far more expensive to manufacture than this ground station, it can be a stepping stone for educational institutions into aerospace engineering and astronomy. As an educational tool it is much easier to bring ground station development to an educational institution than a CubeSat due largely to the lower cost as well as the simplicity of the ground station relative to a CubeSat.

With the above, this ground station would be a perfect tool for promoting astronomy and aerospace engineering to developing nations. On top of this, the ground station can be used for weather and agricultural prediction. This will be incredibly beneficial to developing nations, especially those prone to extreme weather events and those who do not have access to the internet.

This paper explores the development and manufacturing process of Carleton University's ground station. Use cases and deployment of the ground station in developing nations are also examined.

Acronyms/Abbreviations

Commercial Off The Shelf (COTS)
Computer Aided Design (CAD)
University of Toronto's Space Flight Laboratory (SFL)
Satellite Networked Open Ground Station (SatNOGS)
Low Earth Orbit (LEO)
National Oceanographic and Atmospheric Administration (NOAA)
Personal Protective Equipment (PPE)
Infrared (IR)
Internet of Things (IoT)
Suspended Particulate Matter (SPM)

1. Introduction

How do satellites communicate information to Earth? Ground Stations are electro-mechanical systems used for communicating with orbiting satellites. Firstly, this paper will discuss the development and manufacturing of Carleton University's ground station. By using commercial off the shelf (COTS) and 3D printed parts, anyone can source the parts required to build their own ground station, making ground stations increasingly accessible to educational institutions and amateur satellite enthusiasts alike. On top of this, all the software used in the ground station is open source, making the use and deployment of ground stations readily available. Secondly, this paper will discuss why ground stations are good for educational institutions. Seeing as CubeSats are far more expensive to manufacture than this ground station, it can be a stepping stone for educational institutions into aerospace engineering and astronomy. As an educational tool it is much easier to bring ground station development to an educational institution than a CubeSat due largely to the lower cost as well as the simplicity of the ground station relative to a CubeSat. Lastly, this paper will discuss how ground stations can be used for weather prediction. This will be incredibly beneficial to developing nations, especially those prone to extreme weather events and those who do not have access to the internet. This paper explores the development and manufacturing process of Carleton University's ground station. Use cases and deployment of the ground station in developing nations are also examined.

2. Ground Station Development

Ground Stations are electro-mechanical systems used for the reception and/or transmission of electromagnetic signals to/from orbiting satellites. Traditionally, ground stations have been large in size, very complex in design/assembly and inaccessible to educational institutions and amateur satellite enthusiasts alike. Recently, it has been made possible for those aforementioned groups to develop their own ground stations. By using Commercial Off The Shelf (COTS) and 3D printed parts, anyone can source the parts required to build their own ground station, making ground stations increasingly accessible to education institutions and amateur satellite enthusiasts alike. On top of this, all the software used in Carleton University's ground station is open source, making the use and deployment of ground stations readily available. This is beneficial because it enables broader societal participation in the new space era.

The COTS components used in the ground station include structural components, jumper wires, stepper motors and bearings. The 3D printed parts used in the ground station include mounts and gears. All the aforementioned components and 3D printed hardware can be readily found on E-commerce giants such as Amazon and Alibaba. Additionally, the Computed Aided Design (CAD) software used to design the ground station is cloud based and accessible from an internet connection [1]. Using COTS components and 3D printed parts has increased the access to ground stations and has enabled educational institutions and amateur satellite enthusiasts to design and manufacture their own ground stations. In regards to educational institutions, The University of Toronto's Space Flight Laboratory (SFL) and the University of Kansas' School of Engineering have developed their own ground station for use in their respective satellite missions [2], [3]. With respect to amateur satellite enthusiasts, the Satellite Networked Open Ground Station (SatNOGS) program aims to enable other amateur satellite enthusiasts to build and operate their own ground stations by providing open source technologies [4]. In order for successful ground station operations, software is needed to mesh together the mechanical and electrical systems. The software used in Carleton University's ground station is open source and hosted on GitHub [5]. Having the software be open source enables amateur satellite enthusiasts to access our code and provides them the ability to improve our software. This greatly aides in the deployment of our ground station from a software perspective.

The implementation of COTS and 3D printed parts in ground stations has allowed anybody to source the parts required to build their own ground station. Subsequently, increasing the accessibility of ground stations to educational institutions and amateur satellite enthusiasts alike. Supplementary, Carleton University is contributing to the redial availability of ground stations by making its software open source. By utilising the technologies discussed above, anyone can design and operate their own ground station.

3. Use Cases in Educational Institutions

It's clear that a ground station is fairly easy to source but how is this useful to academic institutions? Well for one, the ground stations produced at Carleton University are far less expensive to manufacture than CubeSats which make them ideal for institutions on limited budgets. As well, ground stations do not have to deal with the cost and complexity of launching a payload into orbit as a CubeSat does. Due to their inexpensive nature, these ground stations are a great stepping stone for promoting aerospace engineering and astronomy among academic institutions. Due to their relative lack of complexity and COTS nature, they can be easily sourced and constructed by students. This contrasts the construction of a CubeSat which is typically an enduring and complicated endeavour. The ground stations manufactured at Carleton University are great for educational institutions because they are far less expensive to manufacture than CubeSats, they can be used to promote aerospace engineering, and they are much easier to build than CubeSats. As such, they are a much better educational tool to promote aerospace engineering than a CubeSat.

A large reason many institutions construct ground stations before CubeSats is due to their relatively inexpensive cost; CubeSats are typically far more expensive to manufacture than ground stations built with COTS parts [6]. One reason for this is due to the life expectancy of CubeSats. CubeSats are typically launched into Low Earth Orbit (LEO) [1]. Due to this they experience fast orbital decay which vastly decreases their time in orbit. Reentry trajectories have been known to occur within periods of 1-2 years [6] with an early failure rate of 48% [6]. Of course one could relaunch their payload every 1-2 years but with a launch cost of about $100,000 USD/CubeSat Unit [6], this would simply be too expensive to be considered feasible for most institutions. Besides the cost of putting a satellite into space is the cost of manufacturing the CubeSat itself. The cost of Carleton University's CubeSat has exceeded $10,000 which far exceeds the cost of their ground station, around $1000. Aside from financial costs, the time costs of constructing a CubeSat must also be factored. Time costs are largely associated with student involvement as more hands working on a project typically decrease the time required for completion. At Carleton University, 20 senior undergraduate students work on the CubeSat year round yet despite this the project has been in development for close to a decade. In contrast, Carleton University's original ground station was developed by 2 undergraduate students and 2 professors in 2 years. The ground station project is currently being run by 5 undergraduate students. Thus it is clear that CubeSats are far more expensive to produce than COTS ground stations in both a financial and time-wise sense.

Following this, ground stations are prime contestants for promoting aerospace engineering and astronomy in educational institutions. As was previously mentioned, Carleton University has both a CubeSat project and a ground station project operated by students. While both projects have been extraordinary in providing undergraduate students with hands-on experience constructing industry relevant appliances, the ground station has many less barriers to entry. For one the general mechanisms employed on ground stations can and have been taught to younger undergraduate students as compared to the CubeSat project which is reserved for students in their senior year. In 2021, third year students at Carleton University participated in a project to construct a twin dipole ground station capable of receiving from National Oceanographic and Atmospheric Administration (NOAA) satellites. While the ground station was unmoving, the students learned a generous amount about antenna types, radiocommunication, and static satellite tracking. The students then successfully applied their skills and were able to receive weather images from NOAA 15. Compare this to Carleton University's CubeSat mission which has been going on for close to decade and one begins to see why ground stations are a better solution. For one, the CubeSat project is much more complicated than the ground station project as there are more moving parts. The ground station simply has a motor to control elevation and one to control azimuth and was built in 2 years by undergraduate students with minimal experience. The CubeSat on the other hand has multiple modules onboard and requires much more attention to detail to deal with the harsh environment of space. On top of this, as was previously mentioned, Carleton University's CubeSat is much more expensive than their ground station even without launch costs. Similar to Carleton University, many other institutes have started constructing ground stations. The Maharashtra Institute of Technology currently has a 6 antenna setup which cost about $4000 [7]. While much more complex than the setup at Carleton University, it is still less expensive than a CubeSat. With this setup, they have been able to contact the ISS among other satellites [7]. Similarly, the Rochester Institute of Technology has their own portable ground station which tracks and communicates with satellites in the VHF band [8]. With their ground station they have received from AO-73, the ISS, and NOAA satellites. Ground stations can be far less expensive than CubeSats, they are less complex and their barriers to entry are much lower. For these reasons, grounds stations are a much better option for promoting aerospace engineering and astronomy especially within smaller institutions.

While it's been shown that Carleton University's ground station can be easily sourced and is relatively inexpensive, another benefit is its simplicity in construction relative to a CubeSat. In the construction of a CubeSat, custom fabrication is often required. Carleton University's ground station design combats this by using COTS components wherever possible. When constructing a CubeSat for deployment into orbit, custom fabricated parts must also be cleaned and inspected in a controlled environment before they are integrated into the satellite. This requires a cleanroom as well as Personal Protective Equipment (PPE) and generally adds a further layer of complexity to the manufacturing process. As Carleton University's ground station is designed for use on Earth, this process is not required. CubeSats generally also employ 3 axis attitude determination systems, payloads, and multiple onboard computers, all of which Carleton University's ground station does not. On top of this, CubeSats must factor in magnetic field disturbances in space thus use of materials such as steel is restricted. As well, the CubeSat must be powered through external means such as solar panels while a ground station can draw from a power grid. Also, before launching a CubeSat multiple tests must be performed to ensure that it can withstand the various environments it will be exposed to. These include mechanical tests to ensure it can withstand the loads applied on launch, thermal-vacuum tests to ensure it can endure the low pressures and high temperatures of space, and thermal-vacuum cycling tests to ensure the satellite can withstand the extreme temperature changes of space under vacuum. Clearly, CubeSats are much more complicated than small ground stations as they must account for the various environments they will be exposed to during their lifespan.

Small ground stations are much better educational tools to promote aerospace engineering than CubeSats, at least for smaller institutions. Carleton University has designed a ground station that is less expensive than a CubeSat, much easier to build, and great for promoting aerospace engineering among students. As the ground station uses COTS components and is relatively simple to construct, it can be easily sourced and constructed by students in an engineering program. A CubeSat on the other hand typically requires fabricated parts and is much more complex as it must withstand the various environments of space. As these ground stations are relatively inexpensive, they are a great stepping stone for promoting aerospace engineering and astronomy while on a limited budget. For the reasons above, it is clear that small ground stations make great projects for academic institutions looking to promote astronomy and aerospace engineering.

4. Telecommunication Hazards

It's been shown that small ground stations are beneficial for promoting aerospace engineering and astronomy but what about use cases outside of this? Large scale ground stations are employed around the world to receive data from orbiting satellites for a variety of tasks. One of these tasks is weather data reception and analysis. The ground station designed by Carleton University is capable of receiving weather data from geostationary weather satellites such as GOES-17 and using this one can analyse weather patterns to predict a variety of events. This could be extremely beneficial for places where internet access is limited or hard to access such as parts of rural africa. With this technology one could predict weather, agricultural yield, and extreme weather events.

As was mentioned, Carleton University's ground station has previously received data from a variety of weather satellites such as GOES-17, and NOAA 15. These satellites can provide various types of data from their onboard instruments. GOES-17 for example transmits infrared (IR) images of the Earth as well as visible light images. Analysing these, one can predict a variety of events. One such use case is in predicting weather. By looking at visible images of the Earth one can observe clouds within the atmosphere. As clouds reflect solar radiation, higher cloud densities will appear brighter in visible light images [8]. This data can be helpful in determining precipitation as increases in clouds may indicate increases in precipitation. On top of this, IR images can also be beneficial for analysing clouds. When looking at the atmosphere in the infrared spectrum, brighter spots indicate higher clouds [8]. Using this, one can estimate thunderstorms or fog predictions in certain areas. Tall thick clouds indicate thunderstorms while low clouds may indicate fog [8]. By looking at both visible light and infrared light spectrums over time, one can analyse storms forming over certain areas as well as cloud movement and precipitation. Speaking of precipitation, some infrared bands provide water vapour data which can be seen in received IR images [8]. This is useful as swirling water vapour often indicates a storm in a specific area [8]. With this, ground stations can receive weather data from orbiting weather satellites and one can analyse this data to predict a variety of events such as storms, precipitation, and cloud formation.

While predicting weather may be useful for predicting extreme weather events, what is equally useful is the ability to predict agricultural yields. As weather and agricultural yield go hand in hand, it should come as no surprise that agricultural yields can be estimated using weather incurred from orbiting weather satellites. One of the most useful sources of data is precipitation. By tracking increases or decreases in precipitation as compared to historical data, increases or decreases in crop yield can be predicted [9]. Crops require moisture as well as precipitation to thrive [9]. Crop yield is a function of soil moisture and soil moisture is largely related to precipitation thus as precipitation increases, an increase in crop yield may also occur [9]. On top of tracking precipitation, many satellites can also track temperature. Tracking temperature aides in predicting soil moisture as moisture tends to evaporate from soil as temperature increases [9]. Dryer soil means lower soil moisture which in turn means less crops [9]. To track temperature one can look at the sunlight incurred over a period of time in a specific area and compare it to historical data. If sunlight is higher than average and precipitation is lower than average one can expect a decrease in crop yield for that specific season. Using the above metrics, among others, one can estimate whether crop yields will be higher or lower than an average season. This is extremely beneficial to areas that rely on agricultural production and farming for sustenance and nourishment.

Playing on the previous point, small ground stations could be extremely beneficial to developing nations and rural areas with limited access to the Internet of Things (IoT) such as rural African villages [10]. The main problem with the IoT in these rural communities is a lack of existing infrastructure, a high cost of hardware, and an increased complexity of deployment [10]. Carleton University's ground station design solves each of these problems individually by bundling their solutions into a single device. One thing that must be limited in these communities is the dependence on proprietary infrastructure [10]. By providing individual devices to farms or villages of the like, one can veer away from this exterior dependence. Another problem is the use of integrated components in IoT devices which are often difficult to repair or replace [10]. By using COTS components of relatively simple design, the Carleton University ground station solves this problem with a DIY design orientation. Currently the main problems in rural Africa are lack of access to quality water, decreases in livestock farming, decreases in agricultural farming, and decreases in fish farming [10]. Water quality can be monitored using satellite data [11]. By estimating the amount of chl-*a*, which tracks the amount of algae in water, along with the Suspended Particulate Matter (SPM) in a certain body of water, one can estimate the quality of water in a certain region [11]. In terms of fish farming, one may not be able to directly predict fish populations in rural Africa using satellite images; however satellites can be used to detect aquaculture ponds [12]. Aquaculture ponds are very important in sub-saharan Africa for seafood production [13]. These aquaculture ponds could be the solution to the fish farming epidemic in Africa. As one can see, ground stations can be extremely beneficial to developing regions such as those in rural Africa. By using satellite data captured through small ground stations, one could estimate water quality and predict seafood production yields.

The technology employed in Carleton University's ground station can be used to communicate with orbiting satellites which in turn can provide estimates on weather prediction, agricultural yield, and extreme weather events. These systems could be of utmost value to developing nations and regions where access to the internet is limited such as rural Africa. Carleton University's ground station is capable of receiving weather data from various weather satellites such as GOES-17 and by analysing weather data and patterns one could predict a plethora of weather events. Other large scale organisations utilise similar technology employing larger ground stations to interact with satellites to receive weather data and predict weather events. Doing this on a smaller scale could prove beneficial to regions with limited access to the internet.

7. Conclusion

This paper explores the development and manufacturing process of Carleton University's ground station. Use cases and deployment of the ground station in developing nations are also examined. Ground Stations can be used for weather and agricultural prediction. This will be incredibly beneficial to developing nations, especially those prone to extreme weather events and those who do not have access to the internet. Seeing as CubeSats are far more expensive to manufacture than this ground station, it can be a stepping stone for educational institutions into aerospace engineering and astronomy. As an educational tool it is much easier to bring ground station development to an educational institution than a CubeSat due largely to the lower cost as well as the simplicity of the ground station relative to a CubeSat. By using COTS and 3D printed parts, anyone can source the parts required to build their own ground station, making ground stations increasingly accessible to educational institutions and amateur satellite enthusiasts alike. On top of this, all the software used in Carleton University's ground station is open source, making the use and deployment of ground stations readily available. The satellites orbiting the Earth will forever be a testament of human ingenuity and creativity.

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