# High data rate inter-satellite Omnidirectional Optical Communicator

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## ABSTRACT

We are developing an inter-satellite omnidirectional optical communicator (ISOC) that will enable up to 1 Gbps data rates over a distance up to 200 km in free space. Key features of the ISOC include full sky coverage and its ability to maintain multiple links simultaneously. The ISOC outer frame is a truncated icosahedron small enough to deploy out of a CubeSat. The frame contains photodetector receivers and gimbal-less scanning MEMS mirrors for transmit beam steering. We have developed miniature transmitter housings ("telescopes") that include a single mode laser diode and a MEMS mirror. The frame's vertices feature fast photodetectors for reception and direction finding. In this paper we present design considerations and testing results for an ISOC built to operate at 850 nm. We also discuss a mission concept, labeled Q4, which is being proposed to demonstrate the omnidirectional capabilities of the ISOC. Q4 includes (4) 6U CubeSats furnished with ISOCs and advanced ADCS systems for proper beam pointing. We present design considerations for the Q4 CubeSats and an overall description of the Q4 mission including expected results.

## 1. INTRODUCTION

Modern wireless communications are rapidly becoming bandwidth limited by various parameters of the RF transceivers they utilize - these include antenna gain, transmit power, and frequency. 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]. This technology is already widespread 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 constellation of other CubeSats simultaneously and at gigabit speeds. 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. In this paper we will provide a brief description of the ISOC, show recent progress on the transmitter development and describe Q4, an ISOC technology demonstration that includes (4) 6U CubeSats.

## 2. ISOC DESCRIPTION

The advanced omnidirectional optical communicator (shown in Fig. 1) should allow high data rate communications for inter-spacecraft cross-links as well as for ground up- and downlinks.

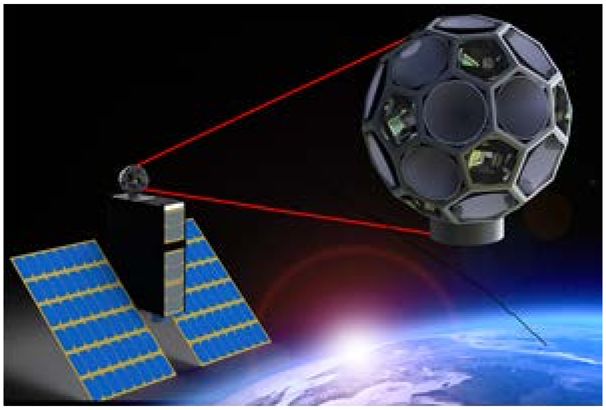

**Figure 1: Inter-spacecraft Optical Communicator.**

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). 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 show that, transmitting with a 1-watt 850 nm laser diode and a 1-inch receiving aperture, 1 gigabit per second cross-link data rates can be achieved at 200 km distances with a BER of $10^{-9}$.

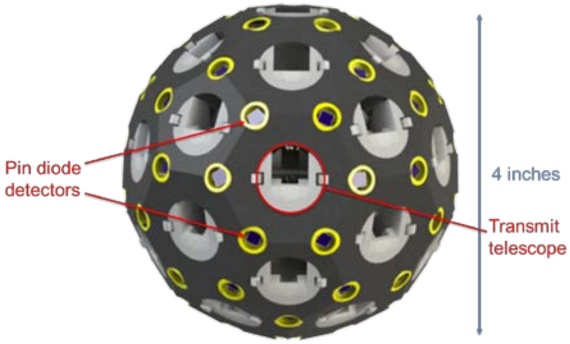

**Figure 2: ISOC truncated dodecahedron geometry.**

### *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 ±12°. An array of strategically located telescopes around the ISOC to provides full sky coverage. A sketch of the ISOC transmit telescope is shown in Fig. 3 and a typical Zemax result in Fig. 4.

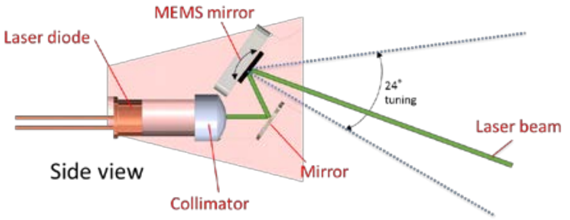

**Figure 3: ISOC transmit telescope.**

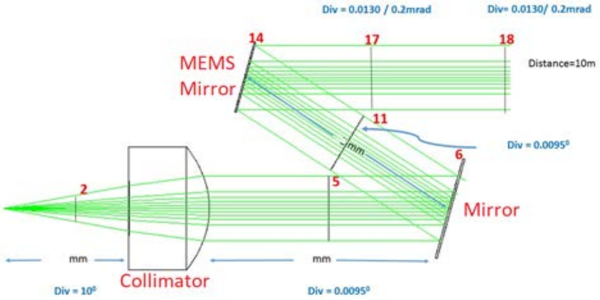

**Figure 4: Zemax simulation result (Fig. 3 geometry).**

We have built and tested several ISOC telescopes with successful results. In Fig. 5 we show a picture taken during testing of one of the ISOC's telescopes.

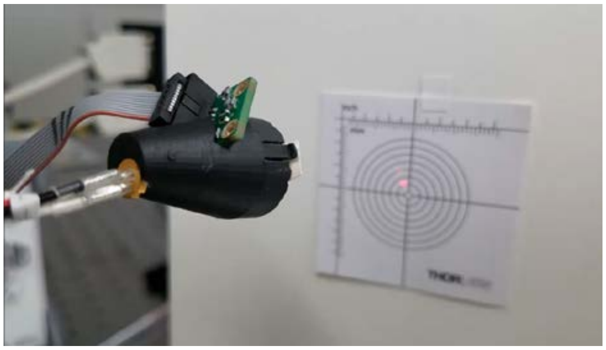

**Figure 5: ISOC telescope during testing.**

Figure 6 shows two ISOCs under testing in our optical laboratory.

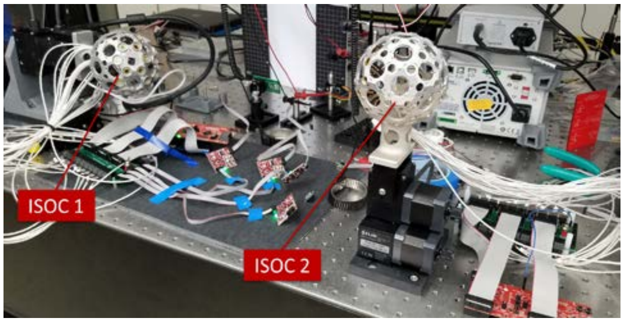

**Figure 6: ISOCs under testing.**

## 3. Q4 MISSION CONCEPT

The Q4 mission is a technology demonstration flight concept to show the advantageous capabilities of the ISOC (Fig. 7). It involves flying a swarm of (4) 6U CubeSats each furnished with ISOCs.

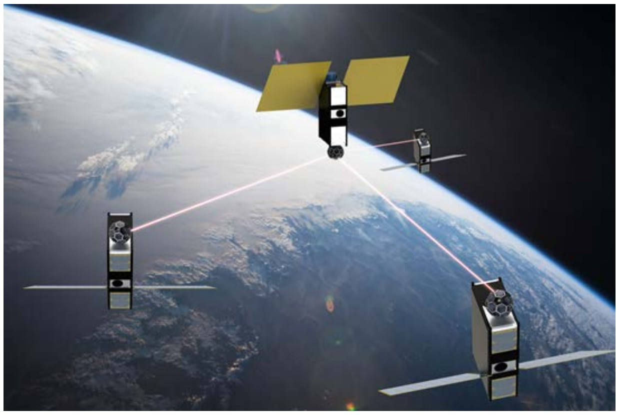

**Figure 7: Proposed Q4 mission to demonstrate the ISOC capabilities.**

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.

### *3.1. Q4 CubeSat*

Each 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.

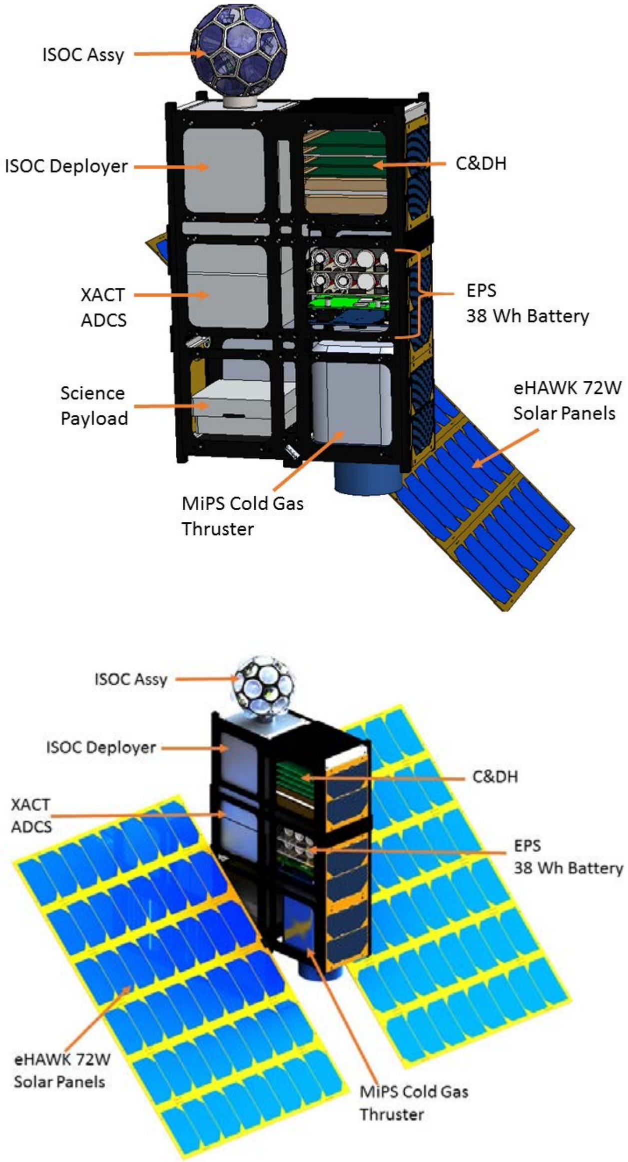

**Figure 8. Images of Q4 CubeSat.**

### *3.2. Orbital Dynamics*

The orbit being considered for the Q4 mission consists of one spacecraft in a circular orbit with a 400km LEO altitude (referred to henceforth as the "leader"), and three other spacecraft ("followers") in slightly elliptical orbits surrounding the center spacecraft. The eccentricity of these other three orbits will cause the spacecraft to move relative to each other as they orbit the Earth, but all the orbits will have the same period, so that the relative motion is repetitive. The Clohessey-Wiltshire model [7] describes linearized dynamics of the follower spacecraft relative to the leader, giving the equations of motion in a coordinate system centered on the leader (local vertical/local horizontal [LVLH] frame). The *x*-axis points radially outward from the earth, the *y*-axis points in the direction of the vehicles tangential velocity, and the *z*-axis is perpendicular to the orbital plane, completing the right-handed system.

Linearizing a follower's equations of motion about the leader's circular orbit gives equations of motion for a follower in the leader's LVLH frame.

$$\ddot{x} - 2n\dot{y} - 3n^2x = f_x \tag{1}$$

$$\ddot{y} + 2n\dot{x} = f_y \tag{2}$$

$$\ddot{z} + n^2z = f_z \tag{3}$$

$$n = \sqrt{\frac{\mu}{a^3}} \tag{4}$$

μ is the Earth's gravitational parameter (3.986x1014 $m^3$ $s^{-2}$) and *a* is the orbit radius (400,000m+6,371,000m). *n* is the angular frequency of the reference orbit, and the period is $2\pi/n$ = 1.54 hrs

Solving analytically the unforced solution (fx=fy=fz=0) gives

$$x = A_x \cos(nt + \alpha) \tag{5}$$

$$y = -2A_x \sin(nt + \alpha) + y_{\text{off}} \tag{6}$$

$$z = A_z \cos(nt + \beta) \tag{7}$$

where α, β, $A_x$, $A_z$, and $y_{off}$ are all free parameters. α and β set the phases of the two modes, $A_x$ and $A_z$ set the magnitude of each phase, and $y_{off}$ is a constant offset in the y-direction. The *x* and *y* motions are coupled due to the velocity variation introduced by the orbit's eccentricity, but the cross-track motion is a free parameter, as are the phases of both modes and the *y* offset of the follower's path in the LVLH frame. These solutions also include drift terms that were set to zero by design for the purpose of our mission. Figure 9 shows a possible orbit under consideration where the followers orbit around the leader at distances of ~100 km.

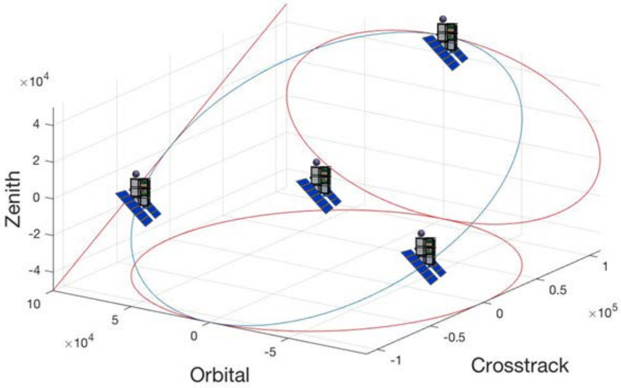

**Figure 9. One possible configuration of spacecraft in the leader LVLH frame (units in meters)**

Numerical simulations carried out in MATLAB show that the maximum angular velocity needed for beam steering between leader and follower is on the order of milliradians per second. In the special case where the followers are in a circle around the leader, the angular velocity is a constant $1.3 \times 10^{-3}$ rad/s. The speed can rise to $3 \times 10^{-3}$ rad/s for more elliptical paths in the LVLH frame.

The Clohessey-Wiltshire model is neutrally stable, but the addition of additional factors such as J2 perturbations (caused by the oblateness of the Earth) and solar radiation pressure will introduce the need for station keeping in the final mission..

Future work will include optimization of the configuration for science and analysis with a more complex model.

### *3.3. Link Budget*

We have put together a very comprehensive optical link budget model to explore the possible dimensions of the Q4 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. For a transmitter aperture of 1.5 cm, receiver aperture of 3.5 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 $10^{-9}$).

**Table 1: ISOC Parameter used for Link Budget Calculations**

| Item | Units | Value |
|---|---|---|
| Geometry | | Truncated Icosahedron |
| Modulation | | NRZ On-Off-Keying |
| Wavelength | nm | 850 |
| Transmit aperture diameter | mm | 15 |
| Receive aperture diameter | mm | 35 |
| Transmit power | W | 1 |
| Data rate | Gbps | 1 |
| Bit error rate | | $10^{-9}$ |
| Range | km | 200 |

### *3.4. Q4 Goals*

As indicated earlier, the main goal of the proposed Q4 mission is to demonstrate the revolutionary features of the ISOC which include full sky coverage, gigabit data rates and its ability to maintain multiple simultaneous links. Additional details of the Q4 mission concept will be published as we develop this mission further.

## 4. CONCLUSIONS

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, design considerations were presented for 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. Additional details of the Q4 missions will 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, or permit high-bandwidth, direct-to-earth communications for (inter)planetary missions.

## 5. ACKNOWLEDGMENTS

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