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Jose E. Velazco, Joseph Griffin, Danny Wernicke, John Huleis, Andrew DeNucci, Ozdal Boyraz, Imam Uz Zaman, "Inter-satellite omnidirectional optical communicator for remote sensing," Proc. SPIE 10769, CubeSats and NanoSats for Remote Sensing II, 107690L (18 September 2018); doi: 10.1117/12.2322367

SPIE.

Event: SPIE Optical Engineering + Applications, 2018, San Diego, California, United States

Inter-satellite Omnidirectional Optical Communicator for Remote Sensing

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ABSTRACT

We are developing an inter-satellite omnidirectional optical communicator (ISOC) that will enable gigabit per second data rates over distances up to 1000 km in free space. Key features of the ISOC include its high data rates and its ability to maintain multiple simultaneous links with other spacecraft. In this paper we present design considerations for the ISOC, including selection of the mission-appropriate geometry, telescope design, receiver design, as well as beam pointing considerations. We also present experimental results obtained with the ISOC prototype. In addition, we present design considerations for a low-Earth-Orbit mission where four ISOC-furnished CubeSats form a swarm suitable for remote sensing. We believe the ISOC could be a technology enabler for future constellation and formation flying CubeSat missions for Remote Sensing.

Keywords: Omnidirectional, Optical, Communicator, Gigabit, swarms, multiple-link, remote sensing

1. INTRODUCTION

Swarms of Earth-orbiting small spacecraft have the potential of providing a unique sensor platform for remote sensing. If each spacecraft is furnished with a high-resolution sensor, and the sensed data can be rapidly shared among the spacecraft, then the entire swarm could act as single unparalleled large and powerful space borne instrument. Modern inter-spacecraft communications are rapidly becoming bandwidth limited due to the RF transceivers they utilize. As emerging technologies, such as swarms of small spacecraft, continue to demand more bandwidth, the need for low-power optical transceivers capable of multi-gigabit link rates will rise. Optical transceivers have the potential to provide order-of-magnitude improvements over existing RF transceivers[1-4]. We are developing a new inter-satellite omnidirectional optical communicator (ISOC) that should be capable of communicating with multiple CubeSats simultaneously at gigabit speeds and that should enable a new generation of swarm platforms (see Fig. 1).

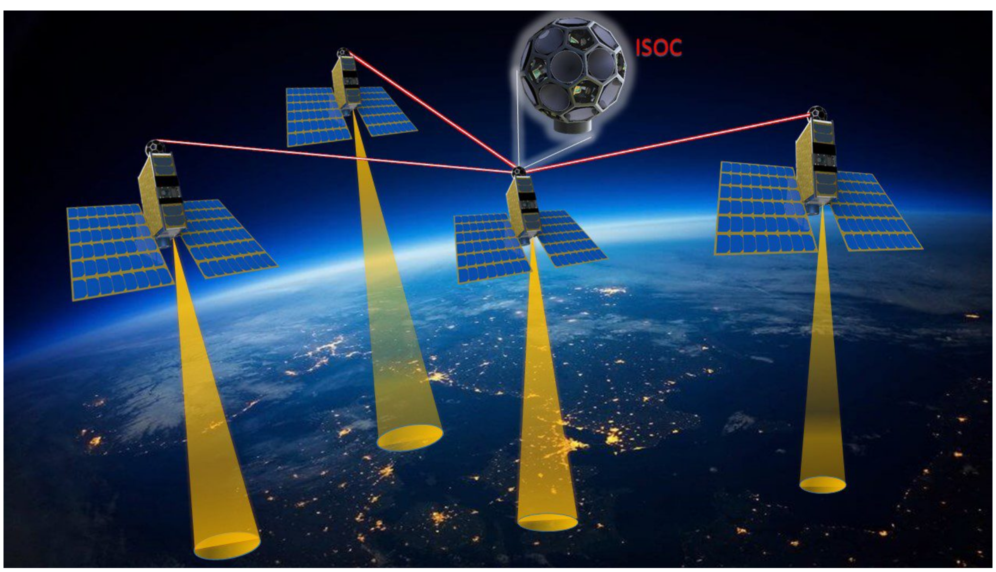

Figure 1. Swarm of CubeSats optically interconnected at gigabit per second speeds via the ISOC.

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CubeSats and NanoSats for Remote Sensing II, edited by Thomas S. Pagano, Charles D. Norton, Proc. of SPIE Vol. 10769, 107690L · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2322367

The ISOC will allow unparalleled ultrafast inter-satellite wireless data transfer for many space applications including formation flying and constellations of spacecraft. Key features of the ISOC include: a) gigabit per second data rates, b) full sky coverage and c) its ability to maintain multiple links simultaneously. Thus, the ISOC shall enable new space borne large instruments by synthetic aperture formation. That is, multiple spacecraft, each furnished with a sensor (and an ISOC), can form a much larger sensor by combining the sensed data via the ISOC. In this paper we will provide a brief description of the ISOC, present initial results of the transmitter development and describe a four-CubeSat concept mission suitable for remote sensing.

2. ISOC DESIGN CONSIDERATIONS

The current ISOC design targets CubeSat applications. The small form factor of CubeSats dictates that the ISOC geometry be limited to a maximum diameter of four inches. In addition, in order to track moving spacecraft and to maintain multiple simultaneous links across the sky, the ISOC includes an array of miniature optical telescopes. Under these design constraints, our preliminary link budget calculations have yielded communications ranges from 100 km to 1000 km at speeds as high as 1 Gbps.

The ISOC design uses a novel scheme where miniature optical telescopes on all facets of a truncated-icosahedral frame provide full sky coverage (Fig. 2). It also employs an array of fast photodetectors for reception of the optical signals. Key features of the ISOC include its high data rates and its ability to maintain multiple simultaneous links with other spacecraft. Initial studies with our link budget model show that, transmitting with a 1-watt 850 nm laser diode and receiving with a 1-inch aperture, 1 gigabit per second cross-link data rates can be achieved at 200 km distances with a bit-error-rate (BER) of 10^{-9}.

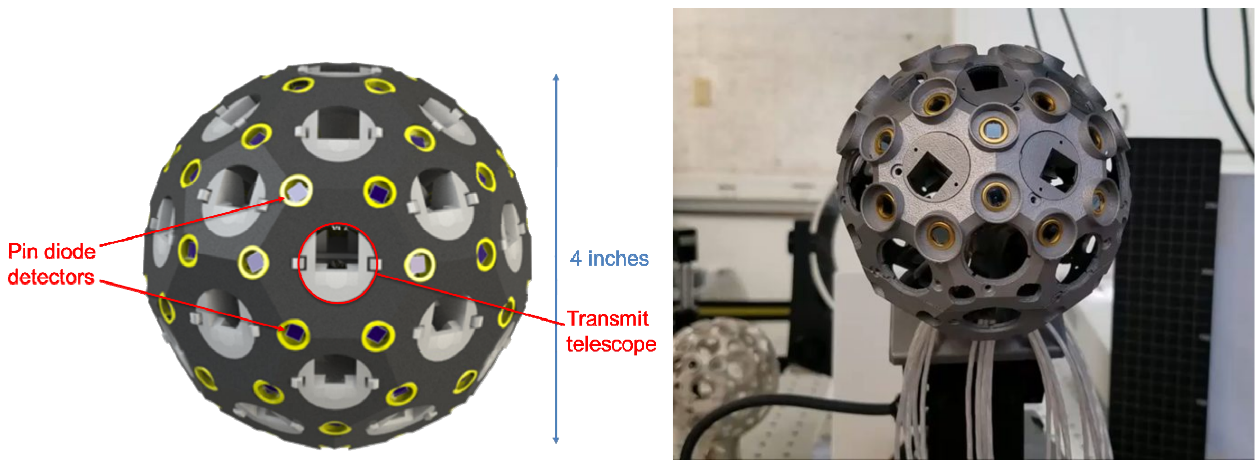

Figure 2: ISOC truncated dodecahedron geometry.

2.1 ISOC Transmit Telescope

In order to obtain full sky coverage, the ISOC is furnished with a set of miniature transmit telescopes. Each telescope consists of (see Fig. 3): a laser diode, a fixed mirror, and a MEMS mirror. The MEMS mirror provides an optical steering range of $\pm 12^{o}$. An array of strategically located telescopes around the ISOC provides full sky coverage.

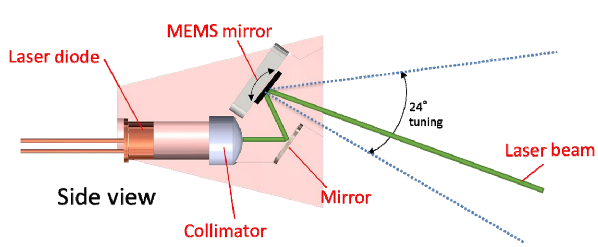

Figure 3: ISOC transmit telescope.

2.2 Link Budget

We have developed a very comprehensive optical link budget model to explore the possible dimensions of the ISOC apertures, amount of laser power, etc., as a function of distance and data rate. Table 1 lists a set of ISOC parameters under consideration. In Case I, for a transmitter aperture of 1 cm, receiver aperture of 2.5 cm, and laser power of 1 watt (using NRZ OOK modulation) we obtain a date rate of 1 Gbps at 200 kilometers, with a BER of 10^{-9} (see Fig. 4). If we change the transmit and receive apertures to 1.5 cm and 7.5 cm, respectively, a data rate of 1 Gbps is obtained at a range of 1,000 km. Figure 4 shows power required as a function of distance for Case I parameters. Note also that for Case I, a data rate of 10 Mbps could be achieved at 1,000 km.

Table 1. ISOC Parameters.

Item	Units	Value	
		Case I	Case II
Wavelength	nm	850	
Transmit aperture diameter	mm	10	15
Receive aperture diameter	mm	25	75
Transmit power	W	1	
Data rate	Gbps	1	
Distance	km	200	1000
Bit error rate		10^{-9}	

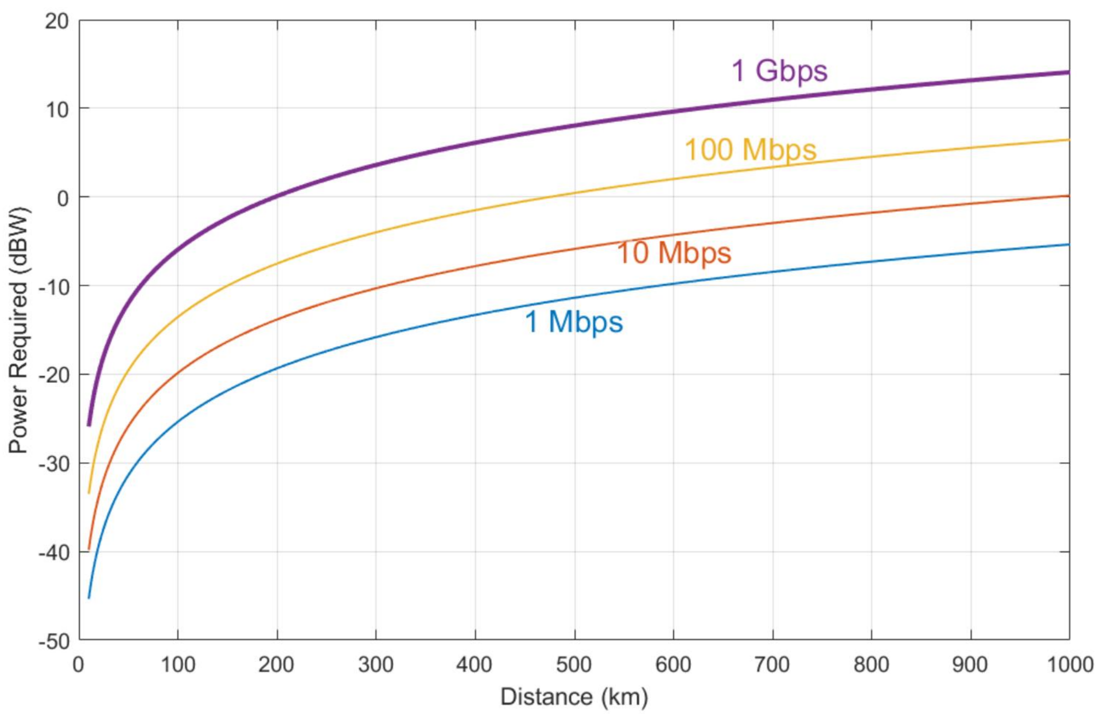

Figure 4: Power required as a function of distance for several data rates. Parameters used are listed in Table 1 – Case I.

3. INITIAL PROTOTYPE RESULTS

We have built and tested several ISOC telescopes with successful results. The telescopes employ the geometry shown in Fig. 3 and include a MEMS mirror. In Fig. 5 we show a picture taken during testing of one of the ISOC's telescopes.

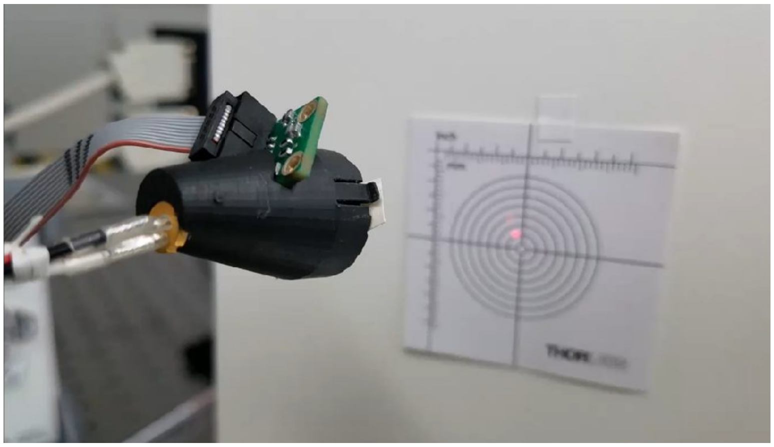

Figure 5: ISOC telescope during testing.

We have also built several versions of the ISOC that include arrays of photodetectors and transmit telescopes. Figure 6 shows two ISOCs under testing in our optical laboratory.

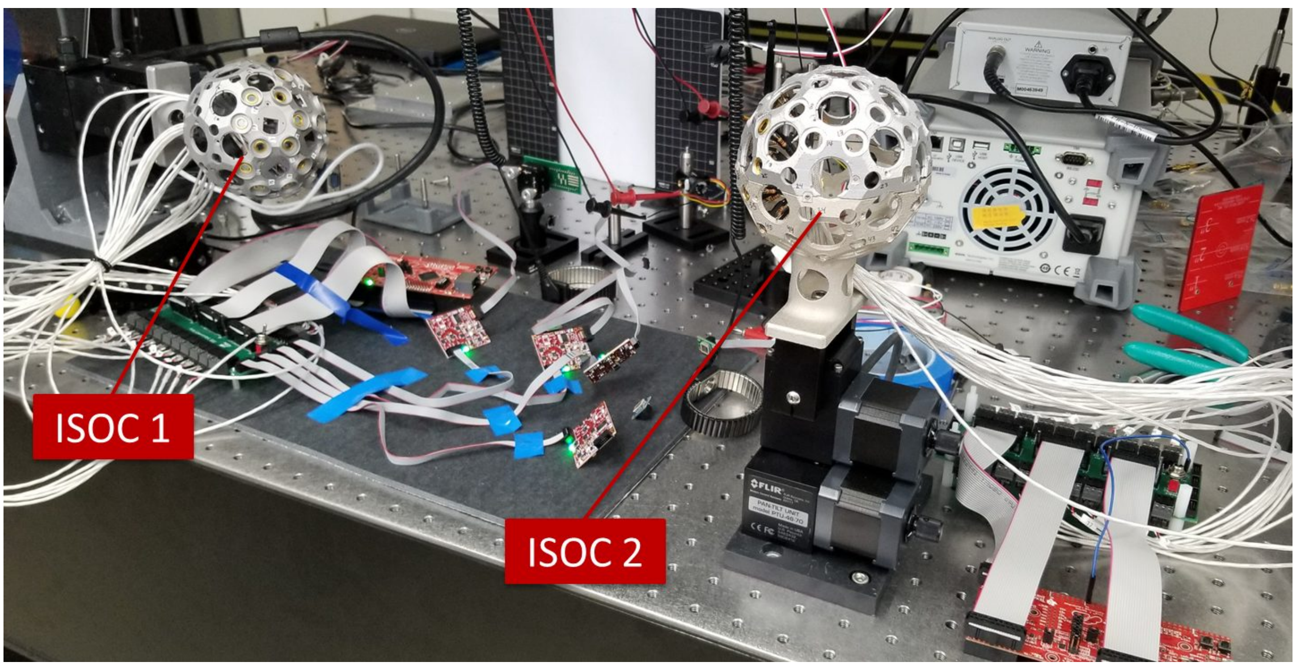

Figure 6: ISOCs under testing.

We are currently performing communications testing between the ISOCs using OOK at short ranges. Subsequently, we plan to increase the range distance and perform further testing.

4. Q4 REMOTE SENSING MISSION

In this section we discuss the Q4 mission, a technology demonstration flight concept to show the advantageous capabilities of the ISOC (Fig. 7) and its potential application for remote sensing. Q4 involves flying a swarm of (4) 6U CubeSats each furnished with ISOCs and with suitable remote sensing instruments.

The main purpose of the Q4 mission is to show: 1) full sky coverage, 2) gigabit-per-second data rates and 3) ability to maintain multiple links simultaneously. The Q4 CubeSats are 6U spacecraft that will be furnished with proven high-TRL components for successful testing of the ISOC.

The Q4 mission is a Low Earth Orbit (LEO) swarm of CubeSats implemented with commercial-off-the-shelf (COTS) technology to provide a high-heritage and modular platform. Q4 features a constellation of LEO CubeSats capable of providing gigabit communications while being able to host a variety of sensors. It will provide a new communications space platform with unparalleled coverage of the Earth's surface. The constellation will consist of 4 spacecraft placed in LEO orbit at an altitude of 400 km with a maximum in-plane distance between CubeSats of 100 km.

To keep it as flexible as possible, we envision launching the four CubeSats as secondary payloads on a launch vehicle to the International Space Station (ISS) at an orbit altitude of 400 km, an inclination of 51.6°, and a right ascension of the ascending node (RAAN) of 257°. The Q4 swarm is shown in Figure 7.


Figure 7: Proposed Q4 mission to demonstrate the ISOC capabilities.

4.1 Q4 CubeSat

Each 6U Q4 CubeSat includes a BlueCanyon XACT ADCS system and an eHawk 72W solar power by MMA (see Fig. 8). The eHawk solar panel is currently being used for many high profile missions such as JPL's MarCO[5], Asteria[6], Lunar Flashlight, NASA's BioSentinel, NEAScout, and ASU's LunaH-Map. The Q4 CubeSats also include a MiPS cold gas thruster.

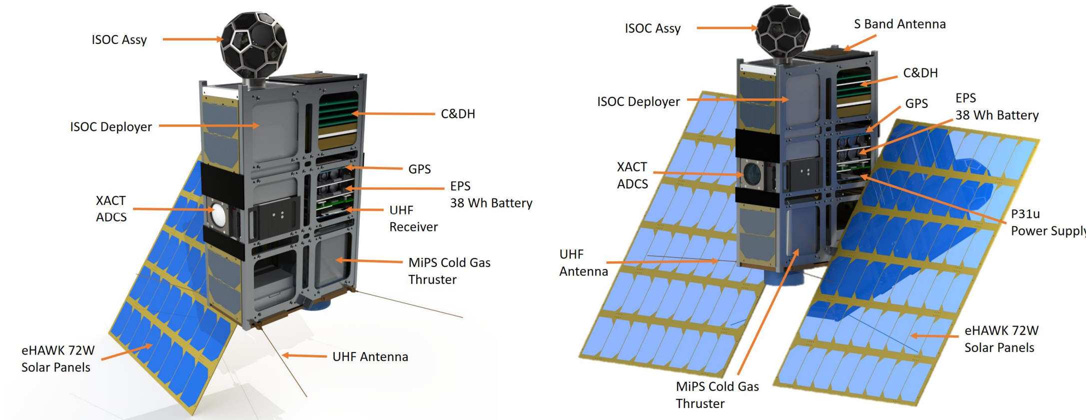

Figure 4. Images of Q4 CubeSats.

5. CONCLUSIONS

In this paper we have presented preliminary results of an inter-spacecraft omnidirectional optical communicator development for future swarms and constellations of spacecraft. Design considerations were presented for the ISOC and its transmit telescopes. In addition, we discussed a technology demonstration remote sensing mission concept labeled Q4. Q4 includes (4) 6U CubeSats, each furnished with an ISOC, in order to demonstrate the novel capabilities of this revolutionary communications system. Chief among these capabilities include full sky coverage, gigabit per second data rates and the ISOC's ability to maintain multiple links simultaneously. Additional details of the Q4 missions are to be reported in future publications. The ISOC is ideally suited for crosslink communications among small spacecraft, especially for those forming a swarm and/or a constellation. Small spacecraft furnished with ISOC optical communications systems should be able to communicate at gigabit per second rates over long distances. This data rate enhancement can allow real-time, global science measurements and/or ultra-high fidelity observations from tens or hundreds of Earth-orbiting satellites.

6. ACKNOWLEDGMENTS

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2017 California Institute of Technology. U.S. Government sponsorship acknowledged.

This work is being conducted with funding from NASA's Small Spacecraft Technology Program.

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