ENABLING LOW-COST DIRECTIONAL COMMUNICATION BY NADIR POINTING USING PASSIVE MAGNETIC STABILIZATION

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ABSTRACT

The demand on data throughput performance of CubeSats has been steadily increasing. While higher frequency RF communication provides a higher data rate it also often requires a highly directive antenna, which in turn requires the satellite antenna to be pointed towards the ground station. An addition of an attitude control system for antenna pointing purposes is often a big burden on the satellite in terms of volume, power consumption and cost. One solution to providing low-cost, passive attitude control is to use a permanent magnet in orienting the satellite. When a satellite or a payload needs to face a certain direction however, passive magnetic stabilization cannot provide that pointing capability as the satellite attitude will depend on the local direction of the magnetic field, which may or may not align with the desired direction of pointing. While passive magnetic pointing may not provide an accurate antenna pointing capability, its simplicity and effectiveness merit a closer investigation. This study describes how a passive magnetic stabilization can provide antenna pointing capabilities to satellites making contact with ground stations located at higher latitudes. This pointing enables low cost CubeSats to implement higher-gain, directional antennas without implementation of a high-cost attitude control system.

1 INTRODUCTION

The demand on data throughput performance of CubeSats has been steadily increasing. This is also reflected in growing numbers of S- and X-band transmitters being commercially available for purchase. While higher frequency RF communication provides a higher data rate, it also negatively affects the ability to close the link. Since small satellites are often limited in power generation capability, a good balance between the increase in transmitted power and increasing antenna gain must be considered. An increase in antenna gain means a highly directive antenna, which in turn requires the satellite antenna to be pointed towards the ground station antenna. Less complex satellites, typical of educational CubeSats, often employ simpler omni-directional antenna designs and do not have the ability to point their antennas. An addition of an attitude control system for antenna pointing purposes is often a big burden on the satellite in terms of volume and power consumption, increasing cost, and often simply is not a feasible option. For university-level CubeSat developers with tighter budget, an off-the-shelf attitude control system cost can double or triple the overall satellite cost.

This constraint also applies to the United States Naval Academy (USNA)'s CubeSat program. The Naval Academy Small Satellite Program is focused on training and educating the future leaders in satellite technology at an undergraduate level, and thus a hands-on component of engineering project experience is a critical part of the program. USNA student projects result in one CubeSat launch a year on average. This means that the satellite system cannot be overly complex and cannot be high in cost to develop. Accordingly, USNA CubeSats have not implemented a reaction wheel assembly for attitude stabilization and control. As CubeSats are getting pushed into higher frequency ranges for their RF communication in the recent years, however, a different low-cost method for pointing the directional antennas is needed to meet the increased performance demands while keeping the resource requirements low. This is the main motivation behind conducting this research.

Two main categories of attitude control methods are passive and active attitude control. Active methods for attitude stabilization can vary from relatively simple system such as magnetorquers to complex and costly options such as control-moment gyros. If a pointing capability is desired, the system must have attitude determination sensors and actuators that can control the satellite in all three axes. Thus, for antenna pointing operations, an expensive attitude control system is required that is also highly demanding in satellite system resources. Passive attitude control options include permanent magnets, gravity gradient booms, and aerodynamic surfaces. While these methods provide rudimentary attitude stabilization for satellites, they are not adequate for CubeSat pointing operations, and thus have not been used in the past for antenna pointing on a CubeSat.

Aerodynamic pointing will provide a relatively stable attitude with an axis pointed in the velocity vector, providing a way to orient the satellite perpendicular to the ground station. However, this method cannot control which of the axis orthogonal to the velocity vector will be facing nadir, thus cannot be used for reliable antenna pointing. A different method using a gravity gradient boom can provide nadir pointing capabilities to satellites. However, this method still requires some form of active control element either from an onboard active control system or from the ground to ensure that the correct side of the satellite is pointed towards the ground. As the boom deploys and orients itself vertically, an equal chance exists for either end of the boom to point nadir. A combination of different methods such as combining aerodynamic control and gravity gradient boom will increase the stability of the satellite but is still not adequate to perform antenna pointing. An example of a hybrid passive-active method for satellite pointing without a full-scale reaction wheel was analyzed by University of Michigan where an active magnetic control was coupled with a passive aerodynamic stabilization in achieving satellite attitude control [1].

One solution to providing low-cost, passive attitude control is to use a permanent magnet in orienting the satellite. Use of permanent magnet onboard CubeSats is a popular choice for passive attitude control. The method that is most often used is to use multiple permanent magnets aligned in the same direction, coupled with damping rods made of hysteresis material to provide rotational damping. There are many examples of university satellites using this method. An example is KySat-1 which included 24 small permanent magnets installed along its rails, along with HyMu80 sheet metal strips for magnetic damping [2]. University of Michigan also implemented the similar method on their satellites in the past (RAX CubeSat, for an example [3]). On a larger, small-satellite scale, UNISAT-4 used the similar setup of permanent magnets and hysteresis rods combination for passive attitude stabilization [4]. Predicting the expected performance of magnetic hysteresis material is not trivial, but there have been many studies that have characterized the on-orbit magnetic damping properties of these hysteresis bars and strips through simulation and experiments. A few of these examples include [5]–[8]. While this method is used often in CubeSats and some small satellites that operate on a lower budget for attitude stabilization, passive magnetic pointing methods have not been adapted for antenna pointing due to the short comings described above. Mainly, the permanent magnet onboard the satellite will always orient itself along the local magnetic field line, which may not be in the direction of the ground station, not allowing the satellite communication system to close the link with the ground station.

While passive magnetic pointing may not provide an accurate antenna pointing capability, its simplicity and effectiveness merit a closer investigation. In particular, the geomagnetic north pole is tilted away from the geodetic north pole in a way that the local magnetic field line in LEO may provide enough pointing torque for directional antennas to do rough pointing. Study of the Earth's magnetic field lines in LEO near the east coast of North America reveals a possible passive-magnetic pointing solution that may enable the satellites to be able to point towards a ground station without requiring any active control. Taking into consideration the latitude of the U.S. Naval academy, a magnetically stabilized satellite can point its antenna close enough (within 30 degrees) to nadir to keep the ground station within a typical beam width a patch antenna [9]. This pointing enables low cost CubeSats to implement higher-gain, directional antennas without implementation of a high-cost attitude control system. This paper describes the expected data throughput performance of notional communication system as implemented on a passive-magnetic pointing 3U CubeSat. The analysis is performed at both USNA ground station and a notional ground station at Vilamoura, Portugal (where 4S Symposium 2022 is held) for comparison.

2 PASSIVE MAGNETIC ANTENNA POINTING

Pointing of directional antenna towards ground station can be achieved using passive magnetic stabilization alone under the right circumstances, as briefly discussed previously. More detailed discussion and analysis can be found in [9], and is summarized in the following section.

2.1 Description of Antenna Pointing Methodology

Normally, satellites utilizing a permanent magnet onboard for attitude stabilization is considered to be oriented perpendicularly to the nadir direction following the local magnetic field lines, especially for satellites passing through lower latitudes. In this scenario, it is mostly impossible to have a directional antenna that is body-mounted on a typical CubeSat to be aimed towards nadir as the satellite spin about the dipole axis cannot be controlled. Fig 1 shows a depiction of this limitation where the rotation about the x-axis cannot be controlled, and thus antenna pointing perpendicular to the axis cannot be controlled.

The situation changes for satellites in orbit, however, especially for at higher latitudes. This is due to the fact that magnetic field lines come together at the magnetic North and South Poles, near the geodetic poles. As the magnetic field line deviates away from local horizontal axis and points closer to "towards the ground" at higher latitudes, satellites with passive magnetic attitude stabilization also point more towards nadir as the x-axis shown in Fig 1 aligns with the local magnetic field. This phenomenon is depicted in Fig 2 [10]. As can be seen in the figure, satellites at a higher latitude starts to point more towards nadir direction. Satellites with passive magnetic control can mount a directional antenna on its dipole axis (x-axis in Fig 1), and can make contacts with ground stations located at higher latitudes.

The research presented in this paper analyzes the communication capability and performance of a notional 3U CubeSat utilizing this passive antenna pointing method. For the analysis, a performance parameter off-nadir angle is defined as the angle between the local dipole axis and the local nadir axis, as shown in Fig 3.

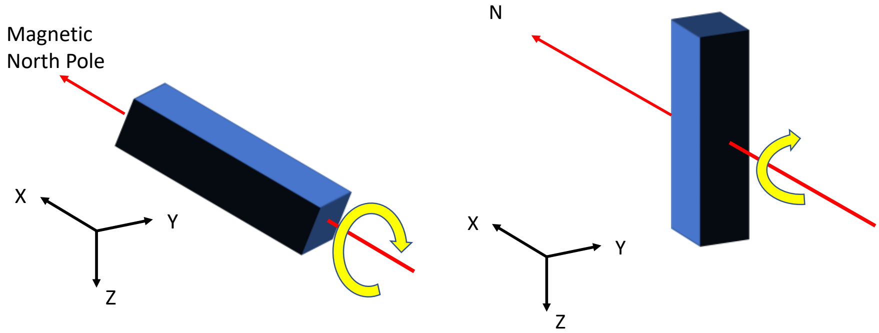

Fig 1 Depiction showing free rotational axis for passive magnetic attitude control.

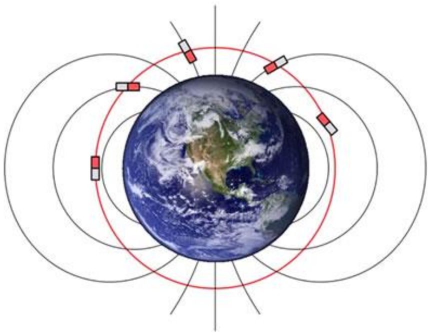

Fig 2 **Depiction of magnet**ic dipole in orbit following the local magnetic field line [10].

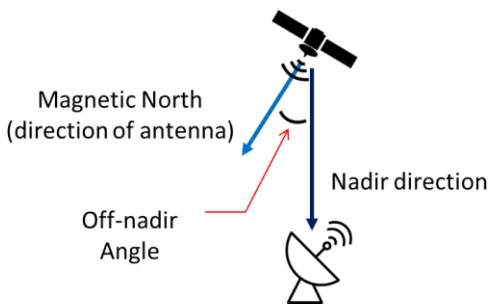

Fig 3 Graphical definition of off-nadir angle.

2.2 Variation of Off-nadir Angle by Location

Calculation of the local off-nadir angle is complicated by the fact that the geomagnetic latitudes do not align with the geodetic latitudes. The geomagnetic field also is constantly shifting, so the local off-nadir angle will vary depending on the location, altitude, and time. A snapshot of the geomagnetic latitude in year 2000, as show in Fig 4, illustrates this clearly. As can be seen, the actual local magnetic field lines vary depending on the location. It is interesting to note the “dip” in the geomagnetic line near the Americas. This signifies that for satellites attempting to make contacts with ground stations located in North America, particularly the East Coast, will have an advantage in being able to orient more towards the nadir direction as the local geomagnetic latitude which determines the off-nadir angle, is higher (better) for the given geolocation of the ground station.

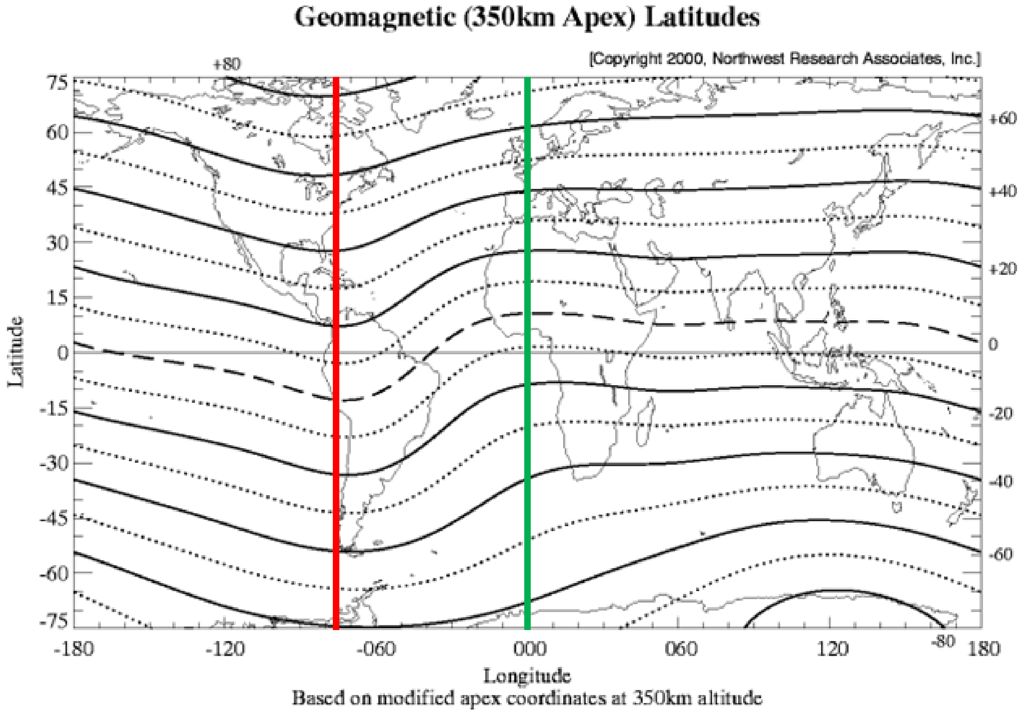

Fig 4. Mapping of geomagnetic latitudes based on modified apex coordinates at 350km altitude [11].

2.3 Satellite Configuration

For the performance analysis, a typical 3U CubeSat configuration was considered. Orbit chosen for this analysis was 400 km circular orbit with inclination of 98.7°. This yields an orbital period of 92.5 min. The satellite is also assumed to have a patch antenna mounted on the +X side that is aligned with the dipole axis, as shown in Fig 1. A half beamwidth of 60° is assumed for the patch antenna. An example antenna beam pattern is shown in Fig 5. Integrating a permanent bar-magnet along the long axis yields a magnetic dipole of approximately 2.5 $A \cdot m^2$. Appropriate levels of damping can also be achieved with two strips of thin film hysteresis rods along the two short axes [9]. Simulations also showed that this magnetic dipole produces torques that are orders of magnitude higher than other disturbance torques at this altitude. With this setup, the satellite can detumble from 15°/s body rates in all three axis to less than 0.5°/s body rates within 40 min [9]. The steady-state pointing accuracy where the dipole axis is aligned with the local magnetic field throughout the orbit is shown to be less than 1° [9], thus the satellite's dipole axis (long-axis of the notional 3U CubeSat) is assumed to be always aligned with the local magnetic field. This analysis result is plotted in Fig 6. The red circles represent the times when the satellite is actually in view of the ground station, assuming the ground station located at USNA. When the satellites are in view of USNA, the local magnetic field rate of change is relatively small such that the pointing/tracking error is less than 0.5°. Power analysis was also performed to ensure that the body-mounted solar panels can supply adequate amount of power to the satellite communication system. Assuming 2.5 W of steady power consumption for the satellite bus, and 20 W of power consumption for the radio transmitter, a typical 3U CubeSat in the described orbit is able to remain power-positive over a two-year mission life with 900 s of contact time per day, which is shown to be less that the actual contact time in this study, as described in the following sections.

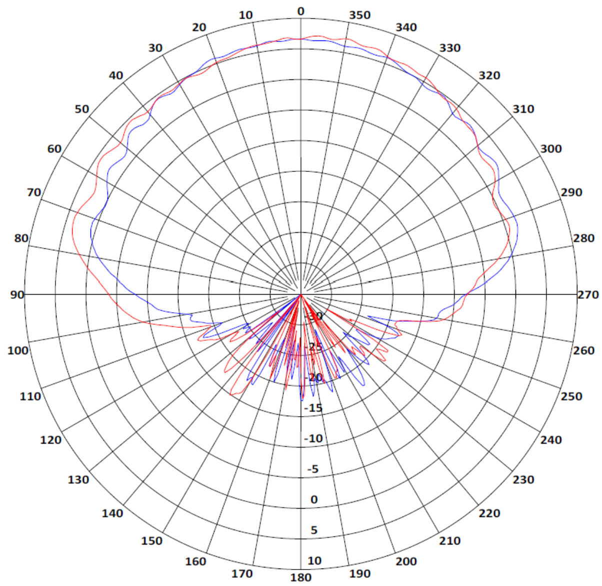

Fig 5 Gain vs. angle plot of Haigh-Farr's X-band patch antenna at 8.25 GHz (credit: Haigh-Farr).

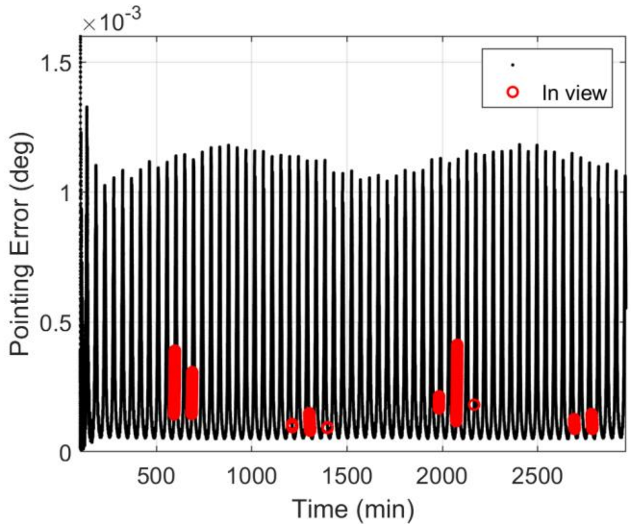

Fig 6 Dipole-axis pointing error over multiple orbits.

3 PERFORMANCE ANALYSIS FOR NOTIONAL GROUND STATION AT VILAMOURA, PORTUGAL

3.1 Antenna Pointing Performance

To quantify the antenna pointing performance, the local down-tilt angle (angle towards nadir from local horizontal) values are tabulated in Table 1. For this analysis, a notional date of 19 June 2024 and an altitude of 400 km were chosen. Analysis showed that the geomagnetic field lines do not vary much in LEO for changes in altitude (only 1 or 2º), thus other altitudes were not considered in order to scope the analysis. From these inclination angles (defined as the down-tilt angle), the off-nadir angles were calculated. The resulting off-nadir angles for northern latitudes at various locations are shown in Fig 7. Longitude of -76.29 °E aligns with the ground station at the U.S. Naval Academy, and 0 °E aligns with Prime Meridian, which is 8.1188° east of Vilamoura, Portugal.

Table 1 Local magnetic field direction at various geodetic longitudes.

Geodetic Latitude (°)	Inclination (degrees down from local horiz.) @ Long = 0°	@ Long = -76.29 ° E
0	117	71
5	106	63
10	93	56
15	81	49
20	69	44
25	59	39
30	50	34
35	42	30
40	35	27
45	30	24
50	25	21
55	21	20
60	18	20
65	15	21
70	12	25
75	9	30
80	7	37
85	4	47
90	7	69

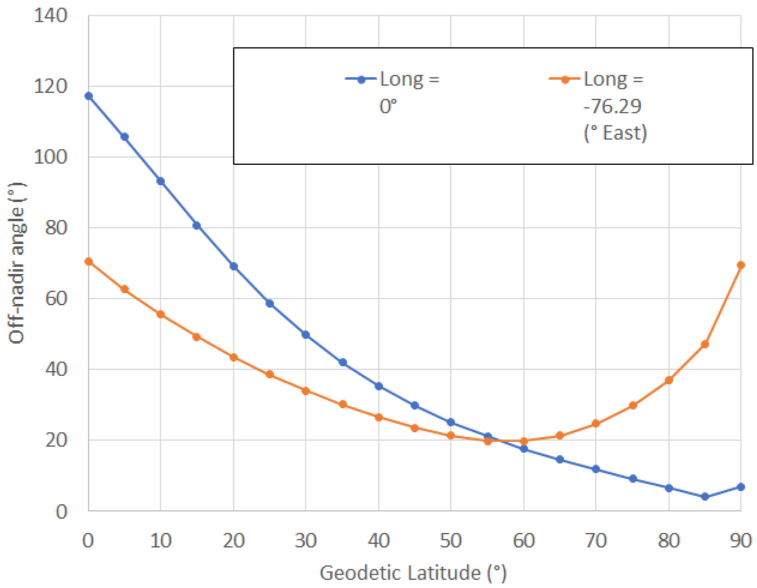

Fig 7 Off-nadir angles for three geodetic longitudes.

For Vilamoura, Portugal (37.0881°N, 8.1188°W), an off-nadir angle of 39° can be achieved for satellites utilizing a completely passive magnetic pointing. This means that when the satellite is directly overhead of the notional ground station Vilamoura, the satellite's directional antenna will be pointing 39° away from nadir. As the satellite passes over the ground station in a sun-synchronous orbit, as assumed in this study, the antenna will be tilted towards north. This means that when the satellite is located south of the ground station, the communication link will benefit from the off-nadir angle, and will be in full view of the 60° half-beamwidth of the patch antenna. Conversely, when the satellite is located to the north of the ground station, the patch antenna will point away from the ground station, and the beamwidth footprint will quickly move away from the ground station, breaking the contact well before the satellite reaches the northern horizon. An example of this is illustrated in Fig 8, which shows a south-to-north pass. The dotted lines represent when the satellite is below the horizon. As soon as the satellite rises above the horizon, the antenna is tilted towards the ground station, and contact can be made immediately, represented by the circles. The satellite then makes its closest approach to the ground station at around 2486 min mark, then starts to move away in northerly direction. As can be seen, the ground station quickly moves out of the beamwidth of the satellite and is assumed to have lost contact, well before the satellite disappears over the horizon.

The contact time will vary from pass to pass. And due to this northern tilt of the antenna, some of the passes do not yield in a usable contact with the ground station. Therefore, a total usable contact time per 24 hr period was used instead to quantify the overall satellite link performance. When analyzed over multiple days, a 3U CubeSat with passive magnetic pointing was averaging 718 s of contact time per day over Vilamoura.

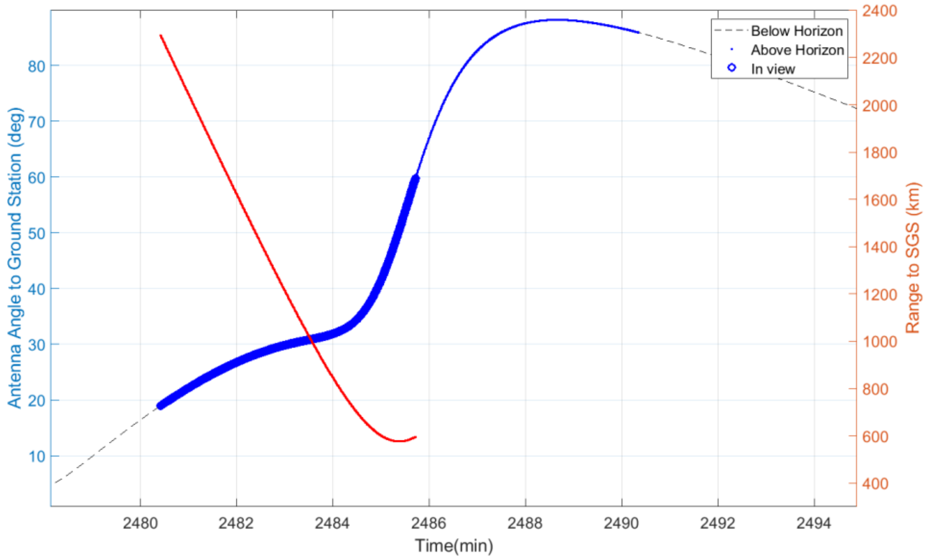

Fig 8 Example satellite pass over the notional ground station at Vilamoura, Portugal.

3.2 Data Throughput Performance

Assuming a typical 3m parabolic dish antenna, a link analysis was also performed (link budget analysis was performed in [9]). For the available 20 W of transmitter power, 2 W of actual transmitted power was assumed. The link performance analysis result is tabulated in Table 2. Assuming a transmitter antenna gain of 2 dBi for the entire beamwidth, the 3U CubeSat in this study can achieve conservative data rates of 90 kbps for S-band and 15 kbps for X-band communication. This transmission corresponds to 8.3 MB of data downlinked per day for S-band implementation and 1.4 MB of data for X-band communication. An average time-in-view for the satellite is 2,200 s per day. If the satellite was using a 9.6 kbps UHF transmitter with an omni directional antenna, the total data throughput per day would be 2.6 MB. This comparison shows that as CubeSats and small satellites are pushed out of the VHF/UHF bands, there exists a potential for an implementation of higher-frequency communication on the satellites, even with the requirement for directional antennas, without requiring an active attitude control system.

A comparison of predicted performance with the USNA ground station is shown in Table 2. The difference in performance is due to the advantage of North American ground stations with favorable geomagnetic field lines, as described in Section 2.2. As can be seen, satellites flying over USNA is able to make longer contacts, and thus able to download more data.

Table 2 Link performance results.

Parameters	Vilamoura GS	U.S. Naval Academy GS
Longitude (°E)	-8.12	-76.29
Latitude ((°N)	37.09	38.99
Off-nadir Angle (°)	39	28
Contact Time per Day (s/day)	718	820
S-band Data Downlinked (MB)	8.1	9.2
X-band Data Downlinked (MB)	1.3	1.5

4 CONCLUSION

In the past, lower frequency communication using VHF and/or UHF bands has been popular among CubeSat and small satellite community, especially for the project teams with limited resources. The omni-directional antennas that often accompany these communication systems removed the requirement for active attitude control systems, which can be a significant draw on system resources and can often be cost prohibitive. With the recent desire, and push, to move to higher frequency bands, a revisit to passive means of antenna pointing is merited.

A passive magnetic attitude stabilization has been widely used in the past by CubeSat and the small satellite community, but it has not been considered as an antenna pointing method as the rotation about the dipole axis cannot be controlled. For higher latitude ground stations, however, it can provide a means for pointing directional antennas towards the ground station. This study showed that a notional 3U CubeSat can make contact with a notional ground station located Vilamoura, as an example, with a directional patch antenna. With this configuration, either S- or X-band radios can be used to close the link with the ground station, and able to transfer a few MB worth of data per day, depending on the chosen orbit. The important thing to note is that the satellite is able to point its antenna towards the ground station and make a contact without any active attitude control. In case of the 3U CubeSat assumed in this analysis, the satellite also does not need deployable solar panels to support a 20 W transmitter to accomplish this. This is a significant reduction in required satellite resources in power, weight, and cost.

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