A Large Aperture Modulated Retroreflector (MRR) for CubeSat Optical Communication

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ABSTRACT

Free space optical communications offers high bandwidth secure communications in an unlicensed spectrum. Enabling a CubeSat with an optical communication link is challenging due to the strict stabilization and pointing requirements brought forth by the inherently narrow optical beam; solutions are often complex and costly. A modulated retroreflector (MRR) is a low power device and, by design, has a large field-of-view thus relaxing the stabilization requirements of the bus. Traditionally, MRRs have been small in area and ill-suited for long range communication links. In this paper we discuss the feasibility of enabling optical communications on a CubeSat and modeling of an increased aperture MRR for CubeSats. We also discuss the alternative MRR implementation tradeoffs and a supporting bus design for an MRR payload.

INTRODUCTION

The advent of sophisticated sensors brings with it an ever growing volume of data that in turn creates an unsatisfied need for higher bandwidth communications. In addition to bandwidth, military applications typically require low probability of intercept and detection (LPI/LPD) and low size, weight and power (SWaP). Radio Frequency (RF) communications are rapidly approaching a bandwidth limit whereby the radio frequency spectrum is overcrowded and has reached capacity for new users. Free-space optical links are finding increased usage for commercial and military systems and have the potential for higher bandwidth, use smaller antennas, lower SWaP , increased directivity of EM radiation, and increased security. An optical communication link also enables anti-jam (A-J) and LPI/LPD communications. The narrow divergence and high bandwidth of optical beams enable point-to-point data links at rates exceeding 1 Gigabit per second (Gbps). These features are inherent in the short wavelength of optics but often require high-quality telescopes with extremely accurate pointing and tracking at both ends of the link.

There is a growing interest in the use of small, less complex, low-cost, rapidly deployable satellites to carry out rapid response missions that traditional large and complex satellites cannot satisfy. The capabilities of these small satellites are limited by SWaP, particularly for high-bandwidth communications. Concerns with current satellite RF communications systems include bandwidth bottleneck, vulnerability to jamming, and high power requirements. Optical communications on a cube satellite (CubeSat) [1] is a new frontier that needs to be explored although there has been minimal research directed towards it.

Recently, several continuing efforts have been conducted to enable small satellites with optical communication capabilities. One example for demonstration of optical communications at 1 Megabits per second (Mbps)is being developed at Tokyo University on a 50kg-class satellite named

RISESAT. RISESAT will be stabilized to a tenth of a degree and use body pointing to aim the laser [2]. A second example by The Aerospace Corporation is a laser communication system for NASA that fits in a 1.5U CubeSat and is capable of 5Mbps and up to 50Mbps. The system utilizes a suite of onboard sensors and, when available, an uplink beacon to improve pointing accuracy to tenths of a degree. The project goal is to demonstrate state of the art in CubeSat body pointing/stabilization and laser technology [3].

In this paper we investigated an MRR as a low SWaP optical communication solution for a CubeSat. We examined the feasibility of an optical downlink from low earth orbit (LEO) to a ground station on earth. The feasibility study assessed Modulated Retroreflector (MRR) technology to provide wide bandwidth optical communications. We found that a critical path in implementing an MRR communication system was the size of the MRR; as this affects the amount of signal returned, a vital parameter over any link distance. We also found that due to the intrinsic optical properties of an MRR and the size restrictions of a CubeSat, increasing the effective aperture of an MRR was not as simple as using a larger MRR. For this paper we considered some of the tradeoffs associated with increasing the aperture of an MRR.

MRR TECHNOLOGIES

An optical retroreflector returns laser light back to the originating source when illuminated by a laser. Unlike a mirror, a retroreflector is not angle dependent, has a large field of view (typically 10s of degrees), and is insensitive to platform jitter. The full angle divergence of the returned beam from an ideal retroreflector is diffraction-limited and is defined by the diameter of the central disk of the Airy pattern [4]:

$$\theta = 2.44\frac{\lambda}{D} , \qquad (1)$$

where λ is the wavelength of light and D is the diameter of the retroreflector aperture. For a 1cm retroreflector and a 1µm laser, the full angle divergence of the central disk is 244µrad. The peak intensity of the central disk is

$$I_0 = \left(\frac{\pi D^2}{4\lambda R}\right)^2 I_i \qquad (2)$$

where R is the range from the retroreflector to the observation plane and I_i is the intensity incident on the retroreflector. MRR systems combine an optical retroreflector with an optical modulator to intensity modulate the retroreflected laser beam back to the interrogator source, thus allowing the MRR to function as an optical communications device without emitting its own optical power. Beside its pointing agnostic optical property, an MRR is a low-power device that reduces the SWaP requirements on a remote platform (CubeSat) while retaining the inherent security of a conventional optical communications link.

An MRR communication link consists of an interrogator side and a remote side. The remote side has the MRR system on it and is typically passive (no optical radiation source) and requires only crude pointing. The MRR is driven by a modem that converts data to a modulation format. The remote side also has a photodetector, which enables a bidirectional optical communications capability. The remote side is simple compared to the interrogator side; low mass and requires little power.

The interrogator side bears the burden of the majority of the SWaP, as it requires a laser and active pointing. The interrogator consists of a continuous wave (CW) laser and optics to set the beam divergence, a separate and often large telescope coupled with a photodetector used to receive the retroreflected laser signal, a modem to demodulate the received signal, and a pointing and tracking system to acquire the remote side and maintain track [5]. Figure 1 shows a high level diagram of an MRR communication system.

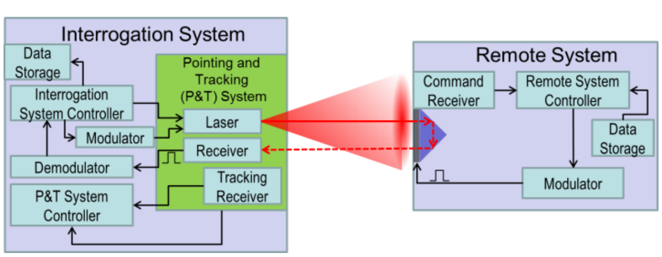

Figure 1: Modulated Retroreflector System Architecture.

There are several common designs for an MRR and each has its tradeoffs in terms of communication performance, aperture size, and ruggedness. For solid corner cube-based MRR systems, the MRR modulator must be the same size as the entrance face of the corner cube which is generally about 1 cm. The Naval Research Lab (NRL) has developed and successfully demonstrated a modulator based on a multiple quantum well (MQW) design. The device has only been demonstrated for terrestrial links, but testing predicts minimal performance degradation in a space environment [6]. By modulating the absorption band of the MQW structure, a narrow bandwidth laser will either transmit or be absorbed through the MQW. The modulation bandwidth is limited by the RC time constant of the modulator, which limits the bandwidth of these MRRs to a few MHz [7].

Another type of retroreflector called, a cat's eye, consists of focusing optics and a reflective surface in the focal plane. For MRR systems based on cat's eye optics the modulator is placed at the focal plane of the optical system and can be much smaller than the size of the collecting optics. Smaller modulators can have a higher modulation bandwidth over larger modulators of the same design because of the reduced resistance-capacitance RC time constant. However, the field of view of the cat's eye systems is much smaller than a solid corner cube (~5º-10° vs. ~45º) and in turn requires better pointing of the MRR towards the interrogator. Additionally, the optical design is generally complex and has tight tolerances; therefore the thermal properties of the optical system must be carefully considered [8].

For MRR systems based on a hollow retroreflector, one of the three mirrored faces is replaced with a modulator. The modulator could be an absorptive/transmissive device or a diffractive/reflective element. Micro-Electro-Mechanical Systems (MEMS) devices are an example of a diffractive/refractive element and can be electrically actuated to form a grating or a flat mirror. The modulation bandwidth of MEMS devices is ultimately limited by the resonance of the mechanical structure which occurs at a few hundred kHz. However, the contrast ratio from the MEMS grating suffers substantially as the modulation speed approaches resonance [9].

One of the tradeoffs in using an MRR is the wavelength of operation. Some of the modulator technologies such as the MQW inherently limit the wavelength to a specific band, while others like the MEMS based MRR work over a broadband. Wavelength selection also limits the number of laser interrogation sources available for a long distance MRR link. Recent advances in fiber laser technology have yielded high quality sources at select wavelengths. Near perfect single mode Gaussian beam quality is available in bands at 1070nm (Ytterbium) and 1550nm (Erbium), power output from a single laser module is a thousand Watts for Ytterbium and a hundred Watts for Erbium; and these numbers continue to grow. A powerful laser will be required to close the link between ground and an MRR in LEO.

The pointing requirements at the MRR end of the link depend on the type of passive retroreflector used. For corner cube retroreflectors, the field of view over which they return power is determined by the corner cube construction material. Glass corner cubes have about a 30-degree full angle field of view. Silicon corner cubes have about a 60-degree full angle field of view. MRRs can also be used in canted arrays to increase the effective field of view and reduce the pointing requirements at the MRR end of the link. An important point to note is that for bidirectional links a photodetector is required at the MRR end of the link and it must work over the same field of view as the retroreflector.

INCREASING MRR APERTURE

When using an MRR for a ground to space link, the size of the MRR aperture is crucial in defining the operational range of the link. We investigate the tradeoffs of using a single large aperture MRR or an array of smaller MRRs. The primary concern with a large aperture retroreflector (hereafter called retro for brevity) over long ranges, such as a few hundred kilometers for LEO, is velocity aberration. Velocity aberration is essentially a pointing error resulting from the Earth to satellite laser pulse round trip time relative to the speed of the earth and the orbiting satellite. For a satellite in LEO at 90 degrees zenith (directly overhead), the velocity aberration is approximately 50µrad. Recall from the previous section, a 1cm retro will result in a 244µrad divergence when illuminated with a 1µm laser. Taking into account the velocity aberration, a considerable loss in signal is introduced at the receiver due to the beam being off-axis by 50µrads. A single large aperture retro can be used, but it will result in a smaller divergence angle and must be engineered to compensate for the velocity aberration so as to reduce the additional loss. A hollow retro can be spoiled by building the reflective faces of the retro canted from the proper orthogonal configuration. If all three faces are equally canted, then a ring of six individual diffraction-limited beams will be returned; the amount of canting determines the ring diameter and the diameter of the retro controls the diameter of the individual spots [4].

We developed a basic propagation model to analyze the effect of velocity aberration for a range of engagement distances and retro sizes. The analysis was baselined by starting with a single retro and determined the optimal diameter in terms of velocity aberration. Next, several configurations were examined which used spoiled retros and arrays of spoiled retros to optimize the retro return pattern at the receiver. The resulting intensity at the receiver from an array of retros is modeled as a superposition of the return from the individual retros, but this is not always the case [10]. Looking at the off-axis (50µrad) received intensity of the array we explored a few designs to optimize the received intensity at the minima of the ring.

The following calculation was done for 50µrad velocity aberration, satellite directly overhead, a 1µm laser, 1W/m^2 incident intensity on the retro, and no atmospheric effects. Figure 2 shows the calculated received intensity for a range of single retro diameters. The received intensity is calculated off-axis from peak intensity by 50µrad due to the velocity aberration. The peak in the chart shows the optimal retro diameter as 1.75cm, or stated another way, for a single retro operating in the above conditions a 1.75cm diameter will yield the highest returned intensity. Figure 3 illustrates the returned intensity profile from a 1.75cm retro in the plane of the receiver. The black trace on the surface indicates the 50µrad velocity aberration; this is the off-axis position where the receiver would detect the returned light. The off-axis intensity due to velocity aberration is 8.65dB below the peak intensity.

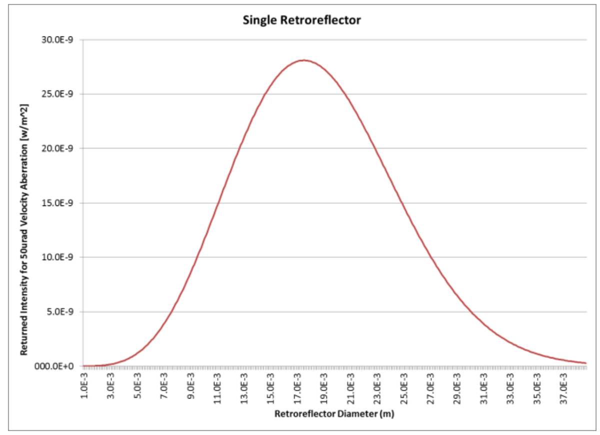

Figure 2: Retroreflected Intensity Measured at 50µrad Velocity Aberration for a Range of Retro Diameters.

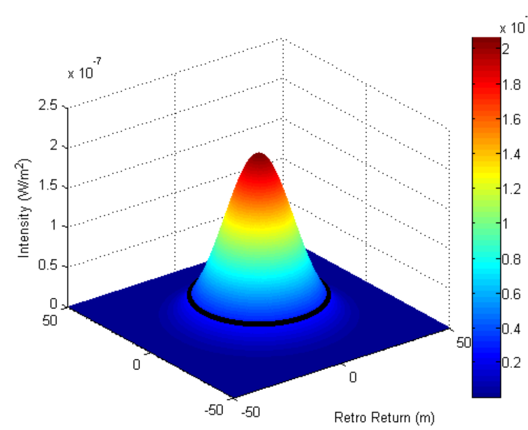

Figure 3: Retroreflector Return for a Single 1.75cm Diffraction Limited Retro.

Next we modeled a spoiled retro covering the entire side of a 1U CubeSat (8cm), with the retro faces canted to produce a 100µrad diameter ring of six diffraction-limited beams, Figure 4 illustrates the result. The diameter of the retro yields narrow, yet intense peaks in the intensity pattern at the receiver. The issue with this design is that when the spacecraft, and thus the retro, undergo rotation then the received pattern rotates as well. These spots have almost no overlap and the valleys between the peaks have nearly zero signal. Without extremely accurate spacecraft stability, this retro design would yield an unreliable communication device, requiring the communication receiver to be designed for the worst case signal level, occurring in the valleys of the ring.

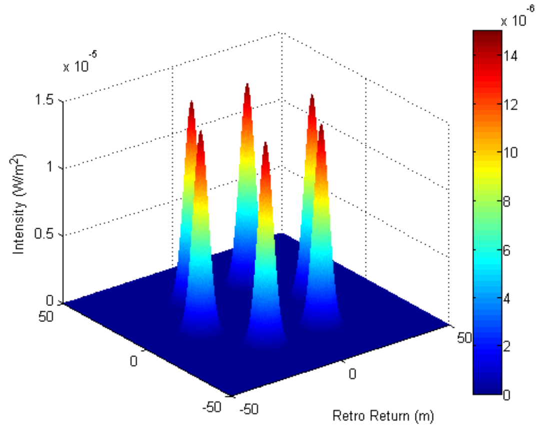

Figure 4: Retroreflector Return for a Single 8cm Spoiled Retro.

Figure 5 illustrates two identical spoiled retros engineered as described above, except with a different aperture diameter. The diameter was chosen to be 4.68cm to fit across the diagonal of the CubeSat face. For this case, the two retros are installed such that one is rotated or 'clocked' 30 degrees azimuthally with respect to the other [4]. This clocking creates a ring of twelve spots equally spaced in angle at the receiver and the valleys of one ring are filled with the peaks of the other ring. This technique mitigates the deep valleys formed by a single large retro, but results in 3dB lower peak intensities of the individual peaks.

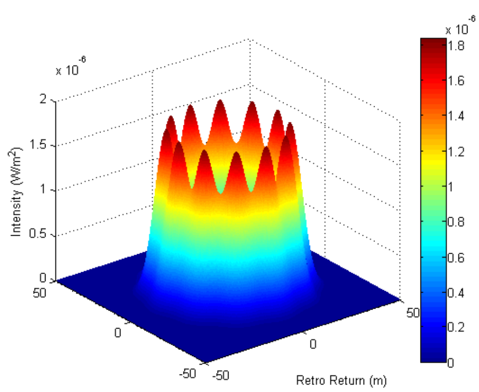

Figure 5: Retroreflector Return for Two 4.68cm Spoiled Retros Clocked.

We then sought to determine the retro requirements to create a ring with 1dB or less peak-to-valley variation. Figure 6 shows the return from four retros, each with 4cm diameter. Two of the retros are clocked with respect to the other two, yielding twelve individual spots. The retro diameters were chosen such that they occupy the full 8cm of the CubeSat face. The ratio of peak-to-valley intensity is calculated as 0.55dB for this configuration.

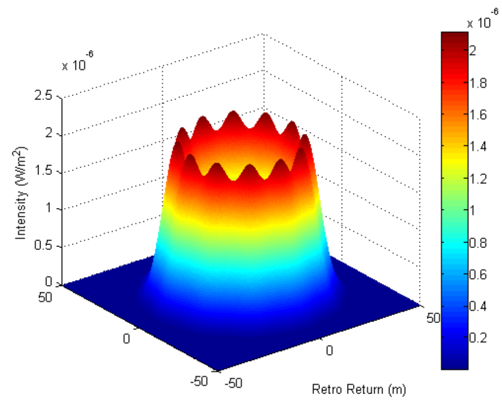

Figure 6: Retroreflector Return for Four 4cm Spoiled Retros Clocked.

Table 1 summarizes the modeled performance of these different retro configurations from a received power perspective. As expected, the large aperture retro delivered the highest peak intensity in the return profile. However, there is a substantial penalty if the receiver is not on axis with one of the peaks. The scenario utilizing four retros has roughly 10dB less peak intensity; however the minimal variation in the intensity profile of the ring would yield a much more robust communication link. The peak intensity is calculated as the maximum intensity in the returned beam profile. The P-V variation is the peak-to-valley variation for the spoiled retro or in the case of a single retro, the ratio of peak intensity to intensity at the velocity aberration.

Table 1: Returned Intensity for Several Retroreflector Configurations.

No. of Retros	Retro Diam (cm)	Spoiled	Clocking	Peak Intensity (W/m^2)	P-V Variation (dB)
1	1.75	N	N	2.06e-07	8.65
1	8.0	Y	N	1.5e-05	45.45
2	4.68	Y	Y	1.84e-06	1.39
4	4.0	Y	Y	2.14e-06	0.55

The practical implementation of each configuration must be considered. An array of MRRs soon becomes impractical both from a cost and engineering perspective as the number of MRRs increases. There are also concerns with an interference pattern resulting from two or more retros in close proximity when illuminated with a laser having a coherence length on the order of meters [10]. For a spoiled retro, there is undoubtedly a high degree of difficulty in accurately canting the faces of a retro to submicroradian tolerance. Figure 2 through Figure 6 were generated for the case of beam propagation in a vacuum. In the real world, absorption, scattering, and turbulence would play a role in the returned beam profile. Turbulence would have the most profound effect by introducing scintillation which would yield beam breakup and speckle [11]. Literature suggests a retro can be designed to spoil the returned intensity into two spots by canting only one of the three retro faces [4]. This would be an attractive solution for a spacecraft with well controlled body stabilization. The resulting returned peak intensity would be higher. Literature also mentions controlling the divergence angle of the individual spot(s) of the retro return. By introducing a long focal length lens (100s of meters) over the aperture of the retro, the individual spots can be diverged beyond the diffraction limit [4] [12]. Different zenith and azimuth angles would result in different velocity aberrations and different engagement distances.

SPACECRAFT BUS

In addition to the MRR, a complete communications payload would require a modem, laser beacon, and a detector on the spacecraft. The modem would be separate from the flight computer and control only the MRR, laser beacon, and detector. The laser beacon would aid the ground station in pointing, tracking, and acquisition. The detector would allow one-way low bandwidth transmission of status and control messages from the ground station to the spacecraft and it could be used as a flag for the modem to start data transmission were the spacecraft being illuminated.

CubeSat bus designs for hosting an MRR payload are currently being analyzed. The bus will consist of all the major spacecraft systems including the flight computer, batteries, electrical power system, solar panels, telemetry/tracking/command (TT&C) communications system, and the attitude determination and control system (ADCS). To reduce costs and design time, the design will use commercial off-the-shelf (COTS) components wherever possible. A modular bus design capable of being reused for additional future payloads with little or no modification is also a secondary goal of the MRR payload bus design.

Geo-tracking is necessary for an optical communication system to achieve low SWaP and reliable optical communications. However, accurate body pointing toward a particular latitude-longitude target is difficult due to the SWaP limitations of a CubeSat. The ADCS is therefore a critical system to ensure the success of the MRR payload. Fortunately, one of the major benefits of the MRR is that pointing requirements can be somewhat relaxed over typical laser transmitter-receiver optical communications systems. The absolute pointing requirement is $\pm 5^{o}$ or better for a hollow MRR design. This limit is imposed by a reduction in the effective cross section of the retro at non-perpendicular incidence angles [4]. To maximize the returned signal, and thus the data rate, we set a design requirement for pointing within $\pm 1^{o}$ of a pre-defined ground position. The bus ADCS must also maintain that pointing accuracy throughout the duration of overflight opportunity.

A common type of ADCS is 3-axis control, it often comprises a combination of 3 momentum wheels and 3 torque rods to exchange angular momentum and control spacecraft attitude. Such systems coupled with accurate attitude detection sensors may be capable of providing better than $\pm 1^{o}$ of pointing accuracy. The addition of an onboard GPS receiver provides accurate position estimates required for precise geo-pointing.

The sensor suite for our CubeSat design includes infrared sensors, magnetometer, gyros, and sun sensors. Two infrared Earth sensors are used to determine the relative angle of the space vehicle with the surface of the earth in three dimensions. A MEMS magnetometer is used to measure a three dimensional magnetic vector and to determine which way is "up" if both IR Earth sensors are not within direct view of Earth. MEMS angular rate gyros are used to determine the rate of angular rotation and used in conjunction with actuators stabilize the space vehicle and provide verification of the IR earth sensor determination. Coarse sun sensors are located on each of the solar panels to determine the angle of the sun with respect to the space vehicle. This additional sensor information provides a secondary pointing vector to verify the space vehicle attitude.

The attitude control portion of the system is composed of two types of actuators, momentum wheels and magnetorquers, which will physically change the attitude (Z-axis pointing vector) of the space vehicle with respect to the surface of the earth. Our design uses three momentum wheels acting as the primary actuators to provide 3-axis control of spacecraft orientation. These actuators have the ability to rapidly and accurately modify attitude, but they only have a finite spin up capability and must be coupled with a secondary actuator. Magnetorquers use an electric current to create a magnetic moment relative to Earth's magnetic field. The magnetorquers do not require much power but provide a relatively slow attitude adjustment. Thus magnetorquers can provide the means to unload the momentum stored in the momentum wheels.

The CubeSat bus design incorporates a UHF radio for sending commands to the spacecraft and downlinking telemetry to the ground. Periodically, updated orbital element predictions for the spacecraft can be uplinked to the CubeSat. These updates are provided as they are released from NORAD which generates the data in the form of two line element (TLE) sets. The command and data handling (C&DH) system utilizes these orbital elements to predict upcoming flyovers. The GPS receiver has relatively high power needs and thus is not used continuously to provide position data. Instead, the GPS receiver is used in advance of flyovers to validate and augment the TLE based predictions. These flyover predictions are utilized by the ADCS system to provide high accuracy body pointing toward the ground station only during flyovers. Pointing requirements are relaxed during the remainder of each orbit and during non-flyover orbits to conserve power. The flyover schedule predictions and a mission clock are also used by the payload to turn on the beacon and MRR when within line of sight of the ground station.

The satellite will most likely be launched as a secondary payload, and thus will not be able to dictate its orbit to the optimal altitude and inclination for this mission. An initial analysis of the duration and frequency of flyovers was conducted to determine the acceptable bounds of orbital altitude and inclination. Based on orbital decay from atmospheric drag, an orbit of less than about 400 km is unacceptable since the spacecraft will de-orbit in a matter of weeks. Orbits above approximately 600 km are also unacceptable, as the spacecraft remains in orbit beyond the 25 year limit imposed by the US Government for the mitigation of orbital debris. We consider an optical ground station located in Cape Canaveral, Florida at a latitude of 28.45°N to communicate with the payload. For this location, the mean flyover duration was calculated and is shown in Figure 7 for altitudes from 400 to 600 km. These studies assume satellite access starting at 0 degrees elevation and are calculated based on one year on-orbit. From Figure 7, the optimal orbit inclination is about 35°for all altitudes, providing about 9.5 minutes at 400 km up to 12 minutes at 600 km. It is important to note that the average coverage time drops at around 50 degrees inclination when the ground trace repeats itself. The coverage times at these inclinations increases or decreases based on the orbit's ascending node longitude relative to the longitude of Cape Canaveral. Prediction of these satellite access windows is important during mission design as it directly affects the volume of data transmitted per pass.

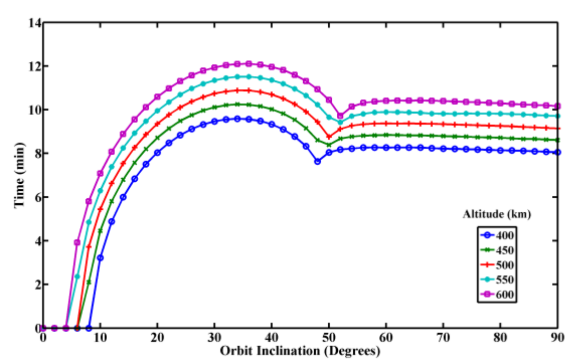

Figure 7: Average Flyover Duration for Various Inclinations.

CONCLUSION

The MRR is a novel optical communication system which can enable low SWaP, high bandwidth, secure communications. The technology has a long heritage in terrestrial applications and shows great promise for space use. Analysis indicates these systems have the capability to enable intersatellite crosslinks and space-to-ground downlinks. Although the achievable data rate is slower than a traditional laser communication system, the low SWaP characteristics make it attractive for CubeSat applications.

We have developed a design which can provide a low SWaP communication capability for satellites that enables high bandwidth, can provide LPI/LPD, and A-J downlink communication. Our modeling results showed that an MRR-based optical communication system can achieve this on a CubeSat platform. We observed that the critical path in closing the communication link was having a sufficient MRR aperture on the CubeSat; and it could be accomplished with a single or an array of retros. As our preliminary analysis showed, it is far from trivial to engineer a large retroreflector. The most significant technology hurdle would be the design and construction of a modulated retroreflector to operate over a multitude of engagement scenarios for a particular orbit. Second to the retro design would be the spacecraft bus and its components. While the intrinsic characteristics of a retro tolerate crude pointing to within several degrees, a stabilized geo-tracking bus would be preferred. We surveyed available COTS CubeSat equipment with sufficient angular slewing rates and pointing stability to provide better than 1° per axis pointing. The hardware is able to achieve this pointing; it then becomes a matter of software development on the flight computer.

Although not mentioned in this paper, we have developed a link analysis tool to model the system tradeoffs for MRR-based communications. The link analysis takes into account atmospheric effects, pointing and tracking errors, hardware efficiencies, as well as other system-dependent performance factors. We are also exploring low power modem and control electronics for the MRR system so as to reduce the power burden on the host spacecraft. Additionally, we conducted a survey of alternative modulator options for an MRR, specifically looking for technologies to enable larger and faster MRRs. We plan to report on these topics in a future article. In closing, our research shows enabling a CubeSat with an MRR optical communication system is realizable with current technology.

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