

Development Status of the Inter-Spacecraft Optical Communicator

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Abstract—Chascii is currently developing the inter-spacecraft omnidirectional optical communicator (ISOC) to provide fast connectivity and navigation information to small spacecraft forming a swarm or a constellation in LEO and cislunar space. The ISOC operates at 1550 nm and employs a dodecahedron body that holds six optical telescopes and 20 external arrays of detectors for determining the angle of arrival of the incoming beams. Additionally, the ISOC features six fast avalanche photodetector receivers for high-speed data rate connectivity. The ISOC should be suitable for distances ranging from a few kilometers to a few thousand kilometers. It will provide ubiquitous coverage and gigabit connectivity among smallsats, forming a constellation around the moon. It will also provide continuous positional information among these spacecraft, including bearing, elevation, and range. We also expect the ISOC to provide fast, low-latency connectivity to assets on the lunar surface, such as landers, rovers, instruments, and astronauts. Chascii is currently developing a lunar ISOC, including all its transceivers, optics, and processing units. We are developing the ISOC as a key candidate to enable LunaNet. In this paper, we will present experimental results of angle-of-arrival testing using various experimental apparatus. We believe the ISOC, once fully developed, will provide commercial, high-data-rate connectivity to future scientific, military, and commercial missions around LEO, cislunar space, and beyond.

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1. INTRODUCTION

It is expected that the next generation of spacecraft constellations will require multiple simultaneous links to communicate among themselves and with the ground. This is especially relevant in cislunar space (see Fig. 1) where a large number of orbiting and surface assets are planning to be deployed in the coming years [1-3].

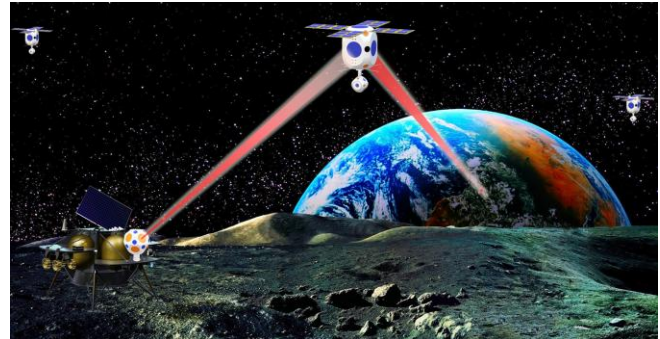


Figure 1. Image showing orbiting lunar assets providing relay connectivity to lunar lander.

As spacecraft sensors' sophistication and demands for higher resolution increase, the amount of data they shall collect, and capture will tend to grow exponentially. Sharing this increasingly large amount of data with other spacecraft and with the ground creates a great demand for faster multiple-link data transfer mechanisms. In addition, there are new applications where large amounts of data need to be transferred from the ground to space and back to ground. These applications include but are not limited to the global internet, the internet of things, cloud computing, data centers, financial market data sharing, smart cities, mobile assets, the military, among others.

Data transfer between spacecraft and ground stations is normally achieved using radio-frequency (RF) signals and is typically limited to speeds of hundreds of megabits per second. As sensor resolution and amount of data continues to improve, RF communications will eventually become the bottleneck that limits the amount of data transfer per unit time. Laser communications, using single telescope optical terminals, has promise in providing higher data rates but suffers from beam pointing issues and a "one user at the time" limitation. In addition, we estimate that for future terrestrial applications such as wireless communication between cars, high data rate Wi-Fi, direct satellite to smartphone communications, etc., there will be a need for a paradigm-shifting, high data rate, multiple-link communications terminal. These new terminals, in addition to providing multi-gigabit multiple-link connectivity, should also feature reduced size, weight and power (SWaP).

We present a novel inter-spacecraft omnidirectional optical communicator (ISOC) that we are developing at Chascii to

provide high data rate low latency connectivity in cislunar space. The ISOC's low SWaP (size, weight, and power) makes it ideally suited for smallsat platforms. We envision installing ISOCs in orbiting spacecraft, landers, rovers, and lunar habitats.

In this article, we provide a report of ISOC's developmental status. In Section 2 we provide an overview of the ISOC including the main features of its current design. Section 3 covers fast steering mirror management. Testing results of ISOC's angle-of-arrival system are discussed in Section 4. Final conclusions are presented in Section 5.

2. ISOC OVERVIEW

At Chascii we are carrying out the design, construction and testing of Chascii's new inter-spacecraft omnidirectional optical communicator that will provide fast connectivity and navigation information to small spacecraft forming a swarm or a constellation in cislunar space (e.g., LunaNet [1-2]). The cislunar ISOC operates at 1550 nm, employs a dodecahedron body holding 6 optical telescopes and 20 external arrays of detectors for angle-of-arrival determination (see Fig. 2). The ISOC will provide full sky (4π steradian) coverage and gigabit connectivity among smallsats forming a swarm or constellation. It will also provide continuous positional information among these spacecraft including bearing, elevation, and range. In addition, we expect the ISOC to provide fast low-latency connectivity to assets on the surface of the moon such as landers, rovers, instruments, and astronauts. Under a NASA SBIR Phase II effort, we are building and testing a cislunar ISOC including all its transceivers, optics and processing units. We are also performing outdoor testing of the resulting ISOC. The outdoor testing will include a demonstration of fast connectivity and multiple link capability of the ISOC. We plan to pursue additional NASA SBIR efforts (i.e., Phase II Extension and Flight Opportunities) in order to develop a flight version and fly the ISOC in low-Earth orbit and cislunar space. We believe the ISOC, once fully developed, will provide commercial, high data rate connectivity to future scientific, military, and commercial missions around cislunar space and beyond.

The ISOC should offer superior performance over existing single-aperture terminals because its architecture was natively conceived specifically for full-sky, multiple-link operation. The ISOC's terminal design, Angle of Arrival (AoA) detection system and high integration are fully conducive to simultaneous multi-link operation while minimizing size, weight, power, and cost (SWaP-C). The ISOC features the unique capability of being capable of providing positional information, when part of a spacecraft cluster (e.g., constellations, swarms, or networks).



Figure 2. Picture of the lunar ISOC.

The ISOC was previously developed by the PI at NASA Jet Propulsion Laboratory (JPL) with funding from NASA's Small Spacecraft Program (STP) for inter spacecraft communications [3-6]. At Chascii we seek to make key improvements to its architecture and develop a flight version of the ISOC for connectivity in the lunar environment and beyond [7-13].

3. FSM MIRROR MANAGEMENT

The ISOC uses a voice-coil, 15mm-diameter fast-steering mirror (FSM) as the main transmit and receive optic. The mirror is gold-plated and is actuated by a miniature gimbal. The gimbal can steer the beam with a ± 50 degrees range (on both x and y axes). The FSM system includes a processor, a proxy board and a mirror assembly (see Fig. 3).

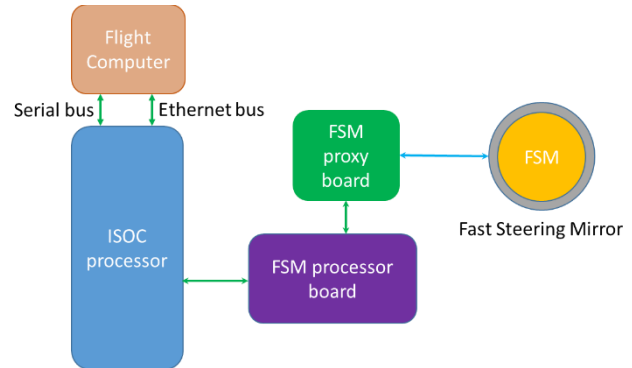


Figure 3. Block diagram showing the various FSM components.

The processor is held by a custom Printed Circuit Board (PCB) which provides the biasing voltages for the processor and for the proxy board. Commands sent to the FSM processor from the flight computer (via the ISOC processor) are directed to the proxy board, which, in turn, sends the proper voltages to steer the mirror in the desired direction. The dual axis fast steering mirror offers the benefit of large deflections and large mirror size in a compact package. The

actuator is based on proven voice-coil technology and includes built-in position feedback for accurate steering control. Figure 4 shows a picture of the FSM system where one can observe the FSM processor board, a proxy board and the actual mirror.

Figure 4 shows pictures of the FSM components.

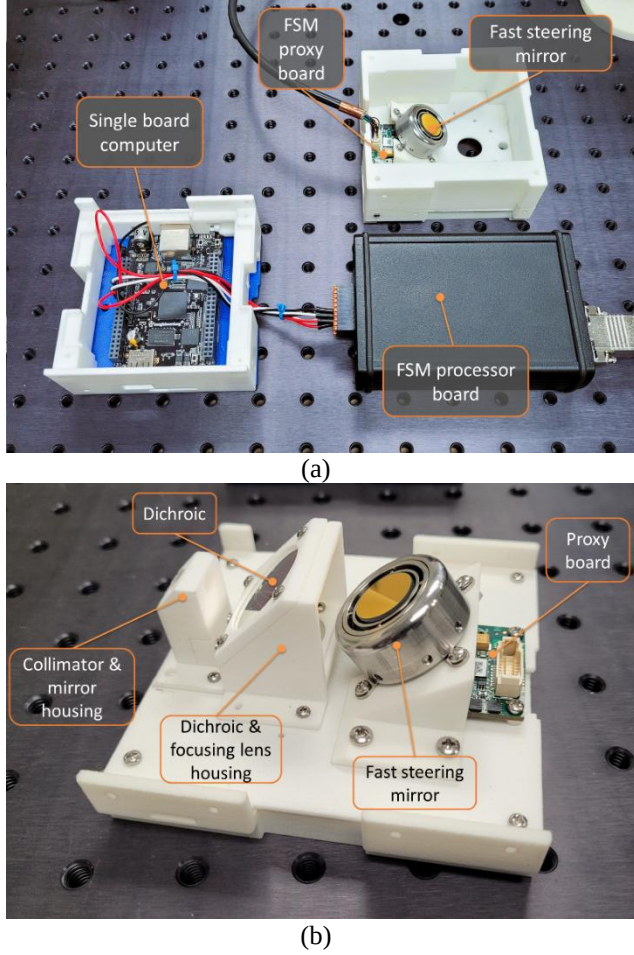


Figure 4. Pictures of the various components of the ISOC's FSM system.

In previous works [14] we reported that we can successfully control the mirror using a control code obtained from the mirror manufacturer. The code uses a SPI bus to send steering commands to the FSM processor board. We can routinely steer the beam in the ± 25 -degree mechanical (± 50 -degree optical) range in both the X and Y directions.

We developed means to manage multiple mirrors and engaging the appropriate one depending on the angle of arrival of the incoming signal. The ISOC has six mirrors to provide full sky coverage (4π steradian), where each mirror provides a coverage of 0.7π steradian. Once the ISOC determines the angle of arrival of the incoming signal, it selects the appropriate FSM that covers that specific AoA. That FSM remains engaged as long as the AoA is in its field of coverage. The ISOC selects a neighboring FSM once the AoA falls out of the field of coverage of the prior FSM, and

so on. Figure 5 shows a picture of two neighboring FSM mirror systems within the ISOC taken during mirror testing.

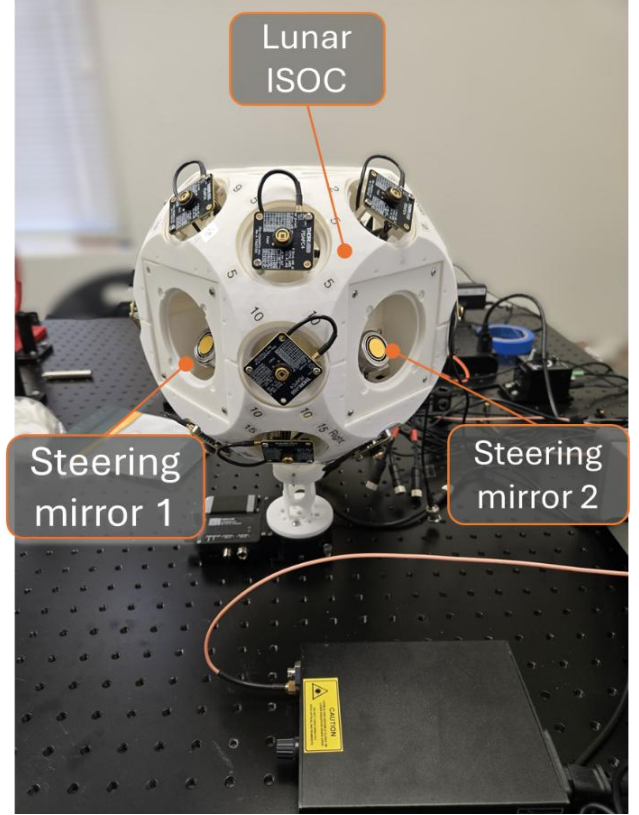


Figure 5. Picture of two neighboring ISOC fast steering mirror systems.

4. ANGLE-OF-ARRIVAL TESTING

Over the past year we pursued thorough testing of ISOC's AoA system. We used multiple experimental setups to gradually advance our AoA system development. The test setups can be operated at 635 nm, 850 nm and 1550 nm, respectively. Figure 6 shows an initial setup we used where one can observe a laser illuminator, an earlier version of the ISOC and a rotary table. The rotary table is computer controlled and is used to change the relative angle of incidence of the optical beam with respect to ISOC. This is our way to emulate circular relative motion between an incoming beam and the ISOC. The rotary tables can be steered with angular accuracies of a few millidegrees.

For AoA testing we used a graphic user interface (GUI) we developed written in Python that includes means for reading the 20 detector values and calculating the corresponding AoA (bearing and elevation). The GUI also includes means to control the various rotary tables we use as well as to export the complete data. The export file includes time, calculated AoA vector, 20 detector readings and the angular position of the rotary table.



Figure 6. Picture of an early AoA measuring system setup where one can observe the laser illuminator (beam expander), an ISOC and an automated rotating stage.

AoA Testing with Compressed ISOC

We performed AoA testing of the AoA system using a new version of the ISOC that we call the compressed ISOC (CISOC). The CISOC has the same number of detectors as the conventional ISOC, but its body is compressed in the vertical direction to achieve the same performance as a regular ISOC, with a smaller volume. The resulting CISOC has an annular shaped body and resembles a doughnut. Figure 7a shows a Computer Aided Design (CAD) image of the CISOC and Fig. 7b shows an actual picture. The CISOC allowed us to perform AoA testing with a more compact system when compared to the larger lunar ISOC. The CISOC is equipped with 20 photodetectors and can be operated at wavelengths in the range of 600 to 1600 nm. The experimental apparatus used to test the CISOC is shown in Fig. 8. It includes a laser illuminator, CISOC, a rotary table, a data acquisition unit (DAQ) and a processor (single board computer or laptop). The CISOC is mounted on the rotary table so we can rotate it with respect to the laser illuminator. The 20 CISOC detectors are read simultaneously by DAQ and fed into the processor. The processor runs our AoA code, which is written in Python. The AoA GUI shows the direction of the current AoA. During typical testing we enclose the entire test apparatus within a shielding enclosure (as shown in Fig. 9) to minimize external background noise.

CISOC is a novel concept for determining the angle of arrival of any optical beam. We plan to pursue patent protection for this new concept. We believe CISOC could have multiple applications including optical ground stations for astronomy and communications, intersatellite links, terrestrial communications, mobile communications, and navigation, as well as IOT and others.

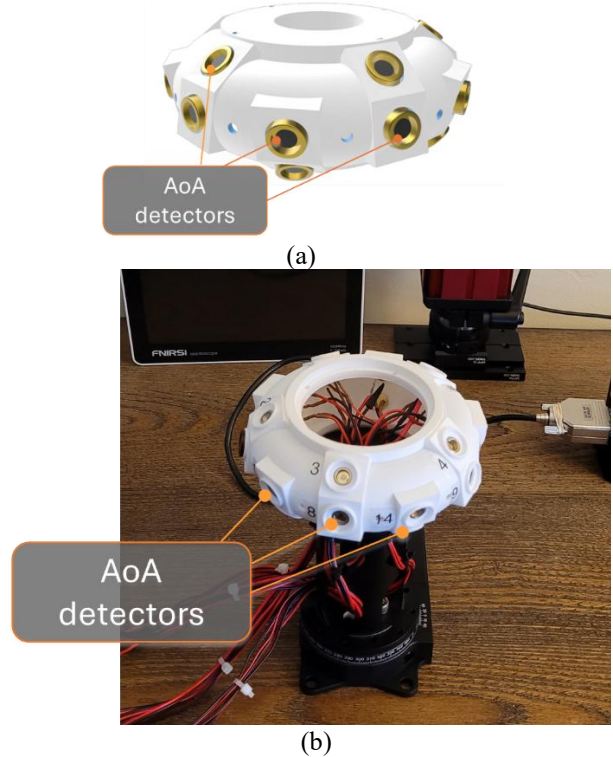
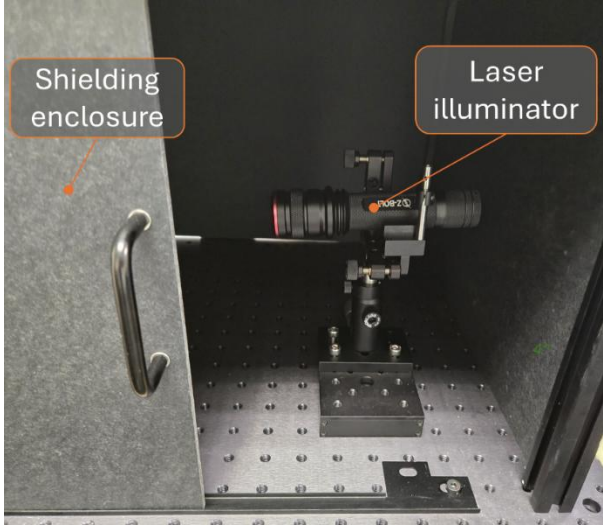


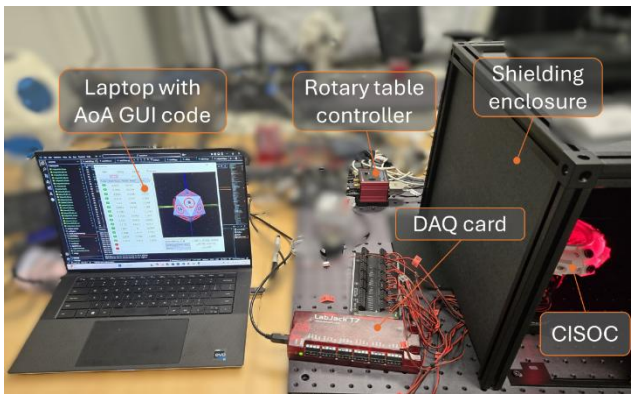
Figure 7. (a) CAD image and (b) picture of CISOC.



(a)



(b)



(c)

Figure 8. Pictures of test setup used for AoA testing of the CISOC.

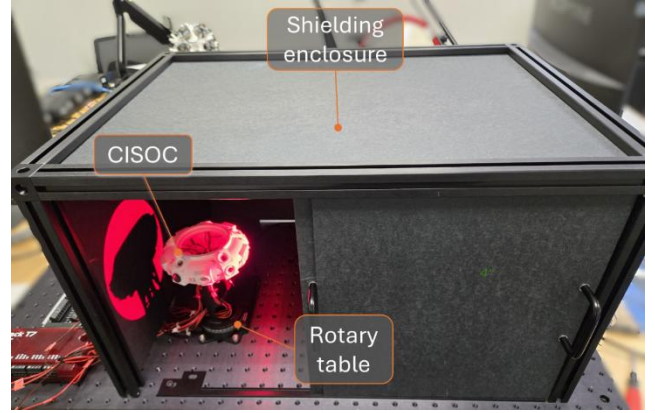


Figure 9. Picture of overall CISOC test setup including a noise shielding container.

In a typical run, we illuminate the ISOC, send commands to steer the rotary table to a given angle, and simultaneously measure the output of the 20 detectors. The code then calculates the AoA angles, which are displayed on the screen. The code also records the readings from each detector at each angular position of the rotary table, as indicated earlier. In Fig. 10 we show the readings of each detector as a function of the rotary table's angular position (in this case for -10 to +5 degrees). All these readings are consistent with their expected values. We typically monitor these readings to verify the proper alignment of the illuminator laser with respect to the center of the CISOC. We noticed that as we improved alignment, we obtained a better match between the measured and ideal AoA values.

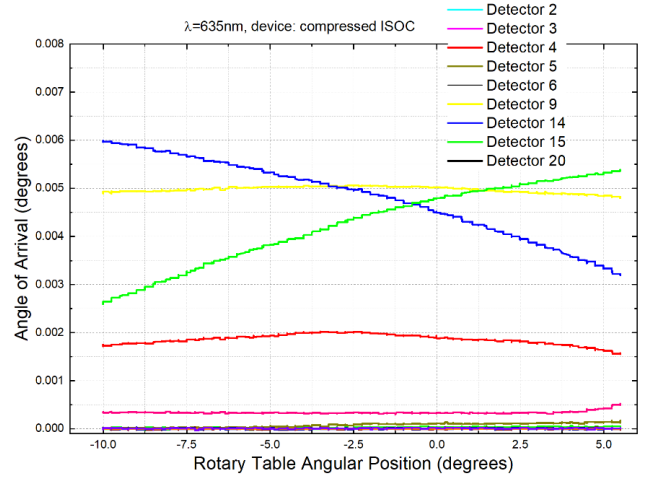


Figure 10. Measured CISOC detector values as a function of angular position of rotary table.

In Fig. 11 we show the calculated AoA angle as a function of the rotary table angle (provided by its encoder). Note that these AoA results show good agreement between the calculated and ideal values. The root-mean-square error between the calculated and real AoA is 160 millidegrees in this case.

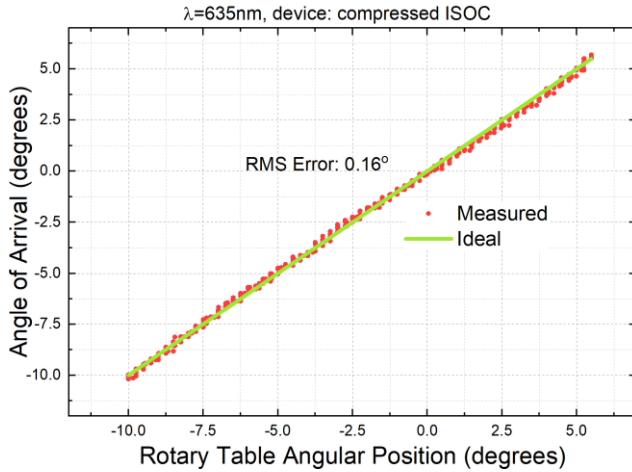


Figure 11. Measured angle-of-arrival as a function of angular position of rotary table.

Another measurement obtained with the CISOC AoA experimental apparatus is shown in Fig. 12 where an RMS error of 150 millidegrees is obtained. The illuminator is a 635 nm laser.

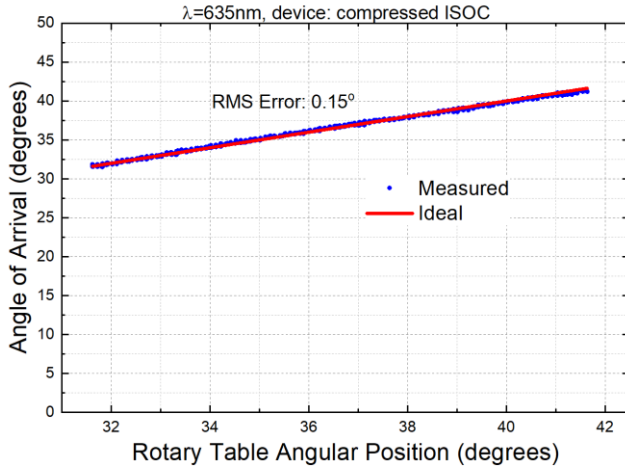


Figure 12. Measured angle-of-arrival as a function of angular position of rotary table.

AoA Testing with Icosahedron ISOC

A big portion of our AoA work involved AoA testing with an icosahedron-shaped ISOC (see Fig. 13). This icosahedron ISOC features 20 sides, where each side contains a PIN InGaAs photodetector receiver. Each photodetector uses a $\pm 12V$ biasing power supply.

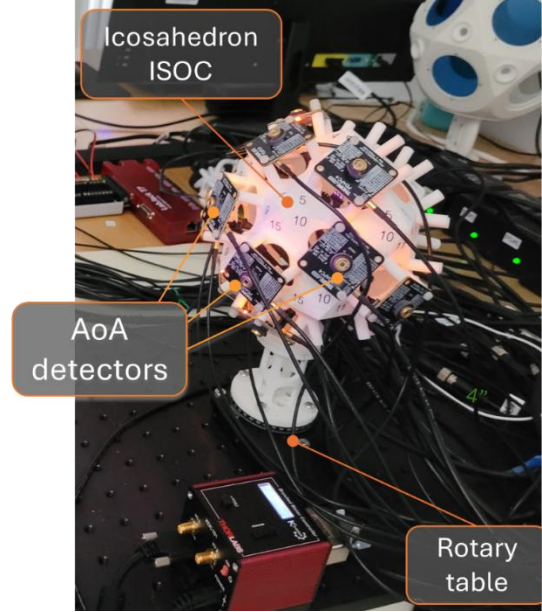


Figure 13. Picture of icosahedron ISOC.

Similar to what we did with the CISOC, for testing the icosahedron ISOC we used the experimental apparatus shown in Fig. 14. A laser illuminator is used to uniformly illuminate the ISOC with a 850 nm laser beam. The ISOC is mounted on a rotary table for AoA testing. A laptop, loaded with our AoA GUI code, is used to steer the rotary table and to read the outputs of the 20 PIN detectors via a DAQ card.

Figure 15 shows typical AoA results as a function of rotary table angle. Note that in case the RMS angular error is 111 millidegrees.

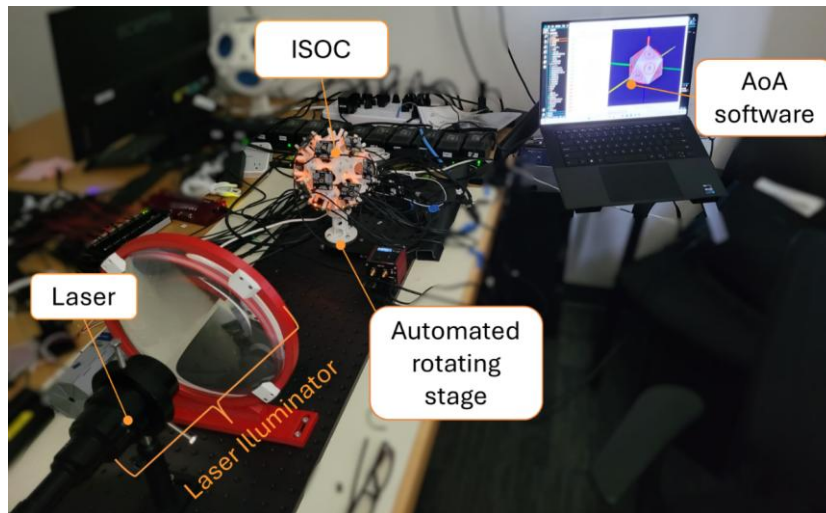


Figure 14. Picture of test setup for testing AoA system.

We believe that the AoA accuracy can be greatly improved (to tens of millidegrees) by carefully calibrating each detector so that all detectors depict uniform performance. Additionally, we could improve AoA accuracy by improving alignment between the laser illuminator and ISOC's center. We are planning to pursue all these improvement steps with the goal of achieving AoA accuracies in the 10 to 20 millidegree range.

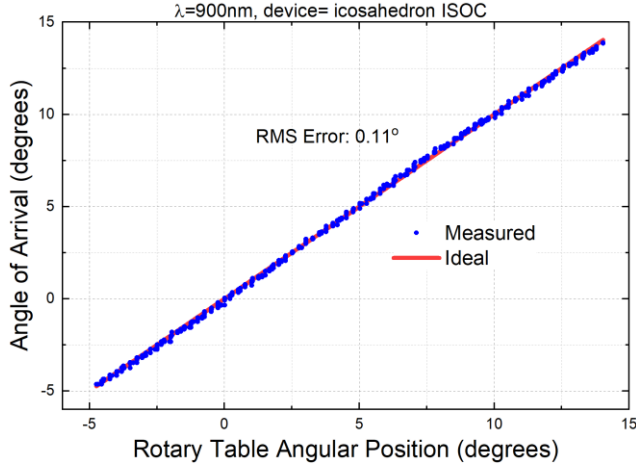


Figure 15. Measured angle-of-arrival as a function of angular position of rotary table. In this case the illuminator laser operates at 850 nm.

Laboratory Testing of ISOC System

As indicated earlier, over the past months we also performed testing of the various subsystems and of the entire ISOC

using various test setups. Figure 16 shows a block diagram of setup #1, where one can observe a DFB laser, a collimator, a beam expander, a receive ISOC, a rotary table, a fast-steering mirror and a target. During this testing, the DFB laser, connected to the collimator, generates a 1550 nm laser, that is expanded via the beam expander and launched into free space. The receive ISOC receives the optical beam via its AoA system. The ISOC is mounted on a computer-controlled rotary table. The ISOC is rotated via the rotary table to emulate motion between the collimator and the ISOC. A data acquisition system is used to read the values of the 20 AoA detectors. The ISOC uses a processor to calculate the AoA using the 20 PIN detector values and commands the FSM mirror to point in the direction of the incoming beam. The outgoing beam hits a target. We monitor the beam spot on the target to verify pointing stability and accuracy.

Figure 17 shows a picture of one version of the experimental setup used to test the lunar ISOC (LISOC). One can observe a laser illuminator, LISOC mounter on the rotary table, a DAQ card and a LISOC transceiver.

In a typical run with this transceiver, we illuminate the LISOC with the laser beam (either at 635, 900 or 1550 nm), the DAQ reads the values from the 20 detectors and as indicated in Fig. 16, calculates the AoA. That AoA angles are subsequently sent to the FSM steering mirror to point in the AoA direction. This is done continuously as the LISOC is gradually rotated via its rotary table. We consistently observe that the FSM mirror points to the right direction, as the LISOC is steered at various angles.

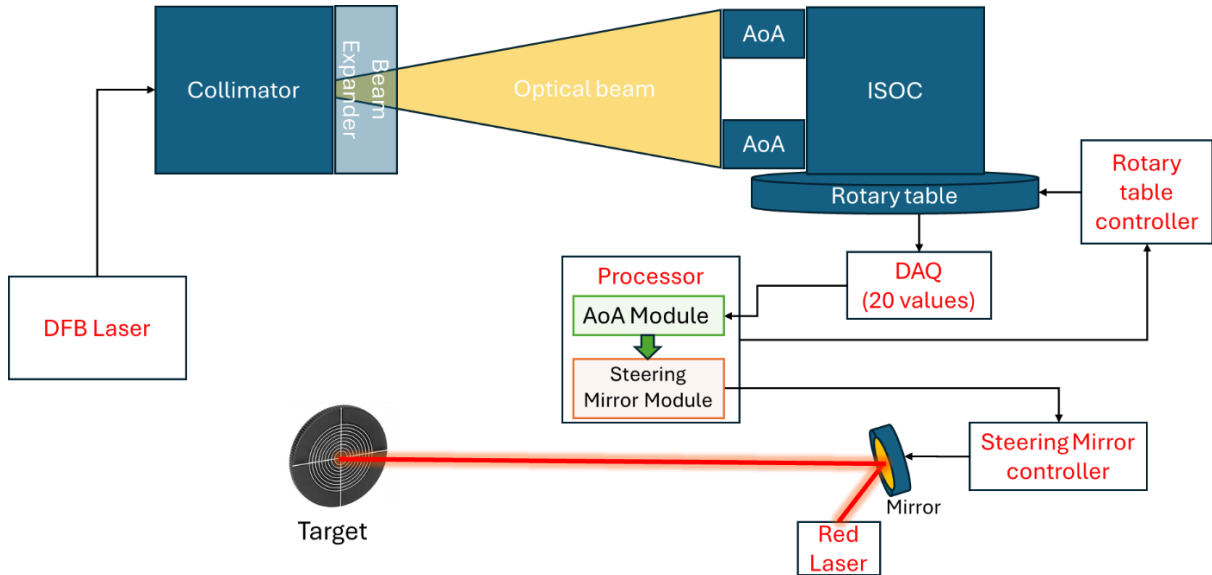


Figure 16. Setup used for testing ISOC system for pointing, acquisition and tracking.

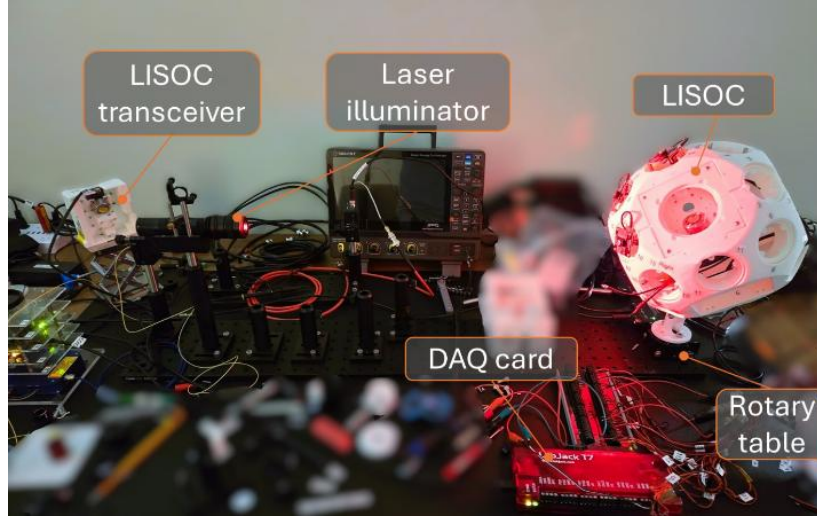


Figure 17. Picture of the setup used for testing ISOC system for pointing, acquisition and tracking.

We also performed LISOC testing with multiple transceivers (mirrors). (Recall that, based on their position within the ISOC, each mirror provides coverage of a portion of the sky.) In this case the LISOC system is operated as indicated on Fig. 18. The LISOC is illuminated by a laser, and the system reads the 20 detectors simultaneously. The AoA angles are then calculated, and the system verifies the stability of the AoA (by making sure multiple successive readings do not greatly differ). Once a stable AoA is obtained, the system determines which of the six mirrors should be engaged (based on the angular coverage of each mirror). The system then sends the AoA values to that mirror. The actual mirror command includes X and Y values proportional to the azimuth and elevation AoA angles.

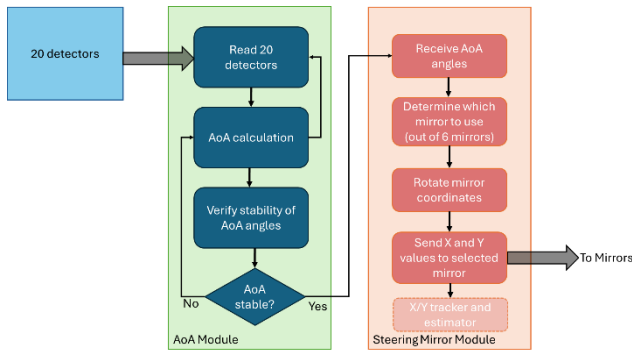
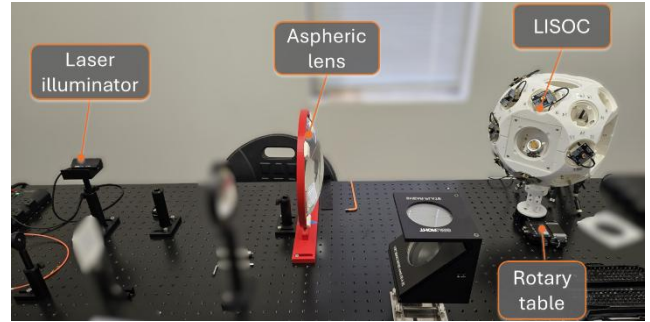
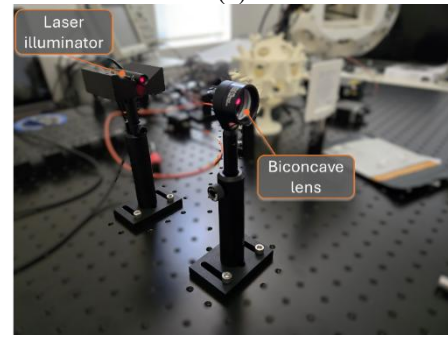


Figure 18. Block diagram showing the AoA and beam steering process of the LISOC system.

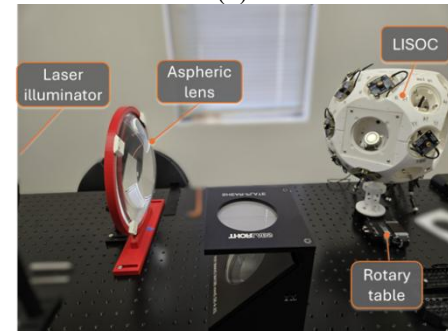
One of the setups used for testing the LISOC system is shown in Fig. 19. This setup is used for AoA and mirror steering testing. It includes a beam illuminator, the LISOC and a rotary table. The illuminator consists of a laser diode, a biconcave lens and an aspheric lens. The distance between the biconcave and aspheric lens is adjusted properly to obtain a collimated beam. The collimated beam is then used to irradiate LISOC.



(a)



(b)



(c)

Figure 19. Pictures of experimental setup used for AoA and beam steering testing of the LISOC.

With the setup shown in Fig. 19 we are routinely able to illuminate the LISOC, obtain AoA angles and steer the mirror(s) in the direction of the AoA angles. This system can be run at 635 nm and 1550 nm wavelengths.

In Fig. 20 we show two LISOCs placed on an optical table for joint testing. In this setup we placed the LISOCs in front of each other, transmit via LISOC #1 and receive with LISOC #2. A 1550 nm DFB laser is used by LISOC #1's transmitter.

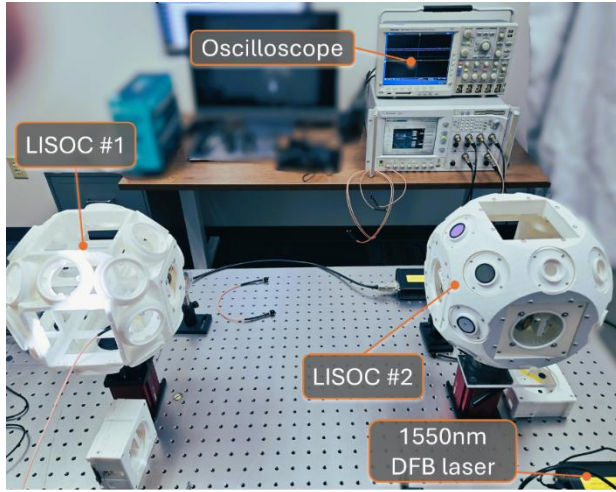


Figure 20. Picture of two LISOCs for joint testing.

Figure 21 shows the latest setup we are using for testing the LISOC where we have added a diffuser to LISOC #1 so when it transmits, it generates a large uniform optical beam that covers the entire LISOC #2. Like what we did with the setup shown in Fig. 19a, we rotate LISOC #2 via its rotary table and observe how the fast-steering mirrors react to the calculated AoA angle.

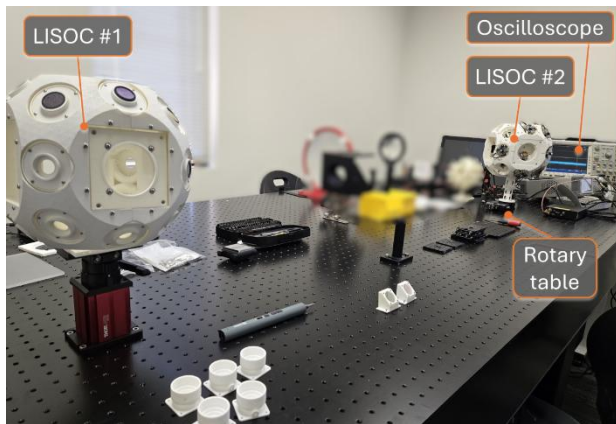


Figure 21. Picture of latest setup used for testing two LISOCs.

After having achieved successful PAT results, our next step is to add a single board computer to each LISOC so we can start performing data transfer tests at various speeds. Figure 22 shows the setup we plan to use to perform data transfer tests. We will use Black Beagle Bone (BBB) single board computers on each LISOC. The BBBs will initially use the Universal Asynchronous Receiver-Transmitter (UART)

protocol for sending and receiving information. UART is a simple way to connect two devices because it only needs one wire for transmission and one for reception. In our case, the wires are replaced by LISOCs' optical beams.

The main task to be carried out in the last quarter of this Phase 2 project is to perform outdoor testing of the LISOC. This will include pointing, acquisition and tracking as well as data transfer tests.

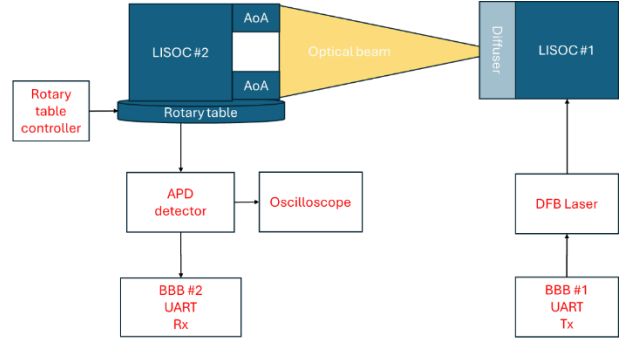


Figure 22. Setup to be used in the coming days to perform data transfer tests between the two LISOCs.

We should mention that we have developed a new terminal that is an outgrowth of the LISOC. We call this device the long-range optical terminal (LROT). The main difference between LISOC and LROT is that the latter uses large (4" to 8" diameter) gimbaled mirrors. These advantageous features will allow LROT to provide connectivity from lunar and GEO distances to Earth at multi gigabit rates. Figure 23a shows a CAD model of the LROT where one can observe its gimbal, mirror and optics. In Fig. 23b we show a picture of the actual gimbals and mirror we have procured for an LROT prototype we are beginning to assemble.

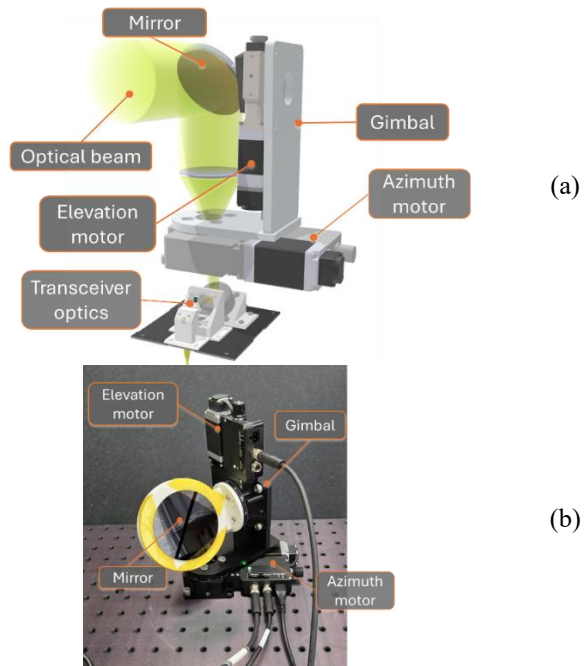


Figure 23. (a) CAD image and (b) picture of long-range optical terminal under development at Chascii. The LROT is a long-range version of the LISOC.

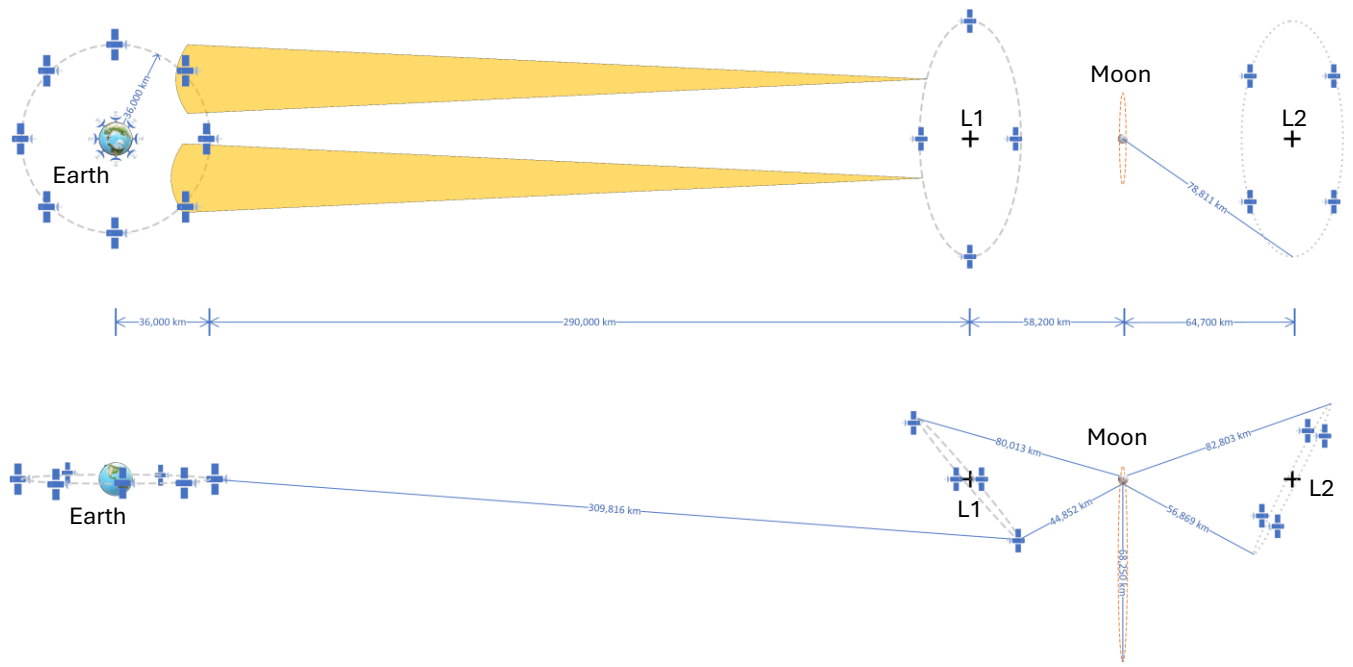


Figure 24. Chascii's ISOC-based cislunar INSPIRE network.

Figure 24 shows the architecture of Chascii's INSPIRE cislunar network [13]. Chascii is proposing to place smallsat in Earth-Moon Lagrange points 1 and 2 (L1 and L2) that act as network nodes. We are proposing to use LISOC and LROTs to create this all optical network. Cislunar INSPIRE consists of sixteen nodes; four nodes in L1, four in L2 and eight nodes in GEO to provide ubiquitous connectivity to cislunar users.

5. SUMMARY

We have presented Chascii's omnidirectional optical terminal that is being developed to provide fast connectivity for constellations of spacecraft in lunar space. We discussed the architecture and main features of the ISOC as well as presented its key capabilities. We presented many angle-of-arrival tests with various setups where we showed that we were able to obtain AoA measurements with an accuracy in the range of 110 to 150 millidegrees. We plan to continue fine tuning our AoA test setup so we can improve the AoA accuracy to the 50 millidegree (or better) level.

We have also been able to perform successful pointing, acquisition and tracking tests with LISOC. We were able to seamlessly calculate the AoA and select the appropriate mirror to track the incoming beam. We have developed algorithms that allow LISOC to select the required mirror to keep the link alive and to seamlessly switch to a neighboring one when the AoA change demands it. We believe the ISOC, once fully developed, will provide commercial, high data rate connectivity to future scientific, military, and commercial missions around cislunar space and beyond.

ACKNOWLEDGEMENTS

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REFERENCES

- [1] Lunar Gateway.
https://en.wikipedia.org/wiki/Lunar_Gateway
- [2] Israel, D. et.al, 2020. "LunaNet: a Flexible and Extensible Lunar Exploration Communications and Navigation Infrastructure and the Inclusion of SmallSat Platforms," Proceedings of the AIAA/USU Conference on Small Satellites, Communications, SSC20-XII-03. <http://digitalcommons.usu.edu/smallsat/2020/all2020/171/>
- [3] M. de Kok, J. E. Velazco, and M. J. Bentum, "CubeSat Array for Detection of RF Emissions from Exoplanets using Inter-Satellites Optical Communicators," in IEEE Aerospace Conference Proceedings, 2020.
- [4] U.S. Patent No. 10,581,525 B2, March 3, 2020. Inventor: Jose E. Velazco. Title: Method And Apparatus for Omnidirectional Optical Communication.
- [5] J. E. Velazco, et al, "Inter-satellite Omnidirectional Optical Communicator for Remote Sensing," SPIE Conf. Opt. Eng. Apps. XXII, 10769-21, San Diego, CA 21 August, 2018.
- [6] J. E. Velazco, et al, 2018 "High data rate inter-satellite Omnidirectional Optical Communicator," Proceedings of the AIAA/USU Conference on Small Satellites, SSC18-WKI-02.
- [7] J. E. Velazco, "Omnidirectional Optical Communicator," in IEEE Aerospace Conference Proceedings, 2019, pp. 1–6.
- [8] J.E. Velazco and J. Sanchez, "Q4 – a CubeSat Mission to Demonstrate Omnidirectional Optical Communications," in IEEE Aerospace Conference Proceedings, 2020.
- [9] J. E. Velazco, et al, "Development of Omnidirectional Optical Terminals for Swarm Communications and Navigation," The Interplanetary Network Progress Report, vol. 42-221, Jet Propulsion Laboratory, Pasadena, California, May 15, 2020.
- [10] J. Velazco, "Cislunar Omnidirectional Optical Terminal for Fast Connectivity and Accurate Navigation," 2023 IEEE Aerospace Conference, Big Sky, MT, USA, 2023, pp. 1-7, doi: 10.1109/AERO55745.2023.10115660.
- [11] U.S. Patent No. 12,095,508 B2, September 17, 2024. Inventor: Jose E. Velazco. Title: Multiple Link Optical Terabit Terminal.
- [12] U.S Patent No. 11,616,574 B2, March 28, 2023. Inventor: Jose E. Velazco. Title: Optical Ground Terminal
- [13] J. Velazco, "Gigabit Cislunar INSPIRE network enabled by Omnidirectional Optical Terminals," 2024 IEEE Aerospace Conference, Big Sky, MT, USA, 2024, pp. 1-13, doi: 10.1109/AERO58975.2024.10521098.
- [14] J. Velazco, "Lunar Inter-Spacecraft Optical Communicator," 2025 IEEE Aerospace Conference, Big Sky, MT, USA, 2025, pp. 1-12, doi: 10.1109/AERO63441.2025.11068744.

BIOGRAPHY



Dr. Jose Velazco is the founder and CEO of Chascii Inc. He is pioneering the implementation of free-space optical terabit networks to enable the information superhighway for the next generation of global connectivity. He seeks to implement an all-optical network via ground, air and space layers using advanced optical terminals. He was a space Technologist at NASA's Jet Propulsion Laboratory where he conducted advanced research and development of new RF and optical technologies and systems for telecommunications, as well as new instrumentation and radar for space exploration. His current research focuses on various small spacecraft mission concepts for low-Earth-orbit, Lunar, and Deep Space applications with the goal of enabling an all-optical spaceborne network. He aims to implement a new interplanetary network architecture along the solar system that uses swarms of optically-interconnected spacecraft as networks for fast communications and novel science. He envisions the interplanetary network as the basis for the space internet that could provide the key connectivity layer required for the future commercial exploration of space.