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MODULATING RETRO-REFLECTORS: TECHNOLOGY, LINK BUDGETS AND APPLICATIONS

Alberto Guillen Salas
SGT Inc. / NASA Ames Research Center, United States
alberto.guillensalas@nasa.gov

Jan Stupl
SGT Inc. / NASA Ames Research Center , United States;

James Mason
University Space Research Association, United States

Satellite communications systems today -- usually radio frequency (RF) -- tend to have low data rates and use a lot of on-board power. For CubeSats, communications often dominate the power budget. We investigate the use of modulating retro-reflectors (MRRs), previously demonstrated on the ground, for high data-rate communication downlinks from small satellites. A laser ground station would illuminate a retro-reflector on-board the satellite while an element in the retro-reflector modulates the intensity of the reflected signal, thereby encoding a data stream on the returning beam. A detector on the ground receives the data, keeping the complex systems and the vast majority of power consumption on the ground. Reducing the power consumption while increasing data rates would relax constraints on power budgets for small satellites, leaving more power available for payloads. In the future, this could enable the use of constellations of nano-satellites for a variety of missions, possibly leading to a paradigm shift in small satellite applications.

I, INTRODUCTION

Modulating retro-reflectors (MRRs) are small devices that allow low powered, high data rate communication downlinks from small satellites. A satellite equipped with MRRs onboard would modulate an incident laser beam (coming from a ground station) and reflect this beam back to Earth with some data encoded on it. This variant of optical communications promises more data downloaded per unit of onboard power than any current communications schemes.

Both higher data rates and lower on-orbit power consumption are (simultaneously) possible with the system described in this paper when compared to traditional radio-frequency (RF) systems. The system exhibits many of the advantages of free-space optical communications using lasers, but eliminates lasercom's precision pointing requirements and appetite for power.

A breakthrough communication architecture based on MRR-equipped satellites and interrogating receivers would allow a smaller/lighter/lower power space communications segment, larger bandwidth, and relief from RF spectrum allocation issues. It is conceivable that MRRs could offer over 100 times faster data rates whilst consuming less than 1/10 on-board power than a traditional RF system, and potentially much more. This revolutionary increase in communications performance for small satellites could enable a myriad of new missions.

Two of the most significant challenges for small satellites, and especially nano-satellites, are their very low on-board power generation and the limited data downlink capacity. Some commercial off-the-shelf (COTS) RF radios can provide the required volume of downlink data but their power requirements [1] make them not suitable for nano-satellites such as CubeSats. The poor data rate to power ratio (bps/W) is a limiting factor that has prevented CubeSats from being further developed and has prohibited their use for more demanding missions.

Taking into account the characteristics of small satellites, the ideal communication system would feature a space segment that allows high bi-directional data rates with low power consumption. It would also have to be compact, to fit in reduced form factors, and to be as simple as possible, keeping most risk of failure on the ground segment, where it is easy to access for repairs. Furthermore, it should not impose specific performance requirements, such as precise pointing, on the satellite bus.

This approach is a possible solution to this communication bottleneck: employing a highly asymmetric system architecture that uses MRRs as the transmitting element in the space segment. This shifts most of the challenging technology off the satellite, either towards a ground station or space-based relay infrastructure.

The Naval Research Laboratory has long invested in this technology and has developed impressive MRR and interrogator prototypes for naval communications, utilizing a specific combination of laser, MRR and detector. There has also been some interest from the private sector in developing this technology, mostly for terrestrial/naval defense applications. However, to our knowledge, there has not been a test of MRR technology in space yet. The MODRAS (Modulating Retro-reflector Array in Space) experiment was planned to be hosted on the ANDE (Atmospheric Neutral Density Experiment) mission, but was not completed.

The following section will give a more detailed technical description of this concept. We compare potential capabilities with the current, RF based approaches, point out potential risks and discuss the impact such a MRR-based communication architecture would have.

II. CONCEPT OVERVIEW

II.I Modulating retro-reflectors for Communication

The proposed MRR-based system consists of a highly asymmetric variant of free space optical (FSO) communications that transfers a majority of the power and pointing requirements to the more accessible (and cheaper) end of the optical link. The beauty of this approach is that it allows the space segment to be passive (in that no energy is emitted) and low power while still allowing high data rates. The communications payload can be designed in a standardized way so that it is cheap, robust and modular. The way this is achieved is by using a high powered laser “interrogator” at one end of the FSO link and a modulated “corner cube” retro-reflector at the other (see Fig. 1).

A retro-reflector is a passive optical device that reflects incident light within its field of view (about 30 degrees full angle) exactly back along its path of incidence. It does this by reflecting incoming light off of three mirrored faces, mounted perpendicularly in the shape of a cube’s corner. The laser ranging community has long utilized retro-reflectors for time-of-flight distance measurements, showing that photons emitted from a coherent source at a ground facility can travel through the atmosphere, reflect off three faces of a retro-reflector on a satellite, travel back through the atmosphere and then be detected by a photodiode at the same facility. Knowing that we can detect such a retro-reflected signal on the ground, it follows that we can impress a bit stream on the signal by modulating the reflectivity of the retro-reflector (see Fig. 2).

There are different techniques to modulate the strength of the reflected signal. Microelectromechanical system (MEMS) deformable micromirrors create a short-lived diffraction grating that scatters the beam. Multiple quantum well modulators (MQW) use the Stark effect to vary the absorption of a transmissive crystal window. Pockels effect electro-optic crystals set up a transmissive diffraction grating that reduces the effective transmission. These, and others, have been tested on the ground but none have so far been adapted for space-to-ground links.

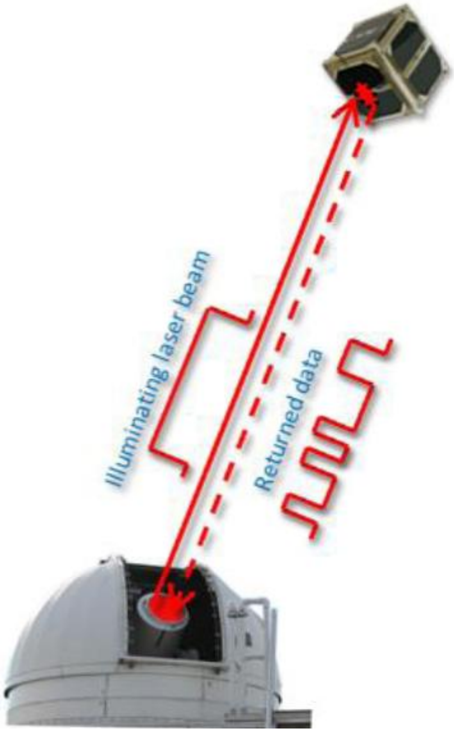

Fig. 1: Scheme of downlink from satellite using MRR technology.

II.II Setting up a Communication Architecture

Packaged efficiently, MRRs can be very small and light devices that couple well with the CubeSat form factor. They are very robust and the required driving electronics are simple - in the simplest variant they only require an applied square-wave voltage and very low current. The interrogator (which could be either a ground segment or a space-based relay satellite) is composed of a laser connected to a tracking beam director to illuminate the MRR, and a detector with its associated optics to pick up the returned data stream. This laser could be a continuous wave "spotlight", or could be pulsed with a carrier frequency to make detection easier. The interrogator would bear all of the high accuracy tracking requirements and the majority of the power requirements. It would also bear most of the potential risk of failure, but could be easily accessed if implemented as a ground segment. One interrogator could communicate with many satellites, but is still constrained by satellite line of sight access times. However, to achieve higher coverage one could envision a network of interrogator terminals, just as RF ground station networks exist today.

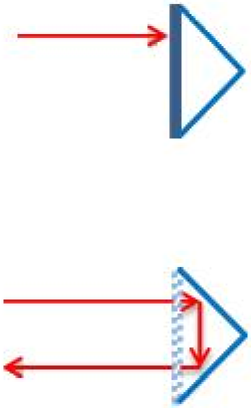

Fig. 2: Scheme of a MQW MRR. Top: modulator absorbing received light and not transmitting. Bottom: modulator transmitting light back to the source.

During operations the ground (or indeed a space-based relay) terminal would track the MRR-equipped satellite and illuminate it with the interrogation laser beam. Small photodetectors (or, in some cases, the modulator element itself) would be able to detect the incident beam and cue the data transmission. If the interrogating beam itself is amplitude modulated, half-duplex communications is possible. In the simplest case this would be done with an on-off keying (OOK) modulation, but ultimately more advanced schemes such as pulse position modulation (PPM) will provide higher data rates. By utilizing polarization modulation on the interrogation uplink and amplitude modulation in the MRR downlink, full-duplex communications can be enabled. The interrogator would be co-located with a receiver telescope, which would have the requisite optics, detectors and electronics to decode the data stream.

The hardware and performance requirements for the ground station are significant but readily available and much of the development work has already been done by the laser ranging and communications communities.

Satellite operators could contract the needed interrogating cycles for a fee, in the same way that commercial RF ground stations work.

II.III Quantifying the link budget

Since the MRR acts both as a receiver and a transmitter in the optical link, we may express the MRR optical link budget in terms of gains and losses:

$$P_{rec} = P_{laser} G_T L_T L_R T_{atm} G_{MRR} L_{MRR} M L_R T_{atm} G_{rec} L_{rec} \qquad [1]$$

Where:

P_{rec} = *received signal power;*
G_{MRR} = *MRR antenna gain;*
P_{laser} = *transmitted power;*
L_{MRR} = *MRR optical losses;*
G_T = *transmitter antenna gain;*
M = *modulation efficiency;*
L_T = *transmitter losses;*
G_{rec} = *receiver antenna gain;*
L_R = *range losses;*
L_{rec} = *receiver losses;*
T_{atm} = *atmospheric transmission;*

For a given system architecture we can therefore predict the received power. Knowing the rate and encoding scheme of the modulating element allows us to calculate the number of photons received by the detector, per transmitted bit:

$$n_p = \frac{Q \cdot P_{rec}}{h\nu\, R} \qquad [2]$$

Where:

np = *photons per bit;*
R = *data rate;*
h = *Planck's constant (6.63 x 10-34 Js)*
v = *frequency of the light = c / λ*
Q =*detector quantum efficiency;*

For example, if we use a 1 kW, 1064 nm laser beam with a 30 arcsecond divergence to illuminate a 1cm MRR that is 500 km overhead (and assume realistic atmospheric and optical losses) we can calculate the power received by a 2 m telescope to be on the order of a nanowatt. If we were transmitting data at a rate of 10 Mbps, our detector would receive about ~500 photons per bit. Today's single photon counting techniques can detect easily these signal levels, provided they are above the background noise. Most of the ambient noise can be blocked with a narrowband optical filter, but backscatter of the laser is a concern (see Section II.IV).

The sensitivity of a given detector system is a measure of the receiver's performance and represents the average optical power that produces a given bit error rate (BER). FSO links frequently use 10^{-6} as an acceptable BER. The sensitivity is dependent on data rate and wavelength and can also be expressed in photons per bit - comparing the detector sensitivity and the received photons per bit allows us to determine whether such an architecture will provide the given link quality (BER).

II.IV Technical Credibility and Potential Risks

The technology required to realize an MRR-based communications system certainly needs further development, and would be greatly advanced by a hardware test bed or test mission. However, the physical principles of optical communications are well understood and have been demonstrated repeatedly. In fact, space-to-ground, ground-to-space and space-to-space laser communications have all been demonstrated on missions such as ILEX, GeoLITE, OICETS, Tesat, Alphasat, EDRS. Similarly, laser ranging of satellites fitted with retro-reflectors has a history of more than four decades. The International Laser Ranging Service (ILRS) has been coordinating these activities globally since 1998, and has a wealth of knowledge regarding tracking and illuminating retro-reflectors and detecting single photon level returns. This long history has allowed the effects of satellite tumbling and atmospheric scintillation to be well documented [2]. The use of MRRs as a means for Mbps retro-communications has been demonstrated both for a ground-to-ground free space link of 16 km and an air-to-ground link [3,4]. NRL used a 1.6 W 1550 nm continuous wave (CW) laser for the Chesapeake Bay demonstrations and an MQW MRR designed for that wavelength. However, the $1/R^4$ losses involved in a space link mean that a much higher power laser is required - commercial laser technology favors 1064 nm for ~kW class CW, yet no large aperture MRR exists at this wavelength that can modulate at multi-MHz.

Reliably achieving similar or better performance in a space-to-ground link is much more difficult, but the basic principles are established and have been verified. Indeed, space links have been investigated before [5] but a systematic study of competing architectures has yet to be completed.

More specifically, the technologies that are likely to be involved all exist, even if their performance has not yet matured to the level required for Gbps communications. There are 10 kW single-mode, diffraction limited, CW lasers commercially available. MQW MRRs have been tested at Mbps for free space and show a good combination of speed/aperture. MEMS MRRs have also been demonstrated for free space links, and allow much larger apertures but at slower speeds [6]. Detectors have advanced, especially Geiger-mode SPADs, allowing very high frequency (short dead times) with very high sensitivity - at the level required for space-ground links [7]. Superconducting nano-wire detectors [8] promise faster speeds and lower dark count rates than avalanche photodiodes. Single photon imaging systems have been built with array of up to 32 x 32 elements, allowing much lower background noise for a given receiver FOV. Several ground segments have also demonstrated fast tracking of satellites and debris using a large telescope with the pointing accuracies needed [9].

There are also some potential risks inherent to the concept towards an implementation of a MRR based communication architecture. One of the most important is atmospheric backscatter from the interrogating beam, whereby photons scattered by the atmosphere reflect back into the receiver's optical path and reduce the signal to noise ratio. Different mitigation strategies can be employed to reduce the effects of atmospheric backscatter, including:

1) Spatially separating the outgoing and incoming optical paths (limited by the reflected beam width).
2) Employing a dynamically pulsed carrier frequency. phased such that the atmosphere just above the receiver is clear when a reflected pulse is expected to return.
3) Frequency filtering of the received signal to select only those photons that have been frequency shifted by the Doppler effect.

High powered CW lasers can only be available at a specific wavelength which would have a strong impact on the entire system, including on the detector choice. Detector efficiency varies depending on the technology and wavelength. If the signal to noise ratio is poor, single photon detectors may be an option, when combined with filters and other measures to reduce the background noise. Indeed, various groups are demonstrating that by using higher order modulation schemes (such as PPM), data can be received at more than one bit per photon [10]. Superconducting nanowire single-photon detectors show much promise [8].

Modulators have not been used in space to ground links and at the moment there is not one obvious choice of modulator that has both a large aperture and a high frequency response. MQW offers the best combination of these two factors, but may ultimately need to be deployed in an array to improve signal to noise ratio.

III. LIMITATIONS OF EXISTING RF SYSTEMS

For small satellites, and CubeSats in particular, onboard energy is always precious. Their low power generation capabilities necessitates strict power moderation and, as a consequence, past missions have failed due to being power negative. Severe duty cycles are common among CubeSats, and directly translates to a constrained downlink capacity.

The limitations of the current CubeSat RF communications infrastructure has been investigated by Kolfas and Leveque [1]: Over 5 years a total of only 797 MB was downloaded from 24 CubeSats. This is simply unacceptable if one believes that the capabilities of CubeSats are increasing to a point where they can conduct useful, data-rich, missions. More specifically, RF requires a lot of transmitted power or a large directional antenna to achieve high data rates. Added to this, the transponder options available for CubeSats have proven unreliable.

While classical lasercom systems allow much higher data rates and very secure connections, they impose extreme pointing requirements upon the space segment. This necessitates complicated, large, and expensive attitude determination and control systems - infeasible for small satellites.

IV. POTENTIAL IMPACT

IV.I A Technology Breakthrough

Advancements in communications technology truly have a cross-cutting benefit to space missions. This is especially true if the technology does not increase cost/complexity/risk of the space segment. We envision a standardized, modular MRR space segment that would increase data rates and lower the power consumption for communications on the spacecraft, freeing up power to enable more sophisticated payloads and missions.

In addition, transferring most of the technological difficulty to the interrogator node reduces complexity, risk and cost onboard the satellite. A ground-based network of interrogators could provide standardized and reliable high speed communications for small satellites for decades.

IV.II A Regulatory Breakthrough

As this network uses directed optical signals, all RF spectrum management issues simply disappear. Obtaining FCC regulatory approval for a mission can take months, and sometimes even falls on the critical path of rapid CubeSat development schedules. Each new satellite needs to repeat this regulatory process, even when operating in the amateur or scientific frequency bands. For an MRR-based laser network, the operator of the interrogators inherits the regulatory responsibility and the responsibility for interrogating the right satellite only when necessary (and paid for). A single framework would allow the network to communicate with all MRR-equipped satellites. The operator would have to work with the Laser Clearing House, but elements of the DOD are demonstrating that this process can be streamlined and automated. Optical interference is highly unlikely, due to the narrow width of the beam. This narrow beam-width communication could even allow different network operators to work at the same wavelength (servicing the same satellites).

IV.III Enabling new Missions/Capabilities

A more efficient communications system, that can service many small satellites, is part of a grander vision motivated by the changing operational environment in low Earth orbit. Space has become more congested and the worsening debris environment has increased the risk (and therefore cost) of operations. One obvious solution is to increase redundancy, but in times of challenging budgets the old way of flying a few highly capable, and very expensive, satellites no longer seems optimal. The risk that one critical national space assets is disabled accidentally, or indeed by foul-play, in a time of need is too high to be ignored [11].

Small satellites present a solution to this problem, as they can potentially provide highly redundant, rapidly deployable and low cost capabilities. Different organization around the world, both public and private, have recognized this and started their own small satellite programs. Smaller satellites offer shorter development times, on smaller budgets, and can fulfill many of the functions of their larger counterparts. One of the main features of micro-satellites is their short design life, meaning that they can benefit from leading edge technology by accepting more risk. CubeSats are one of the more widely adopted form factors and there is an emerging trend, recognized by the Air Force, and increasingly by NASA, towards CubeSat as a platform for technology and capabilities development.

If an MRR-based communication network is combined with cheap micro-launchers and an effective space traffic management system then a new risk-embracing and democratized approach to the development of satellites would be realized. This approach allows the significant hardware investment from the (much more advanced) consumer electronics industry to be leveraged, while pushing innovation into the software domain. Shorter development cycles and in-space testing could be possible instead of decades long, risk averse missions. This vision of the future of space systems has greatly reduced barriers to entry, allowing many more players to access space and to invent new, unimagined missions and applications that utilize space as a shared resource.

V. CONCLUSION

MRRs onboard satellites offer the potential for high data rate downlinks whilst requiring very little power. The increased capabilities enabled by this technology would result in a breakthrough for small satellites, whose power budgets are usually dominated by RF communications. MRRs are simple, small, rugged and light devices that can be easily integrated into small satellites such as CubeSats.

This communication architecture keeps the vast majority of engineering complexity and power consumption on the ground and does not impose strong performance requirements on the space segment (I.e. only coarse pointing is necessary).

All of the component level hardware requirements for such a communications architecture are commercially available and appear mature enough to be integrated. This includes both pulsed and CW lasers, tracking beam directors, photon detectors and MRRs.

The necessary development work is mainly in systems engineering and integration & testing.

An MRR communications architecture could have a very strong impact on the whole space industry by accelerating the trend towards smaller satellites, through enabling data-rich missions and lowering the existing barriers to entry for new players.

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