Omnidirectional Optical Communicator

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Abstract—**We are developing an inter-satellite omnidirectional optical communicator (ISOC) that will enable cross-link communications between spacecraft at Gbps data rates over distances of up to thousands of kilometers in free space. The ISOC will allow superfast cross-links and will be a technology enabler for swarms and formation flying spacecraft. The ISOC under development features a truncated dodecahedron geometry that can hold an array of fast photodiode detectors and gimbal-less MEMS scanning mirrors. The main goals of the ISOC development include: 1) full sky coverage, 2) Gbps data rates and 3) the ability to maintain multiple simultaneous links. We have developed two omnidirectional communicator prototypes capable of full-duplex operation. We are using advanced single-mode laser diodes operating at 850 nm capable of producing hundreds of milliwatts of laser radiation. We are also employing MEMS-based beam steering mirrors, and fast PIN photodiodes to achieve long-range communications. The ultimate goal of the project is to achieve full duplex operation at 1 Gbps data rates over 200 km and slightly lower data rates at longer distances. In this paper we describe the overall ISOC architecture and present the design tradeoffs for gigabit data-rate operation. We also present preliminary NRZ On-Off Keying communications simulation results obtained using our optical link budget model. 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 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, or permit high-bandwidth, direct-to-earth communications for planetary missions.**

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1. INTRODUCTION

With the advent of the Internet of Things, smart cities, worldwide internet access and fast on-the-move communications, modern wireless RF communications are rapidly becoming bandwidth limited by various parameters of the transceivers they employ. Among these parameters include antenna gain (aperture size), transmit power, and frequency. Also as emerging technologies, such as swarms of small spacecraft, continue to demand more bandwidth while featuring lower SWaP, 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]. This technology is already widespread in the telecommunications industry in the form of fiber optic links, but free-space optical communication has yet to be explored in full depth. This project aims to develop a new inter-satellite omnidirectional optical communicator (ISOC) capable of communicating with a swarm of other CubeSats simultaneously at gigabit speeds (see Fig. 1).

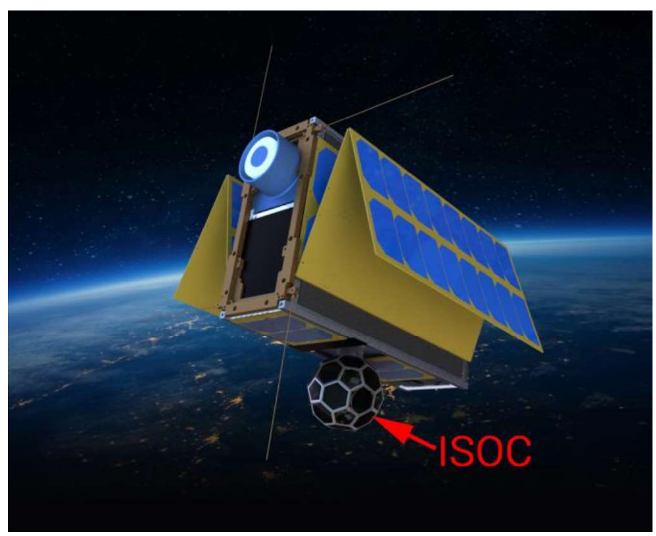


Figure 1: Inter-spacecraft Optical Communicator.

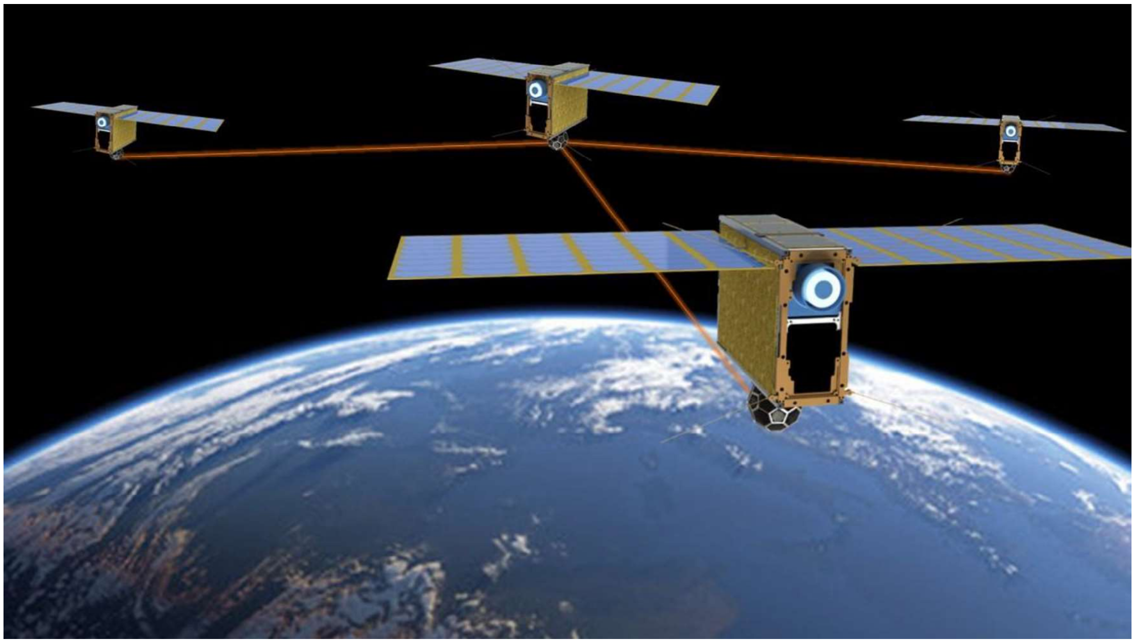


Figure 2. Spacecraft swarm interconnected via the Inter-spacecraft Optical Communicator.

The ISOC effort involves the design, prototyping, and testing process for critical subsystems of this communicator, including transmit telescopes, MEMS mirror modules for laser pointing, receive photodetector arrays, and optical link budget calculation. The ISOC will be able to offer three main features: 1) high data rates, 2) full sky coverage and 3) the capability to maintain multiple links simultaneously. A key application of the ISOC is in swarms of spacecraft (see Fig. 2). Other commercial applications of the ISOC include UAVs, the Internet of Things, smart cities, etc. In this paper we will provide a brief description of the ISOC, show recent progress on the transmitter development and describe the spacecraft design for Q4, a future ISOC technology demonstration mission that includes (4) 6U CubeSats.

2. DESCRIPTION OF ISOC

The advanced omnidirectional optical communicator should allow high data rate communications for inter-spacecraft cross-links as well as for ground up- and downlinks.

The ISOC design uses a novel scheme where miniature optical telescopes on all facets of a truncated-icosahedral frame provide full sky coverage (Fig. 3). Key features of the ISOC include its high data rates and its ability to maintain multiple simultaneous links with other spacecraft. Preliminary studies with our link budget model (presented below) show that, transmitting with a 1-watt 850 nm laser diode and employing a 1-inch receiving aperture, 1 gigabit per second cross-link data rates can be achieved at 200 km distances with a BER of 10^{-9}.

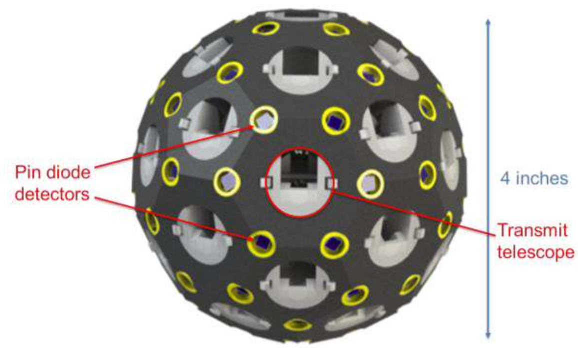


Figure 3: ISOC truncated dodecahedron geometry.

3. 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. 4): a laser diode, a fixed mirror, a MEMS mirror and a 3x bi-confocal lens (not shown in Fig. 4). The MEMS mirror provides an optical steering range of ±12º. The 3x lens expands the steering to $\pm 36^{\circ}$. An array of strategically located telescopes around the ISOC provides full sky coverage. A sketch of the ISOC transmit telescope is shown in Fig. 4 and a typical Zemax result in Fig. 5.

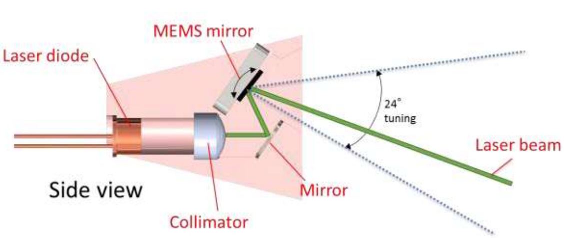


Figure 4: ISOC transmit telescope.

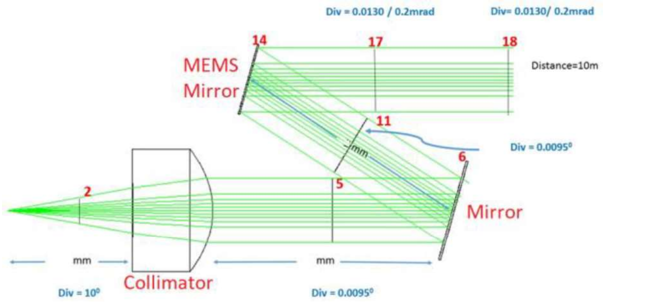
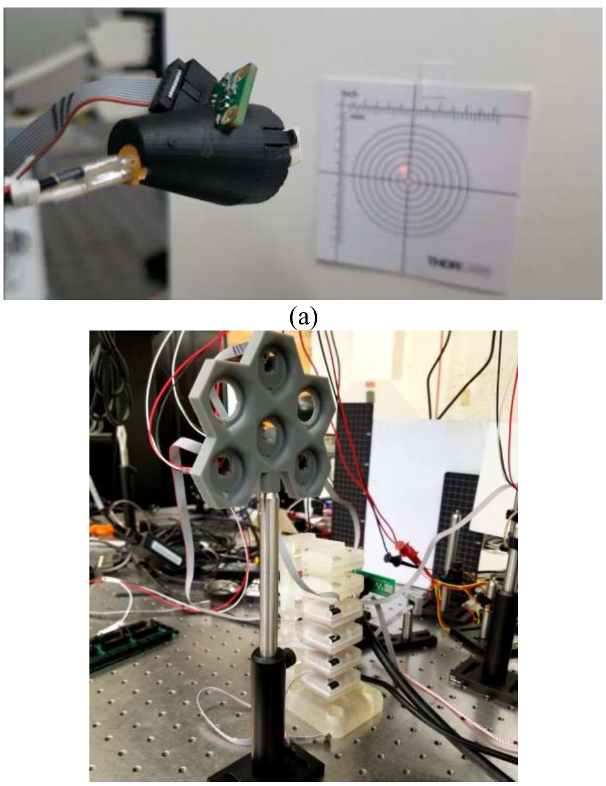


Figure 5: Zemax simulation result (Fig. 4 geometry).

The MEMS mirrors provide 2D steering and are manufactured by Mirrorcle. Each ISOC telescope is planned to furnish with 1-watt laser diodes. Assuming a diode efficiency of 25%, it is expected that the power consumed by each telescope will be about 4 watts. If 20 watts are available onboard for optical communications, we estimate that 4 telescopes (4 links) could be operated simultaneously.

We have built and tested several ISOC telescopes with successful results. In Fig. 6a we show picture taken during testing of one of the ISOC's telescopes. A 6-telescope holder is shown in Fig. 6b during angle-of-arrival testing.



(a)

(b)

Figure 6: ISOC's (a) single telescope and (b) multiple telescopes during testing.

Figure 7 shows two ISOCs under testing in our optical laboratory. Each ISOC is installed on computer-controlled platforms. The platforms are programmed to move in azimuth and elevation so as to emulate motion between two spacecraft.

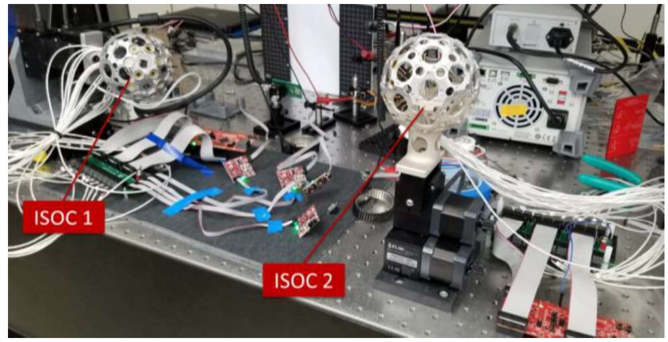


Figure 7: ISOCs under testing.

4. ISOC Pointing and Tracking

The ISOC employs arrays of miniature transmit (Tx) telescopes and receive (Rx) photodetectors (Fig. 8) to provide secure high data rate communications. The Tx telescopes receive pointing commands and communications data from an FPGA whereas the Rx photodetectors feed the incoming signals to the FPGA via suitable analog-to-digital converters (ADCs). The Tx telescopes are used to transmit the communications signals to neighboring assets. The Rx photodiodes receive optical communications signals from other spacecraft and allow to determine the bearing and elevation of the incoming signals via a proprietary technique. Once bearing and elevation of the incoming signal is calculated by the FPGA, the ISOC can direct the appropriate telescope to communicate with the generator of the incoming signal.

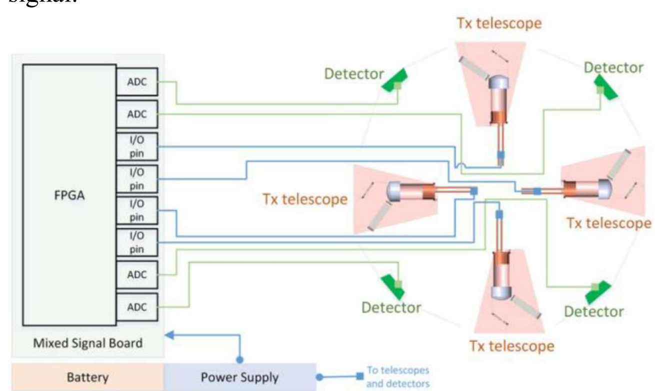


Figure 8: Simplified block diagram of the ISOC.

5. Q4 Mission Concept

The Q4 mission is a technology demonstration flight concept to show the advantageous capabilities of the ISOC. It involves flying a swarm of (4) 6U CubeSats each furnished with ISOCs (Fig. 9). 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.

Figure 9: Proposed Q4 mission to demonstrate the ISOC capabilities.

5.1. Q4 CubeSat

Each Q4 CubeSat includes a BlueCanyon XACT ADCS system and an eHawk 72W solar power by MMA (see Fig. 10). 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.

6. 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. For the link budget model, a MATLAB code was created that calculates the link budget for multiple inter-satellite distances. The code is able to calculate a traditional link budget or find the power required for a certain bit error rate, distance and bitrate. The code currently supports NRZ-OOK and M-PPM modulations for both a Gaussian and Poisson noise channels but other modulations are planned to be added. The code allows the user to calculate a specific link performance or to find the power required over a range of link setups. The latter requires more computation time since it uses an iterative solver. Users input parameters such as the detector performance values, transmit power, offset angles, required bitrate, etc. A more detailed description of our link budget model is planned to be published elsewhere. 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. 11a). 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 (Fig. 11b).

Table 1- ISOC Parameters for Link Budget Calculations

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 11 shows optical power required as a function of distance for the two cases discussed above. Note that for

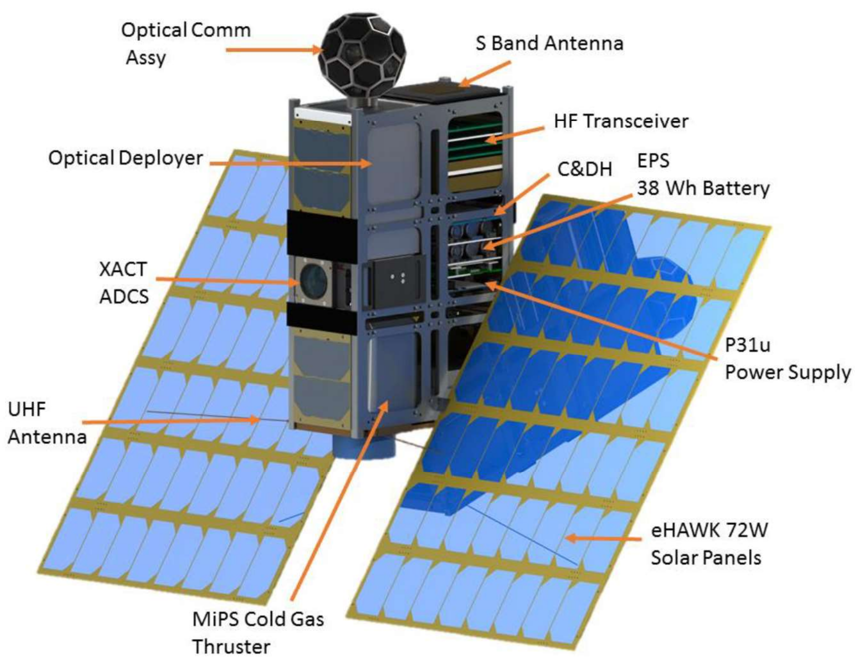
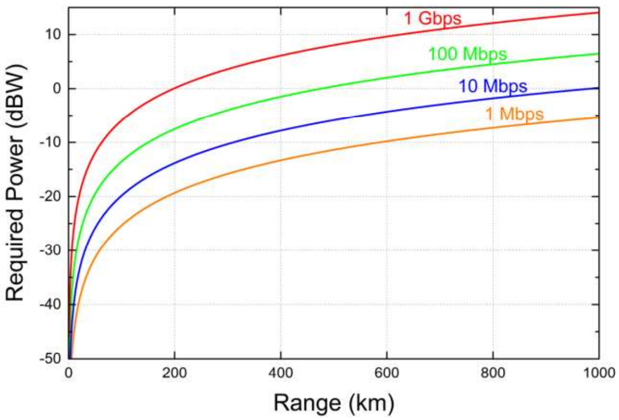
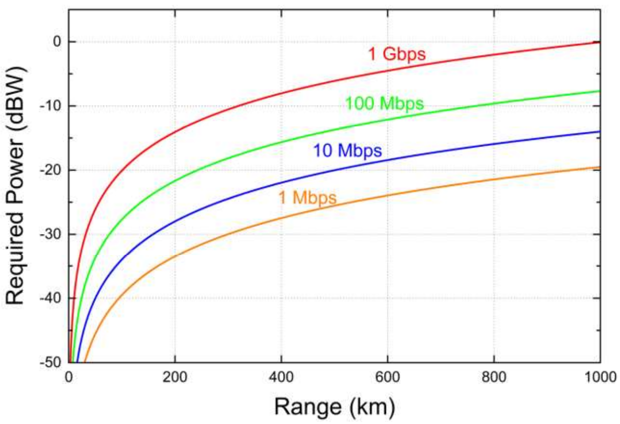


Figure 10. Image of Q4 CubeSat.

Case I, a data rate of 1 Gpbs can be obtained at 200 km and 10 Mbps at 1,000 km.



(a)



(b)

Figure 11: Optical power required as a function of distance for several data rates. Parameters used are listed in Table 1 (a) Case I and (b) Case II.

Note also for Case II, 1 Gbps data rates can be achieved at 1,000 km. It is clear that the size of the receive aperture is a key parameter for achieving high data rates. We are currently exploring options to further increase the ISOC's receive aperture in order to obtain multi gigabit data rates at 3,000 to 5,000 kilometers.

7. CONCLUSIONS

In this paper we have presented preliminary results of an inter-spacecraft omnidirectional optical communicator that is being developed for future swarms and constellations of spacecraft. General design considerations were presented for the ISOC and for its transmit telescopes. In addition, we discussed a technology demonstration 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. 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. Commercial applications of the ISOC include the Internet of Things, gigabit space communications, spaceborne cloud computing, smart cities, as well as terrestrial gigabit wireless communications and networking.

8. ACKNOWLEDGMENTS

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10. BIOGRAPHY

Dr. Jose Velazco *is JPL's principal investigator for the Omnidirectional Optical Communicator and has over 20 years of experience in carrying out R&D projects. Dr. Velazco has extensive experience in implementing wideband receivers for electronic surveillance applications including wide-open and superheterodyne receivers where he acquired expertise in direction-of arrival (Direction Finding) hardware and software. Recently he worked on an advanced multimegabit Optical communicator for ground application and on an all-digital phase-array radar. He is currently working jointly with University of Michigan on the design of a small CubeSat constellation mission for testing various network protocols. In addition, he is developing a gigabit Omnidirectional Optical Communicator with University of California Irvine for CubeSats. Dr. Velazco's current interest include the implementation of spacecraft swarms and formation flying as well as all optical spaceborne networks. He is also the technical supervisor of JPL's Applied Electromagnetic Group, which develops advanced communications microwave and millimeter-wave transmitters, as well as high sensitivity receivers for NASA's Deep Space Network.*