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Inter-spacecraft Omnidirectional Optical Communicator for Swarms

Jose E. Velazco, Danny Wernicke, Joseph Griffin, Andy Klaib, Sean Cornish, John Huleis
Jet Propulsion Laboratory
4800 Oak Grove Drive, Pasadena, CA 91109; (818) 354-2305
{Jose.E.Velazco, Daniel.R.Wernicke, Joseph.C.Griffin, Andy.Klaib, Sean.E.Cornish, John.N.Huleis}@jpl.nasa.gov

Ozdal Boyraz, Imam Uz Zaman
University of California, Irvine
Irvine, CA 92697; (949) 824-1979
{Oboyraz, zamani}@uci.edu

ABSTRACT

We are developing a low SWaP (size, weight and power) inter-spacecraft omnidirectional optical communicator (ISOC) to enable spacecraft swarms. The ISOC employs arrays of lasers telescopes and detectors fitted inside a truncated dodecahedron geometry to provide full sky coverage. Each telescope operates at 850nm and includes a 1W laser diode, collimator, MEMS mirror and steering lens. The photodetectors are strategically arranged around the ISOC body and are used for continuous angle-of-arrival (AOA) calculation of the incoming signals using proprietary AOA algorithms. The ISOC provides full sky coverage (4π steradians) and will be able to maintain multiple gigabit links simultaneously. In this paper we will present the latest experimental results obtained with the ISOC including high data rate communication tests between 2 ISOCs. We will also present results of our swarm simulator that includes 4 ISOCs mounted on computer-controlled moving platforms. Lastly, we will present design details of a technology demonstration mission concept for validating the ISOC as well as examples of future swarm missions that could be enabled by this technology.

1. INTRODUCTION

Small satellites (smallsat) missions have the potential of delivering substantial science return, at a portion of the cost of larger flagship counterparts. Furthermore, if smallsats can be configured in clusters or swarms, the technological and science return could equal or eventually surpass the returns of larger ships. Two key technical challenges for realizing spacecraft swarms are: 1) fast and stable interconnectivity among the spacecraft and 2) adequate metrology to accurately and

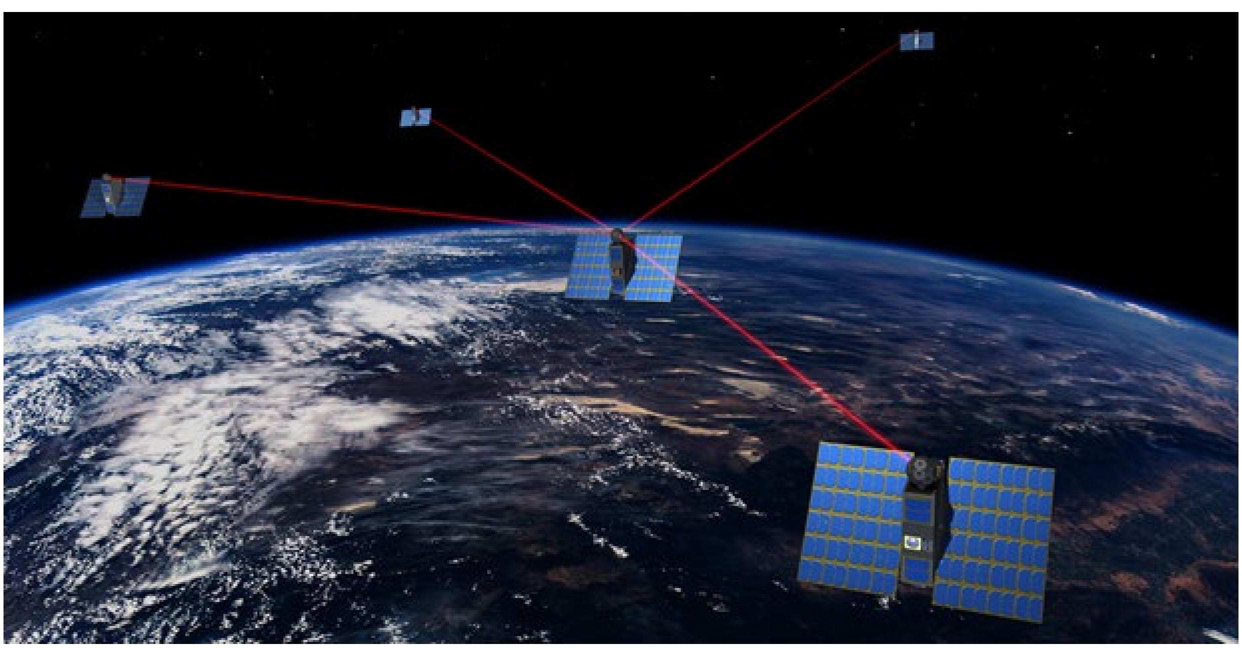

Figure 1: Smallsat swarm interconnected via the Inter-spacecraft Optical Communicator.

continuously determine the exact position of the ships forming the swarm. We are developing an interpacraft optical communicator (ISOC) that is ideally suited for swarm applications (see Fig.1) and that will provide adaptable high data rate communications as well as highly accurate metrology. In section 2 of this paper we will discussed design considerations of the ISOC's transmit telescopes including test results. Angle of arrival measurements are shown in section 3. Section 4 discusses Q4, a technology demonstration mission we are proposing for the ISOC.

2. ISOC DESCRIPTION

The advanced omnidirectional optical communicator (shown in Fig. 2) 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. 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}.

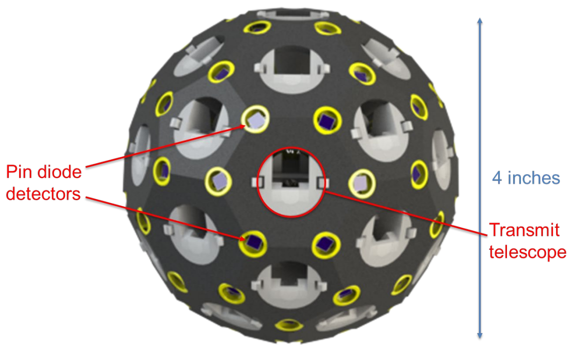

Figure 2: ISOC truncated dodecahedron geometry.

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.

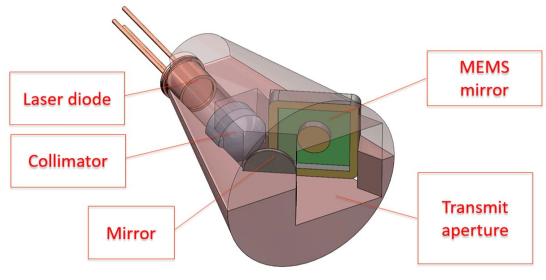

Figure 3: ISOC transmit telescope.

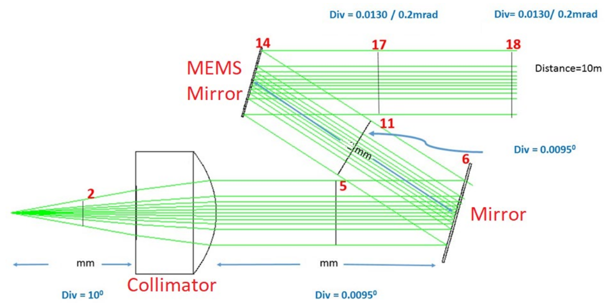

Figure 4: Zemax simulation result (Fig. 3 geometry).

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.

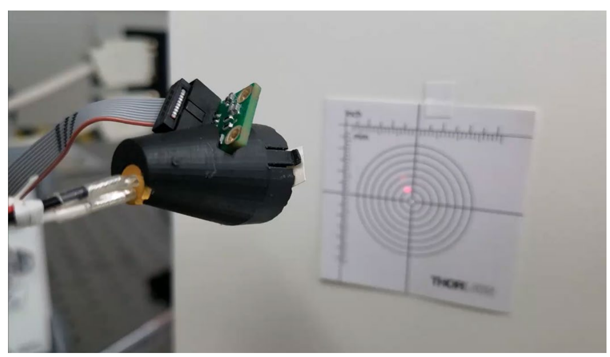

Figure 5: ISOC telescope during testing.

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

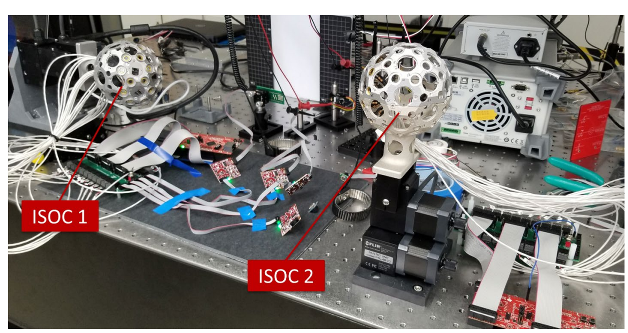

Figure 6: ISOCs under testing.

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.

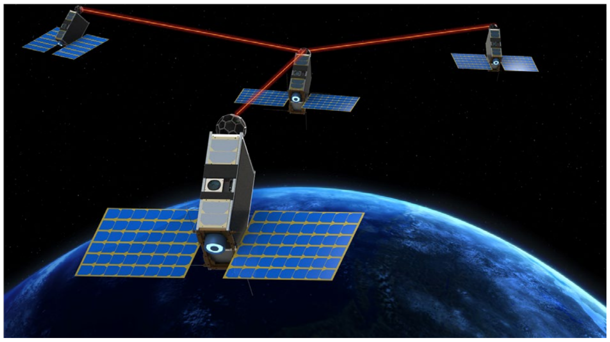

Figure 7: Proposed Q4 technology demonstration mission for the ISOC.

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.

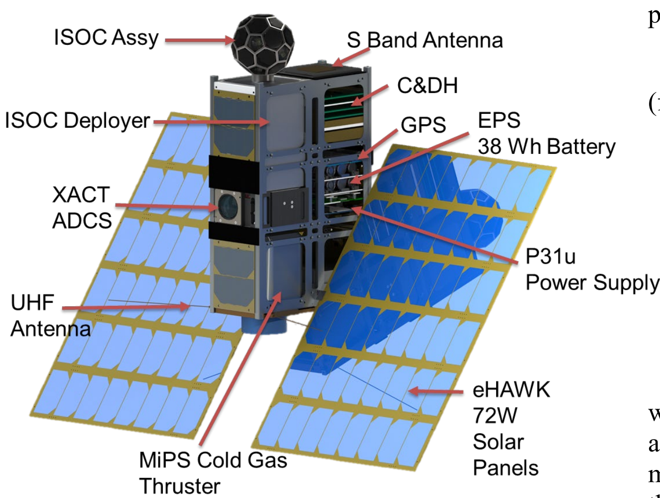

Figure 8. Image of Q4 CubeSat.

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.

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

$$\ddot{y} + 2n\dot{x} = f_y \quad (2)$$

$$\ddot{z} + n^2 z = f_z \quad (3)$$

$$n = \sqrt{\frac{\mu}{a^3}} \quad (4)$$

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

$$x = A_x \cos(nt + \alpha) \quad (5)$$

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

$$z = A_z \cos(nt + \beta) \quad (7)$$

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.

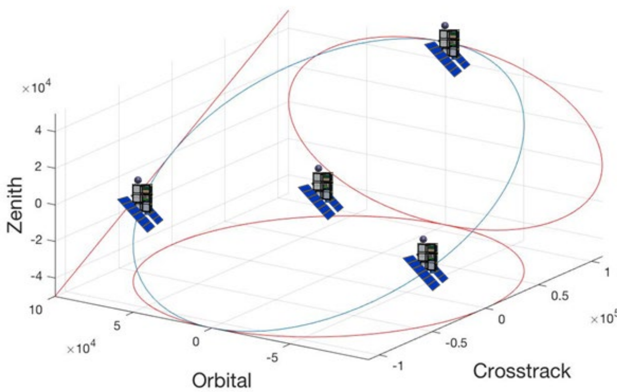

Figure 9. One possible configuration of spacecraft in the leader LVLH frame (units in meters)

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 1.3x10^{-3} rad/s. The speed can rise to 3x10^{-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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