Phase I Report

Ground Station and Tracking System for Western's CubeSat

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Introduction

Western University's CubeSat Project is designing two parallel CubeSat satellite systems, with different communication frequency bands, that will undergo a trade-off, launching only one of them in 2021. *They lack an accessible system on the ground that can provide real-time communication with the satellite, monitor and predict movement of the satellite, and correct antenna direction based on its trajectory*. This ground system must be robust to either communication schemes.

The goal of this project is to design and build a functional satellite tracking ground station with high alignment accuracy between the CubeSat in orbit and the ground station, to achieve better communication and data transfer. The project scope will cover the electrical and mechanical subsystems for motor actuation and sensory data acquisition, control system for mitigating tracking error, and the orbital prediction algorithm that the ground station will employ to track the satellite's orbit.

The purpose of this report is to provide necessary background information and context for the project, outline the choices made throughout the design process and the supporting analyses, and provide all details thus far with regards to the final design. First, the design requirements and constraints were identified. Taking these into account, several concepts were generated, and concept selection was completed using various design techniques. This was an iterative process to determine and justify the choice of mechanical structure, antennae placement, and actuation components. Finally, a CAD model, material selection, and supporting calculations for the final design were completed.

Background Information

A CubeSat is a miniature satellite intended for low earth orbit (LEO), measuring some multiple of 10x10x10 cm and weighing less than 1.33 kg each. Western's two CubeSat designs will communicate in different frequency bands – UHF and S-band, requiring two separate Yagi and parabolic dish antennae. In a design meeting, Dr. Bourassa stated that with satellite tracking, the parabolic antenna will need to rotate between 15 to 165 degrees and operate around 2 GHz and a Yagi needs a 30 degree field operating around 300 MHz. In terms of mechanical construction, the antenna needs to be securely attached to the base so it does not move, which will aid in the accurate positioning of the antenna as environmental factors would not alter its positioning.

Electromagnetic interference (EMI), also called radio-frequency interference, is when a disturbance generated by an external source affects an electrical circuit (especially integrated circuits and rotators) through electromagnetic induction, electrostatic coupling, or conduction. In DC motors, the mechanical interaction between the brushes and commutators occur, creating an EMI frequency between 100 kHz to 100 MHz. However, this frequency range is below the working frequency of both antennae, so this will not be an issue with the ground system.

Though ground stations have been a well known aspect of satellite use, there has been a burst of do-it-yourself ground stations in recent years, constructed from various off the shelf, commercial components. Innovation Solutions in Space is a company with a variety of ground stations designed specifically for small satellites in LEO. They have one ground station in particular that has both Yagi and parabolic antennae that can track satellites using a steerable antenna system that can be remotely controlled through the internet, with speeds up to 6˚/sec. This ground station is unique in how it is able to function in both S-band and UHF band frequencies; however, lacks the ability to be fully autonomous and is meant to track multiple satellites at once, lacking detail for any specific satellite. GOMSpace's AS2000 ground station also supports both S-band and UHF, but has a fixed height and needs to be mounted high above ground in a flat area. SatNOGS has a collection of various amateur ground station elements that are inexpensive and easy to implement, which can serve as a guideline or source of inspiration. After researching many existing ground stations, they all seem to lack some design element such as autonomy, adjustable heights, and portability. Our ground station aims to fill this gap and since it is focused on tracking a single satellite, it will have higher precision and be able to provide more detailed information.

Project Objectives and Constraints

The main constraints for the ground system are that it must be able to physically align itself with the CubeSat, be able to geo-locate itself so its location does not have to be fixed, monitor and predict orbital trajectory to track, correct antenna direction if communication is not established, and be resistant to the effects of the external environment. The main project objectives are for the ground station to be easily transportable, require low maintenance, and be manufactured from as many off the shelf commercial components as possible.

Concept Generation

Concept generation was split into three main subassemblies that form the total ground station – the base, actuation system, and antennae placement. Starting with the base, several ideas were considered, taking in to account portability, stability and ease of manufacturing. Overall, the ideas were to have large trusses and cross beams, with a large base to increase stability and transfer loading forces evenly around the structure to avoid concentrated stress elements. Figures 1 to 3 below illustrate these styles. Another concept that was generated was a box base, as seen in Figure 4. This feature keeps the base stable while also allowing for all electronics to be enclosed and protected from external elements, such as wind and dust. Additionally, this design has the advantage of potentially doubling as a storage container for the other components to make transportation easier.

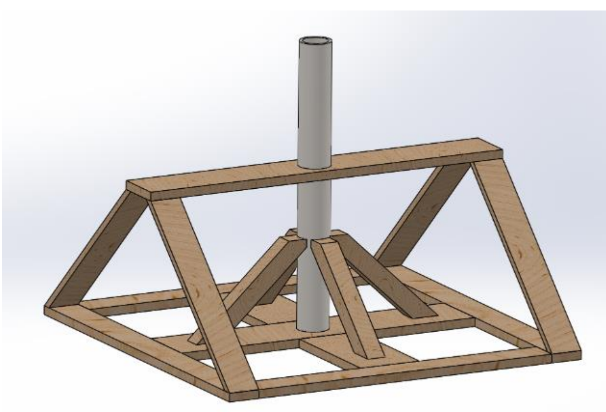
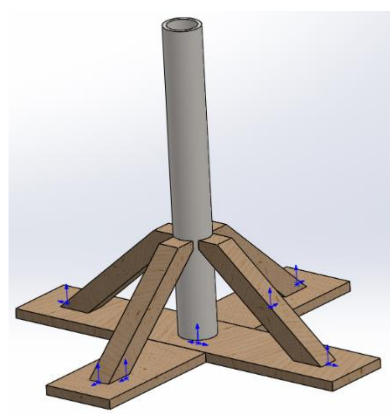



Figure 1 (left): Cross base with truss reinforcements

Figure 2 (right): Cross base with pole support beam

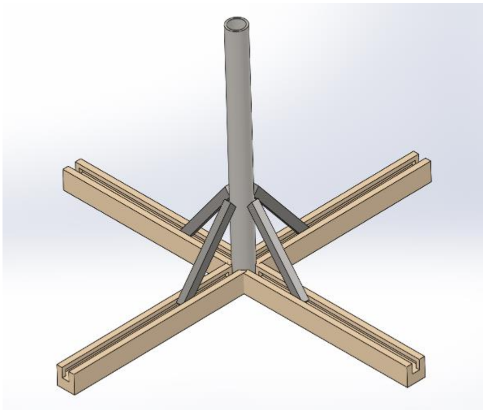
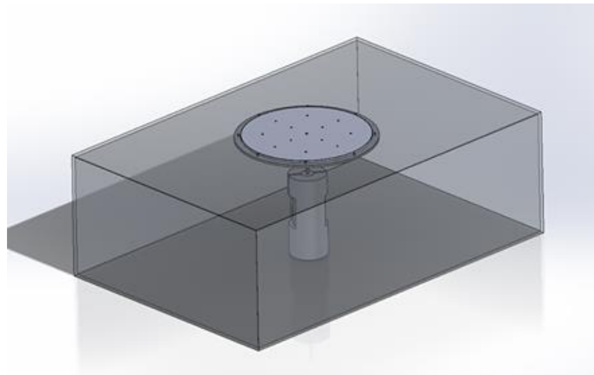
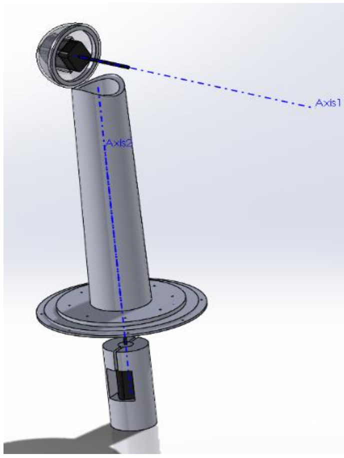
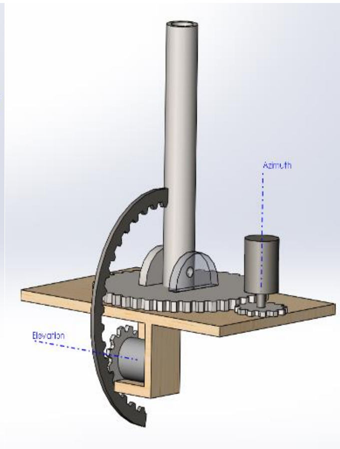
 

Figure 3 (left): Cross base with collapsible quadpod

Figure 4 (right): Box base

Next was the actuation system. The main consensus was to have two axes of motion, to control the azimuth (horizontal angle) and the altitude (vertical angle) of the antenna. Since control of these angles would require a change in angular position, electric motors were selected as the actuators that would be used to achieve the desired motions. One concept was to use a rotating platform driven by a motor to control the azimuth and a motor nested at the next joint (the elbow) to control the altitude, seen in Figure 5. The next concept uses a gear train to compensate for the torques that might be present in the system because of the large actuation systems. The azimuth is controlled by a gear and pinion while the altitude is controlled by a configuration like a planetary gear set, but with only the sun and outer ring, seen in Figure 6. The remaining designs are variations of coincident azimuth and altitude motors. Figure 7 is a system with one motor for azimuth and one for altitude which causes the platform mounted at the end to rotate with 2 degrees of freedom, which is interfaced with the antennae at the end. By orienting this platform as desired the antennae will also share that orientation as they have the same frame of reference. Figure 8 is the same concept however features two altitude motors to increase the torque as well as rotational accuracy. The final design in Figure 9 uses a rotator controller which is essentially same having a single azimuth and altitude motor with co-incident axes of motion, as it can control two degrees of freedom by itself.





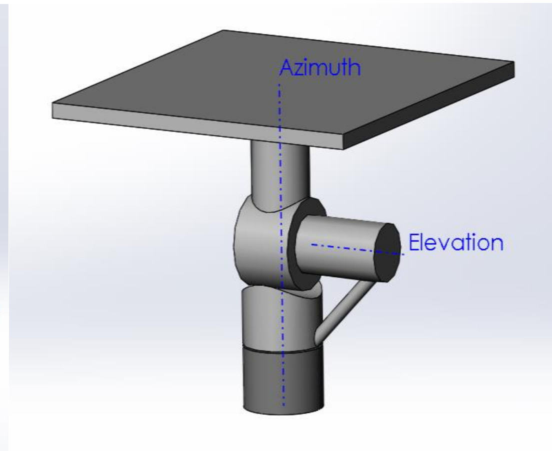
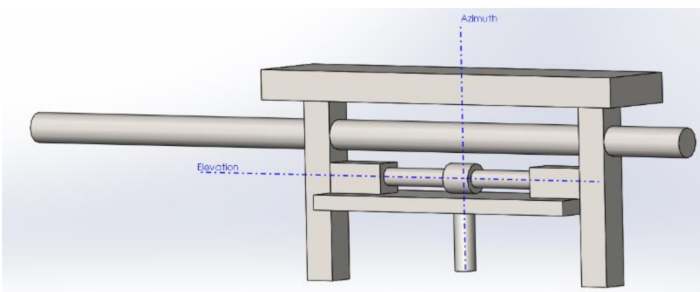


Figure 5 (left): Rotating platform with elbow motor

Figure 6 (middle): Motor and geartrain

Figure 7 (right): Single azimuth single elevation



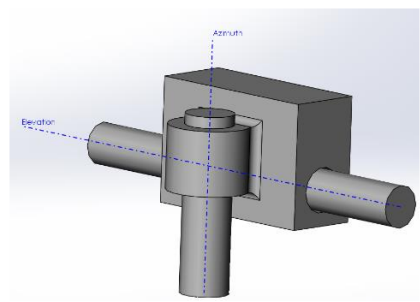
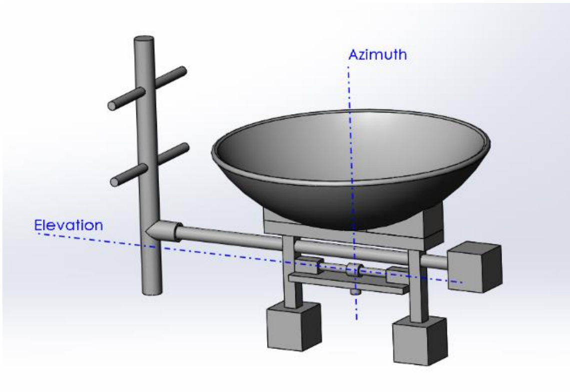


Figure 8 (left): Single azimuth and dual elevation

Figure 9 (right): Rotator controller

Finally, concepts were generated for the antennae placement of the parabolic dish and Yagi. The original concepts were for the ground station to have a configuration with both types of antennae mounted at the same time since this would eliminate the need to mechanically configure the ground station’s antennae type for the different communication frequencies; however, this idea was scrapped since this introduces unnecessary complexity to the design (these concepts are seen below in Figures 10, 11 and 12). The new concept is to have a universal interface between the ground station and antennae so that either the Yagi or parabolic dish antennae can be mounted as required.



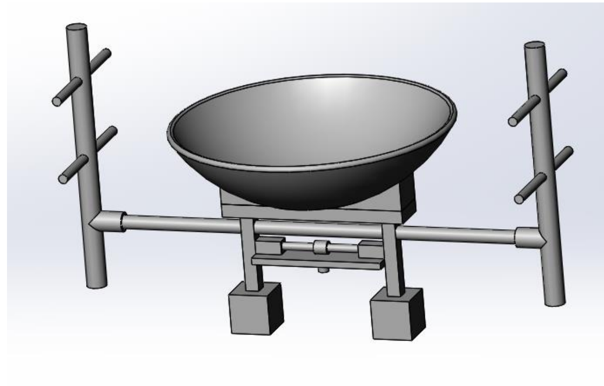


Figure 10 (left): Single yagi with counterweight

Figure 11 (right): Dual yagi

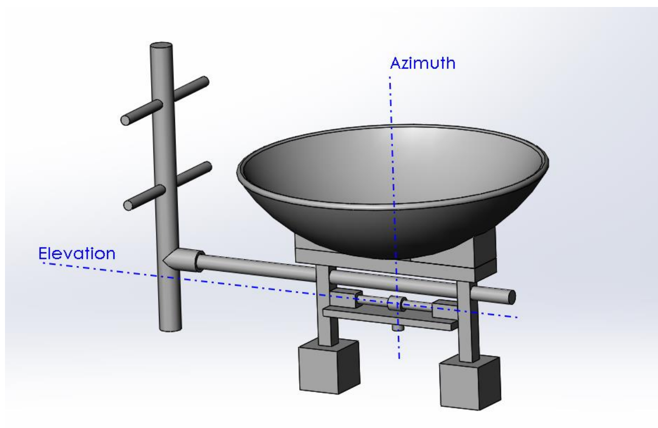


Figure 12: Single yagi with no counterweight

Concept Selection

When selecting concepts some main properties that we wanted to conserve needed to be stated. For the base design, the specifications were that it needed to be portable, easy to assemble, stable, rigid, robust, inexpensive, and implementable/realizable. Of these specifications the most important factors were rigidity, robustness and cost, which is reasonable because a design that is not rigid will fail under the significant load, a lack of robustness will leave it unable to operate in the wide range of operating conditions found outdoors and the cost should be limited so that the base can be built within the budget. For the actuation system the specifications were that the system be lightweight, accurate, high resolution, low complexity, low cost and implementable. From these specifications the most important were accuracy, resolution and implementation since a system that is not accurate and lacks good resolution will make data transfer between the satellite and the ground station difficult. Being implementable implies that the system can be designed, built and function as expected within reasonable expectations. Finally, the antennae placement design was decided on using a Go-No Go Matrix, with requirements of the placement being balanced, rotationally symmetric, portable, low cost, and implementable. The two best concepts were the single Yagi/parabolic dish with a counterweight for balance and the modular design which allows for the antenna type to be changed. The follow tables are the matrices used for making the decisions using the specifications.

Table 1: Decision matrix of base design specifications

	Portable	**Ease of Assembly**	**Stability**	**Rigidity**	**Robustness**	**Cost**	**Implementation**	**Total**	**Weight**
Portable	1	2	1	0.33	0.5	2	0.5	7.33	0.136
Ease of Assembly	0.5	1	1	0.5	0.5	0.5	1	4	0.074
Stability	1	1	1	0.75	0.5	0.5	0.5	5.25	0.098
Rigidity	3	2	1.33	1	1	1.33	1	10.66	0.198
Robustness	2	2	2	1	1	1.33	0.75	10.08	0.188
Cost	0.5	2	2	0.75	0.75	1	1.33	8.33	0.155
Implementation	2	1	2	1	1.33	0.75	1	8.08	0.150
							Total	**53.73**	**1**

Table 2: Results of evaluation of base design options with respect to Table 1

	Truss Base and Quadpod	**Truss Base with Outer Square and Truss Reinforcements, and Quadpod**	**Box Base**	**Only Tri- or Quadpod**
Portable	0	0	0.136	0.136
Ease of Assembly	0.074	-0.074	0	0.074
Stability	0	0.098	0.098	0.098
Rigidity	0.198	0.198	0	0
Robustness	0	0.188	0	-0.188
Cost	0	0	0.155	0.155
Implementation	0.150	0.150	0.150	0
Percentage	**42.2**	**56**	**53.9**	**27.5**

Table 3: Decision matrix of actuation system design specifications

	Lightweight	**Accuracy**	**Resolution**	**Complexity**	**Cost**	**Implementation**	**Total**	**Weight**
Lightweight	1	0.33	0.33	1	0.75	0.5	3.91	0.097
Accuracy	3	1	1	2	1.33	1.33	9.66	0.240
Resolution	3	1	1	1.33	1	0.75	8.08	0.201
Complexity	1	0.5	0.75	1	0.75	1	5	0.124
Cost	1.33	0.75	1	1.33	1	0.75	6.16	0.153
Implementation	2	0.75	1.33	1	1.33	1	7.41	0.184
						Total	**40.22**	**1**

Table 4: Results of evaluation of actuation system design options with respect to Table 3

	Rotating Platform and Motor at Top of Pole	Single Azimuth/ Elevation at Top of Pole	Single Azimuth and Dual Elevation	Rotator Controller	Motor and Gearbox
Lightweight	0.097	0	-0.097	0.097	0.097
Accuracy	0.240	0	0.240	0.240	0
Resolution	0	0	0.201	0.201	0
Complexity	-0.097	0.124	0	-0.124	-0.124
Cost	0	0.153	-0.153	-0.153	0.153
Implementation	0	0.184	0.184	0.184	0
Percentage	**24**	**46.1**	**37.5**	**44.5**	**12.6**

Table 5: Go/No Go Screening for antennae placement options

	Balance	Rotational Geometry	Portability	Cost	Implementation	Overall
Parabolic in Centre with Yagi on Side, with Opposing Counterweight	Go	No Go	Go	Go	Go	**Go**
Parabolic in Centre with Yagi on Each Side	Go	Go	No Go	No Go	No Go	**No Go**
Parabolic on one Side, Yagi on the Other	No Go	No Go	No Go	Go	Go	**No Go**
Modular (Antennae Replacement)	Go	Go	Go	Go	Go	**Go**

From Table 2, the best concepts were the truss base with square reinforcements and quadpod, as well as the box base. Since the box base is hollow the two designs were used together, with the truss base being placed within a box base to enclose and protect all the electronics. Additionally, the truss base adds stability and rigidity to the box, which is why the two designs are used in tandem. For the actuation system, the single azimuth and altitude and rotator controller came very close to each other, which is expected as the two operate similarly. The separate motors design was selected as it is marginally easier to implement as for the rotator controller proprietary software and controls need to be implemented to get the desired operation, which is unnecessary added complexity. Finally, for the antenna placement the top designs were the single Yagi with a counterweight and the modular design. After discussion with the design panel and our project advisor, it was realized that having both antennae mounted at the same time served no real purpose as only one satellite would be in orbit at a time and only the antenna functioning in the same frequency band as the CubeSat in orbit would need to be used. For this reason, the modular design was selected and is still low maintenance as the antennae change would only need to be conducted when a new satellite is launched that operates at a different radio frequency.

Final Design

The final design combines the base, actuation system, and antennae placement designs that were chosen with the use of the decision matrices. The final design with the dish and the Yagi antenna can be seen in Figures 13a and 13b respectively. Telescoping poles are to connect the base to actuation system to provide more rigidity, as seen in Figure 14.

Figure 13a (left): Final design with parabolic dish antenna

Figure 13b (right): Final design with Yagi antenna

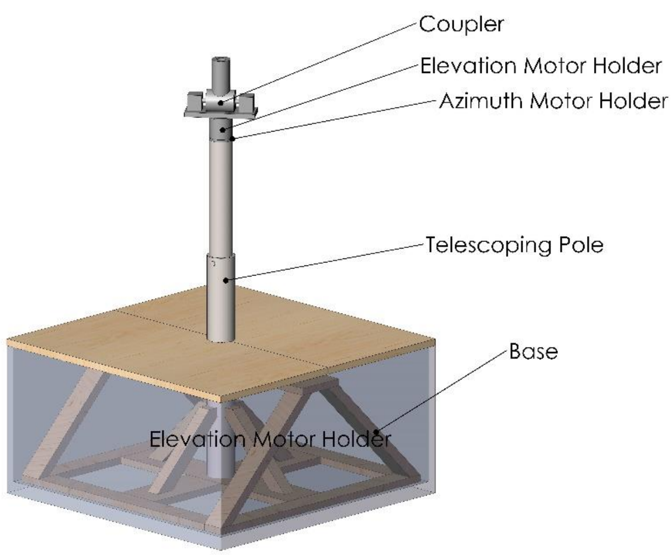


Figure 14: Detailed view of base and connection system

For the final actuation system subassembly, silicon nitride ball bearings were added to the azimuth motor holder. These allow the entire top platform to rotate while the motor and the platform below remain stationary. The elevation coupling also rests on ball bearings. The boxes on the sides of the coupling are placeholders for the motor. The motor holder on one side and a round bearing used to hold the motor shaft on the other side. These features can be seen in Figure 15.

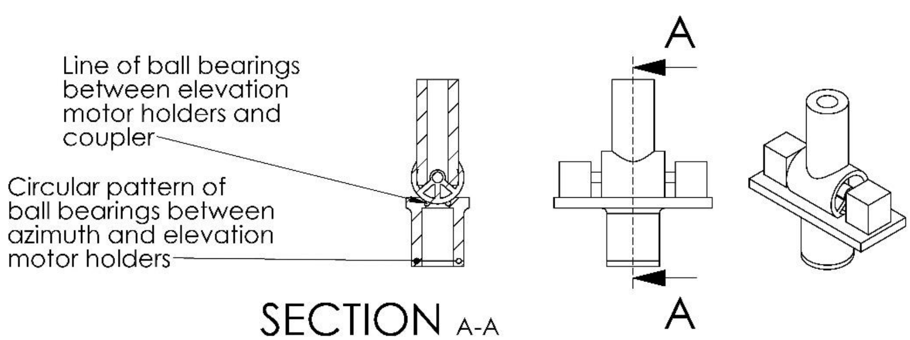


Figure 15: Ball bearings of elevation coupling

Currently, the material selected for the base (Figure XX) is wood as it is inexpensive, dense, and easier to machine than metal substitutes. However, steel, or other metal extrudes might be used if the base is not sufficiently heavy to be stable. The material selected for the telescoping pole is aluminum 6061 due to its high strength to weight ratio and resistance to corrosion. Medium carbon steel (AISI 4140) was selected for the azimuth and elevation motor holders, coupling, and antenna pole as it has a high yield strength and will not deform under the load of the dish.

Conclusion

Thus far, the preliminary design of the mechanical system of the ground station has been completed, with the selected base, actuation system and antenna placement concepts which should allow for the ground station to effectively track the satellite in space. The base is effective in sustaining large loads and by incorporating the encasement aspect, it should also require low maintenance. The actuation system operates the two main axes of motion and thus should allow for accurate pointing and the modular antennae design removes the added complexity of using dual antennae. Additionally, with the background research, material selection and scaling completed, further mechanical simulations and testing can be performed, and the actuator and sensor selection process can proceed. Further iterations will build on the principle choices made to date and ideally will not require any major redesigns or decision reevaluations.

References

[1] A. Mehrparvar, CubeSat Design Specification, 13th ed. California Polytechnic State University, San Luis Obispo, California, 2014. Available: https://static1.squarespace.com/static/5418c831e4b0fa4ecac1bacd/t/56e9b62337013b6c063a655a/1458157095454/cds_rev13_final2.pdf [Accessed: October 18, 2018]

[2] J. Keesee, “Ground System Design”, Massachusetts Institute of Technology, 2004.

[3] M. Khedkar and G. Dhole, A Textbook of Electric Power Distribution Automation, 1st ed. New Delhi, India: Laxmi Publications, Ltd., 2010, pp. 34-36.

[4] NASA, "An Introduction to National Aeronautics and Space Administration Spectrum Management", 2016. Available: https://www.nasa.gov/sites/default/files/atoms/files/spectrum_101.pdf [Accessed: November 2, 2018].

[5] J. Volakis, Antenna Engineering Handbook. [S.l.]: McGraw-Hill Education, 2018.

[6] A. Hughes and W. Drury, *Electric Motors and Drives: Fundamentals, Types and Applications*, 4th ed. Newnes, 2013.

[7] "Radiocommunication Devices", Government of Canada, 2018. [Online]. Available: https://www.ic.gc.ca/eic/site/smt-gst.nsf/eng/sf08655.html [Accessed: November 11, 2018].

[8] O. Montenbruck, "Kinematic GPS positioning of LEO satellites using ionosphere-free single frequency measurements", German Space Operations Center, Wessling, 2003. Available: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.578.4609&rep=rep1&type=pdf [Accessed: October 15, 2018].

[9] N. Ertugrul and P. Acarnley, "A New Algorithm for Sensorless Operation of Permanent Magnet Motors", IEEE, 1994. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=273630 [Accessed: October 4, 2018]

[10] "Angle sensors, potentiometers, rotary encoders | MEGATRON", 2018. [Online]. Available: https://www.megatron.de/en/category/angle-sensors.html. [Accessed: October 26, 2018].