

Paving the path for Low-Elevation Space-to-Ground Optical Communication Links: Preliminary Link Experiments

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ABSTRACT

Low-elevation space-to-ground optical communication links can extend satellite visibility windows and improve geographic coverage but remain challenging due to increased atmospheric propagation effects. This paper presents preliminary results from a collaborative JAXA–ESA campaign involving the LUCAS geostationary optical communication terminal and two optical ground stations in Athens and Thessaloniki, Greece. Operating at elevation angles below 9°, in receive-only mode, without uplink beacons, successfully acquired and tracked the 1550-nm LUCAS optical signal during pointing, acquisition, and tracking phases. No active communication phase was initiated at this stage. The campaign demonstrated site diversity through repointing between the two Greek stations within a single experimental session and confirmed the feasibility of omitting the raster-scan phase in the LUCAS acquisition sequence. Pointing-offset measurements further indicated a drift of approximately 50 μ rad/h, motivating further investigation. These results provide an initial experimental basis for future low-elevation GEO optical feeder-link studies and operational optimization.

Keywords: LUCAS, optical ground station, low elevation, optical communications, experiment, pointing

1. INTRODUCTION

Satellite-to-ground optical communications are typically operated above a minimum elevation angle to mitigate the adverse effects associated with long atmospheric propagation paths. Extending optical links to low elevations (i.e towards the edge of the coverage area, elevation angles as low as 10°) would significantly increase the geographic spatial coverage for Geostationary-Earth-Orbit (GEO) satellites (typically a factor-of-2 spatial coverage improvement). Conversely, for LEO satellites, as their apparent angular velocity is lower at low elevations, a significant time of the pass is spent at low elevations. Therefore, achieving connectivity at low elevations would significantly increase temporal coverage (e.g typically a factor-of-2 temporal coverage improvement for a circular polar orbit). This capability is of direct relevance to both classical and quantum optical communications. Achieving reliable optical communications at low elevation is expected to rely on a combination of advanced techniques for mitigating atmospheric turbulence and channel impairments, along with the development of enabling technologies that can be integrated within the operational constraints of both space and ground segment optical communication terminal architectures.

Experimental campaigns have progressively established the viability of space-to-ground laser links. ESA's bidirectional experiments between the ARTEMIS satellite and the OGS at the Teide Observatory demonstrated repeated GEO links while characterizing pointing, acquisition and tracking (PAT) performance and atmospheric effects [1]. Subsequent testing between the EDRS-A laser communication terminal and the ESA ground station further extended this GEO space-to-ground heritage [2]. For LEO links, the joint JAXA–DLR KID0 campaign received a 50-Mbit/s optical signal from OICETS over elevation angles ranging from 2° to 45°, achieving a BER on the order of 10^{-6} and providing measurements of scintillation and atmospheric coherence [3]. More recently, the OSIRISv1 signal from the Flying Laptop satellite was acquired at an elevation angle as low as 0.5° and remained visible for approximately ten minutes[4].

In this context, this contribution presents preliminary experimental results from an ongoing collaborative activity between JAXA, ESA, and Optical Ground Stations (OGSs) in Greece. In 2020, JAXA launched the Laser Utilizing Communication System (LUCAS) into geostationary orbit, equipped with a C-band optical communication terminal capable of supporting both inter-satellite optical links and optical downlinks.

In March 2026, an experimental optical-link campaign was conducted between the LUCAS GEO satellite and two optical ground stations in Athens and Thessaloniki, Greece. From both sites, LUCAS was observed at very low elevation angles below 9° . Experimental sessions took place during the nights of 2 and 9 March, and during dusk and nighttime on 16 March. The OGSs operated in receive-only mode, without uplink beacons, and no active communication phase was initiated at this stage. The results show that both Greek OGSs successfully acquired and tracked the 1550-nm LUCAS optical signal during the pointing, acquisition, and tracking phases using infrared cameras integrated into their telescope systems. The campaign further demonstrated site diversity in a single experimental session, with the LUCAS terminal repointing between the Athens and Thessaloniki OGSs. It also showed that the raster-scan phase could be omitted from the LUCAS pointing, acquisition, and tracking sequence, while pointing-offset measurements revealed a monotonic drift of approximately $50 \mu\text{rad/h}$, warranting further investigation.

The remaining of the paper is structured as follow: In Section 2 a brief description of LUCAS is included, in Section 3 a description of the OGSs and the experimental set ups are exhibited and in Section 4 the experimental results are presented. Section 5 concludes this manuscript.

2. LUCAS

LUCAS is Japan's latest data relay satellite system, launched by the Japan Aerospace Exploration Agency (JAXA) in 2020. The system achieves an optical data transmission rate of 1.8 Gbps, equivalent to that of the European Data Relay System (EDRS), by employing optical communications in the $1.5 \mu\text{m}$ wavelength band, which is also widely used in terrestrial fiber-optic networks. Although the deployment of user satellites was delayed by several years relative to the original schedule due to issues on the launch vehicle side, LUCAS successfully demonstrated inter-satellite optical communication with its first user satellite, Advanced Land Observing Satellite-4 (ALOS-4), in 2024. LUCAS employs a hybrid architecture consisting of optical inter-satellite links and a Ka-band RF feeder link between the relay satellite and the ground station. The Ka-band feeder link utilizes 16-QAM modulation together with polarization multiplexing to improve spectral efficiency. The optical inter-satellite links are divided into a Forward Link and a Return Link. The Forward Link, defined as the transmission path from the ground station to a user satellite via LUCAS, operates in the 1540-nm wavelength band with a symbol rate of 60 Mbaud, providing a user data rate of 50 Mbps. The Return Link, defined as the transmission path from a user satellite to the ground station via LUCAS, operates in the 1560-nm wavelength band with a symbol rate of 2.5 Gbaud and supports a user data rate of 1.8 Gbps [5]. In addition to wavelength division, opposite circular polarizations are assigned to the Forward and Return Links. The use of different wavelengths and circular polarizations enables the transmit and receive optical signals, which differ significantly in power level, to share a common optical path within the optical terminal while achieving high Tx/Rx isolation.

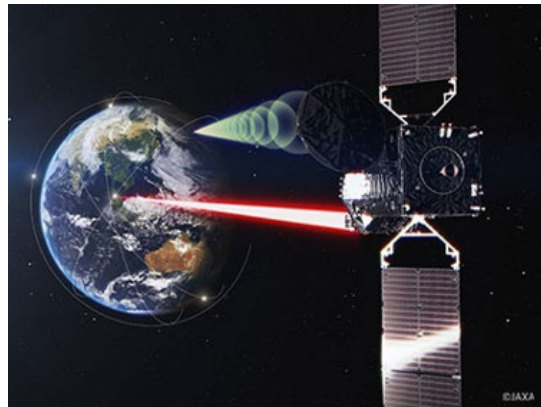


Figure 1 On orbit image of LUCAS

In parallel, JAXA has been conducting a variety of optical feeder-link experiments within Japan with the long-term objective of establishing optical connectivity between future non-terrestrial networks (NTNs) and terrestrial networks (TNs). In collaboration with the National Institute of Information and Communications Technology (NICT), JAXA has also been carrying out regular atmospheric channel characterization experiments using NICT's optical ground station

(OGS) located in Okinawa, southwestern Japan. These experiments have been used to assess the seasonal dependence of atmospheric turbulence effects and to evaluate the performance improvement achieved through forward error correction (FEC) techniques [6], [7]. From Okinawa, LUCAS is observed at an elevation angle of less than 40° , providing a relatively favorable propagation geometry for optical feeder-link experiments. Since LUCAS is positioned in geostationary orbit over the Indian Ocean and is visible from Greece at an elevation angle of less than 10° , which is significantly lower than that of the Okinawa experiments, it represents an appropriate GEO node for the particularly challenging and scientifically interesting experiments described in this study. The resulting propagation path traverses a substantially larger portion of the Earth's atmosphere, enabling the collection of measurement data under conditions that have not previously been investigated in the LUCAS optical feeder-link experiments.

3. OPTICAL GROUND STATIONS & TEST BEDS

3.1 Athens OGS

Athens OGS was deployed at the premises of the National Observatory of Athens (NOA), located on Lofos Koufos in Penteli, approximately 18 km northeast of central Athens [8]. The site altitude was approximately 500 m above sea level. The geodetic coordinates adopted for telescope pointing and link calculations were $38^\circ 02' 53.54''$ N and $23^\circ 51' 53.30''$ E, with an approximate ellipsoidal height of 540 m.

The optical telescope used was a Celestron CPC Deluxe 1100 HD telescope with a 279.4-mm clear aperture, a nominal focal length of 2800 mm and a focal ratio of (f/10) [9]. The telescope was configured for receive-only operation. A Baader 10×60 guide scope with a focal length of 250 mm, equipped with an auxiliary optical camera, provided an additional wide-field channel for alignment and coarse target acquisition [10].

A C-RED 3 Short-Wave Infrared (SWIR) camera was connected at the back focus of the telescope and used as the primary acquisition and tracking detector. The C-RED 3 employs a (640×512) -pixel InGaAs detector with a pixel pitch of $15\mu\text{m}$ and a spectral response covering approximately $0.9\text{--}1.7\mu\text{m}$, including the 1550-nm wavelength of the LUCAS signal [11]. In combination with the telescope's nominal 2800-mm focal length, the detector provided a plate scale of approximately $1.1''/\text{pixel}$ and a full-frame field of view of approximately $0.20^\circ \times 0.16^\circ$, corresponding to approximately $720'' \times 576''$ (or $720 \text{ arcsec} \times 576 \text{ arcsec}$). By using a focal reducer (f/6.3), the plate scale was increased to approximately $1.57 \text{ arcsec}/\text{pixel}$

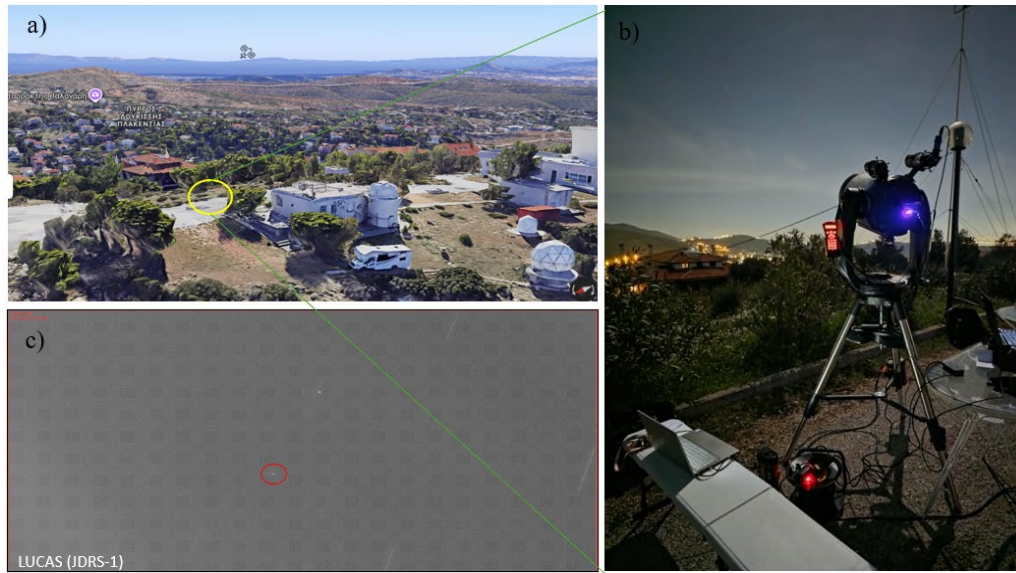


Figure 2. a) National Observatory premises, b) OGS, c) LUCAS as seen from the optical camera behind the guide scope

(or $1.57''/\text{pixel}$), providing a field of view of approximately $0.28^\circ \times 0.22^\circ$. The Rayleigh diffraction limit of the 279.4-mm aperture at 1550 nm is approximately 1.4 arcsec. Although the camera supports full-frame operation at up to 600 frames/s,

the campaign acquisition configuration provided frame rates of up to 300 frames/s and exposure times shorter than 0.1 ms. Pre-campaign characterization indicated a minimum detectable optical input power below -75 dBm under the selected operating conditions. This sensitivity was sufficient for the received-power levels predicted by the optical link budget and enabled the camera to be employed for detection, acquisition and tracking of the low-elevation LUCAS signal.

3.2 Thessaloniki OGS

The Thessaloniki OGS is operated by the Aristotle University of Thessaloniki (AUTH). The geodetic coordinates adopted for telescope pointing and link prediction were $40^{\circ}33'45.01''$ N and $22^{\circ}59'44.25''$ E, at an ellipsoidal height of 112.50 ± 0.02 m. The station is housed in a dome and was configured for fully remote operation. A networked video camera, an all-sky cloud sensor and a local weather station provided environmental monitoring throughout the campaign.

From this site LUCAS is observed at an elevation angle less than 9° . The optical telescope was a Celestron C11 Schmidt–Cassegrain with a 279.4-mm aperture, a nominal focal length of 2800 mm and a focal ratio of f/10, operated in receive-only mode. A secondary optical telescope, used as a guider, was a Celestron 11" Rowe-Ackermann Schmidt Astrograph (RASA) with a 279.4-mm aperture, a nominal focal length of 620 mm, and a focal ratio of f/2.2. Both telescopes were carried on a PlaneWave L-350 direct-drive alt-azimuth mount controlled through the PlaneWave Interface (PWI4). The mount provides encoder resolution of 0.069" on each axis and slew rates of up to $50^{\circ}/s$. For the session reported here the pointing model was built from 89 acquired points and returned a model fit residual of 7.3" RMS. The inside of the station, with the telescopes pointing to LUCAS is shown in Figure 3a).

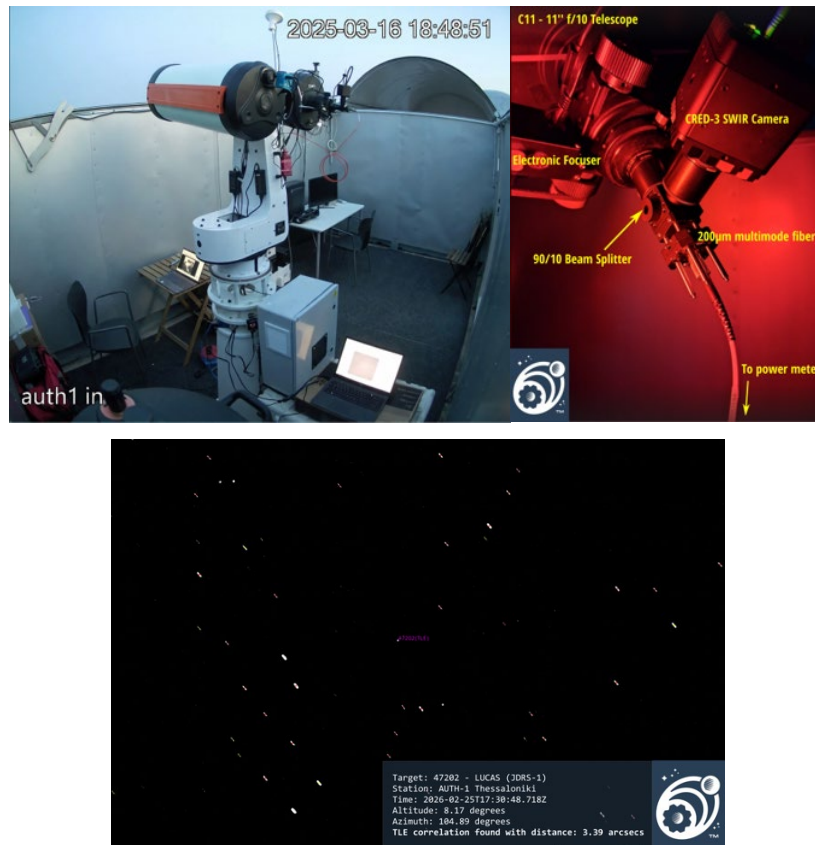


Figure 3 a) AUTH OGS Pointing at LUCAS, b) optical assembly, c) An astrometric reduced image of the LUCAS FoV acquired from the RASA finder telescope.

The back-end optical chain is shown in Figure 3b). Light leaving the telescope passes through an electronic focuser to a 90/10 beam splitter which divides the beam between an acquisition and tracking channel and a radiometric channel. The

acquisition and tracking channel, attached to the 10% port of the splitter, feeds a C-RED 3 short-wave infrared camera (First Light Imaging), which employs an uncooled 640×512 InGaAs detector with a $15\text{-}\mu\text{m}$ pixel pitch and a spectral response spanning $0.9\text{--}1.7\text{ }\mu\text{m}$. The radiometric channel, attached to the 90% port of the splitter, is coupled into a $200\text{-}\mu\text{m}$ -core multimode fibre feeding a Thorlabs S154C fibre-coupled InGaAs photodiode power sensor.

At the 2800-mm focal length, the fibre core ($200\mu\text{m}$) subtends $14.7''$ on the sky and, at $f/10$, the beam enters the fibre at a numerical aperture of 0.05 , far inside the acceptance of the fibre. The fibre therefore acts as a field stop that is several times larger than the seeing-limited spot expected at an air mass of nearly seven, so that turbulence-induced spot broadening does not by itself produce coupling loss. The penalty is a correspondingly large acceptance solid angle for sky background, which is the dominant consideration for the dusk measurements reported in Section 4.1. Figure 4 shows sky background measurements at LUCAS line of sight, measured the day prior to the experiment, as a function of time.

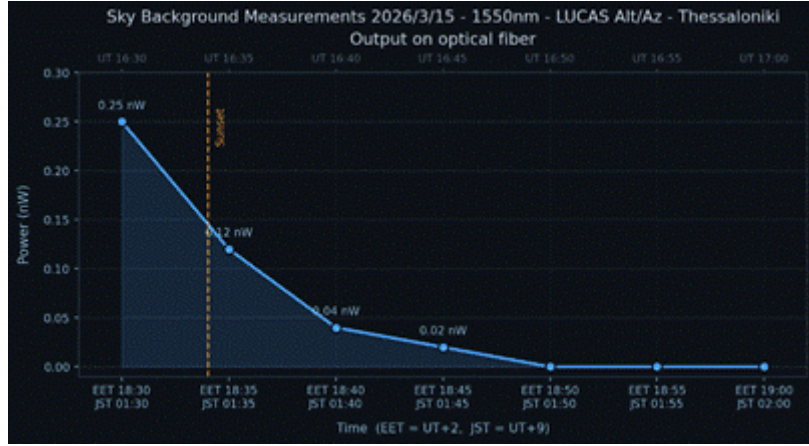


Figure 4. Sky background measurements of the LUCAS altitude and azimuth coordinates.

The S154C sensor is calibrated over $800\text{--}1700\text{ nm}$ with a specified working range of 100 pW to 3 mW (-70 dBm to $+5\text{ dBm}$), a resolution of 10 pW , a linearity of $\pm 0.5\%$ and an absolute measurement uncertainty of $\pm 5\%$, traceable to NIST and PTB. All recordings were made with the sensor responsivity set to 1550 nm and were logged continuously at a sampling rate of approximately 300 samples per second. The C-RED 3 was operated at frame rates of 50 , 100 and 300 frames per second with integration times between 3 and 20 ms .

4. EXPERIMENTAL RESULTS

Three experimental sessions were conducted from the Greek optical ground stations during the nights of 2, 9 and 16 March 2026. The third session, on 16 March 2026, is described here in detail because it was the most complete: it combined both the acquisition in the CRED camera and coupling to the multimode fiber.

All operations were coordinated in real time with the JAXA operations team over a shared video link. The session was structured into four phases. Station set-up ran from $17:00$ to $17:30\text{ EET}$. A dusk session followed from $17:30$ to $19:00\text{ EET}$, beginning at a solar elevation of -4.4° , that is, within civil twilight. Between $19:00$ and $21:00\text{ EET}$ the satellite entered eclipse, from $19:35$ to $20:45\text{ EET}$, and the interval was used to re-slew to LUCAS on a TLE-based ephemeris, confirm the target visually, and align and focus the fibre channel on Betelgeuse. A night session ran from $21:00$ to $23:00\text{ EET}$, and a blind-tracking experiment closed the evening between $23:00$ and $23:30\text{ EET}$. Conditions were clear throughout, with an ambient temperature of $12.7\text{ }^\circ\text{C}$, a relative humidity of 68% .

The acquisition procedure followed the alternative LUCAS pointing, acquisition and tracking sequence for ground stations described in Section 4.2.1, with the addition of an initial spiral scan at each pointing offset. The LUCAS terminal was commanded successively to a set of open-loop pointing offsets; at each offset a spiral scan was executed first, followed by a random scan, and the ground station reported detections back to the operations team in real time. This is the dataset

referred to in Section 4.2.2 as having been acquired with the cooperation of the Greek OGS team for the purpose of estimating the offset direction from the spiral-scan reception pattern.

During the dusk session, spiral-scan illumination was detected at offsets 5, 2, 1 and 7, while the random scan produced a detection only at offset 7, first at 18:40 EET. Telescope offsets were then adjusted and fibre coupling was established at 18:45 EET, with the first calibrated power-meter recordings captured from 18:52 EET. During the night session, spiral-scan detections were obtained at offsets 7, 8, 5, 9 and 10, and again the random scan succeeded only at offset 7. Taken over the whole evening, the spiral scan produced detections at seven distinct pointing offsets (1, 2, 5, 7, 8, 9 and 10) whereas the random scan produced detections at one. This is the expected consequence of the difference in angular coverage between the two phases and it quantifies, from the ground segment, why the random-scan-only sequence requires repeated manual offset adjustment.

Once established at offset 7, the random-scan link remained reproducible for the remainder of the evening, from the first detection at 18:40 EET until the end of the final measurement at 23:10 EET, a span of about four and a half hours. The blind-track experiment, conducted from 23:00 EET, slewed the telescope to LUCAS purely on a TLE-derived ephemeris with the visible-band acquisition camera disabled (RASA telescope), and recovered both spiral-scan and random-scan detections at offset 7 within six minutes of the start of the phase.

Finally, LUCAS demonstrated site diversity within a single experimental session by repointing its laser communication terminal between the Athens and Thessaloniki OGSs, separated by more than 300 km.

4.1 Received Irradiance (OGS) data

Twelve calibrated recordings of 120 s duration each were acquired on 16 March 2026 with the fibre-coupled power sensor. Table 1 summarises them. Optical powers are as measured at the fibre output, that is, after the 90/10 beam splitter and the fibre-coupling optics, and are not corrected for the throughput of the receive chain.

Table 1 Fibre-referred peak optical power recorded at the Thessaloniki OGS on 16 March 2026. Each record is 120 s long. Local time is UTC + 2 h.

Phase	Scan / offset	Start (UT)	Start (EET)	Peak (nW)	Peak (dBm)
Dusk	Random, offset 7	16:52:34	18:52:34	0.299	−65.3
Dusk	Random, offset 7	16:56:41	18:56:41	0.442	−63.5
Night	Random, offset 7	19:11:36	21:11:36	7.245	−51.4
Night	Random, offset 7	19:14:24	21:14:24	4.215	−53.8
Night	Random, offset 7	19:30:49	21:30:49	6.199	−52.1
Night	Spiral, offset 8	19:41:44	21:41:44	0.293	−65.3
Night	Spiral, offset 5	19:55:59	21:55:59	0.886	−60.5
Night	Spiral, offset 7	20:07:57	22:07:57	1.065	−59.7
Night	Random, offset 7	20:13:42	22:13:42	1.052	−59.8
Night	Spiral, offset 9	20:34:27	22:34:27	0.414	−63.8
Night	Spiral, offset 10	20:46:04	22:46:04	0.687	−61.6
Blind track	Random, offset 7	21:08:31	23:08:31	2.229	−56.5

Every record consists of a train of discrete illumination events against a flat baseline, as expected when a scanning transmit beam sweeps repeatedly across a stationary receiver. The baseline noise is approximately ± 5 pW peak to peak, giving a practical detection threshold of order 5 pW, or −83 dBm, at the fibre. A residual zero offset of about −8 pW is present in

several records and should be removed before any statistical analysis; it is consistent with the 10 pW resolution specification of the sensor. It should also be noted that the weakest events approach the lower end of the sensor's specified working range.

The spiral-scan records exhibit a highly regular structure. Illumination events recur at intervals of 23.5 to 24 s in every spiral record, which is a direct ground-based measurement of the revisit period of the LUCAS spiral scan at this offset radius. Several records show the station being illuminated twice within a single revolution, separated by 1 to 2 s, which is consistent with the beam crossing the station on two adjacent turns of the spiral. The random-scan records show a far higher and irregular event rate, as expected from a pseudo-random pattern confined to a much smaller angular region.

The peak power recorded during the night session exceeds that recorded at dusk by more than an order of magnitude, rising from 0.30 nW at 18:52 EET to 7.24 nW at 21:11 EET. Two contributions are expected: the optimisation of fibre coupling carried out between 21:10 and 21:20 EET, and the reduction in sky background between civil twilight and full night, which is significant given the 14.7" acceptance field of the fibre.

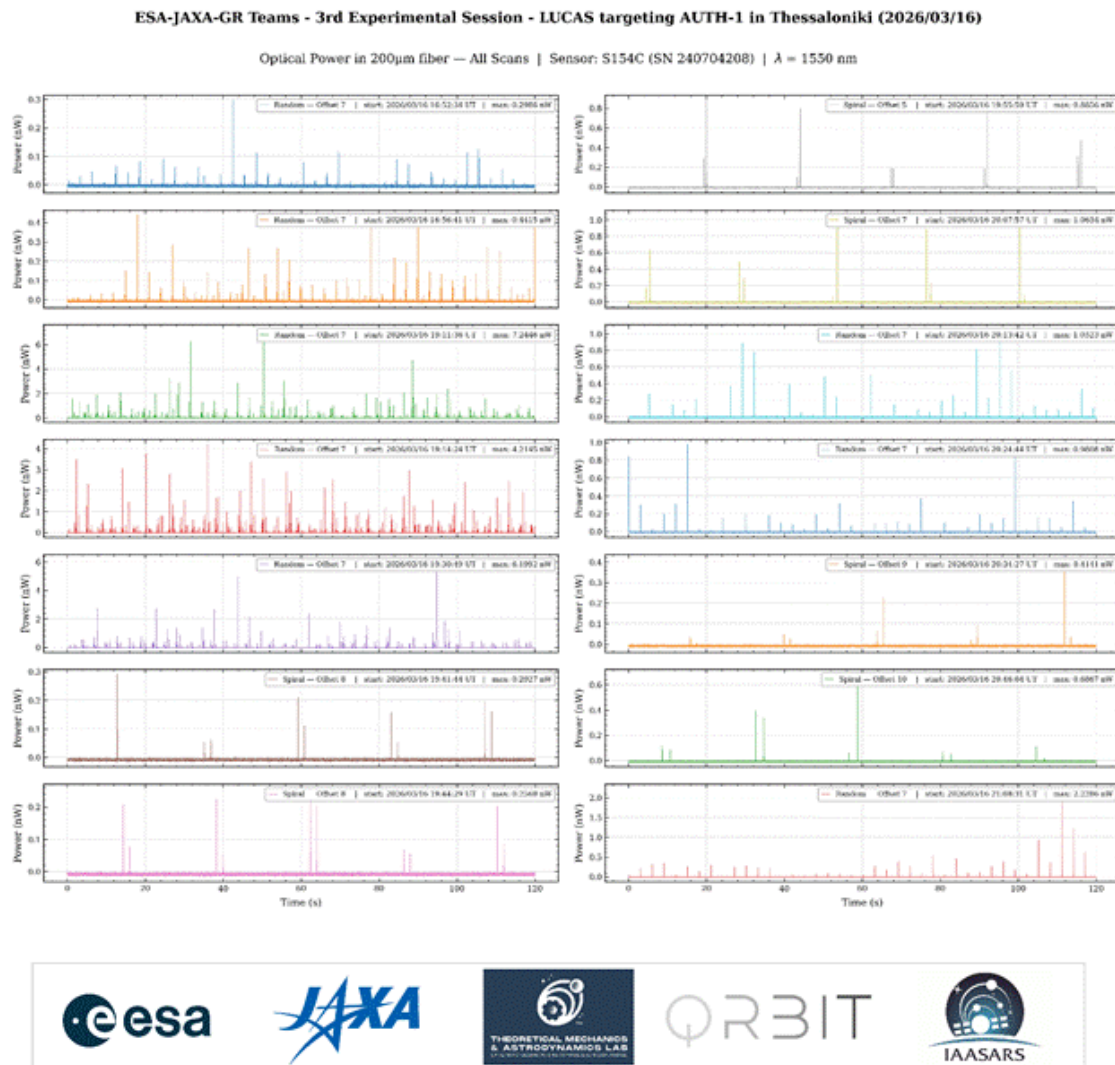


Figure 5 The measurements of the power meter recordings for the whole session of 16/03/2026 from the AUTH OGS. See also Table 1 for more details.

4.2 LUCAS experimental results

4.2.1 LUCAS PAT Sequence for Optical Ground Stations

As shown in Figure 6, the nominal LUCAS acquisition procedure assumes that the counterpart terminal is equipped with a raster-scan capability.

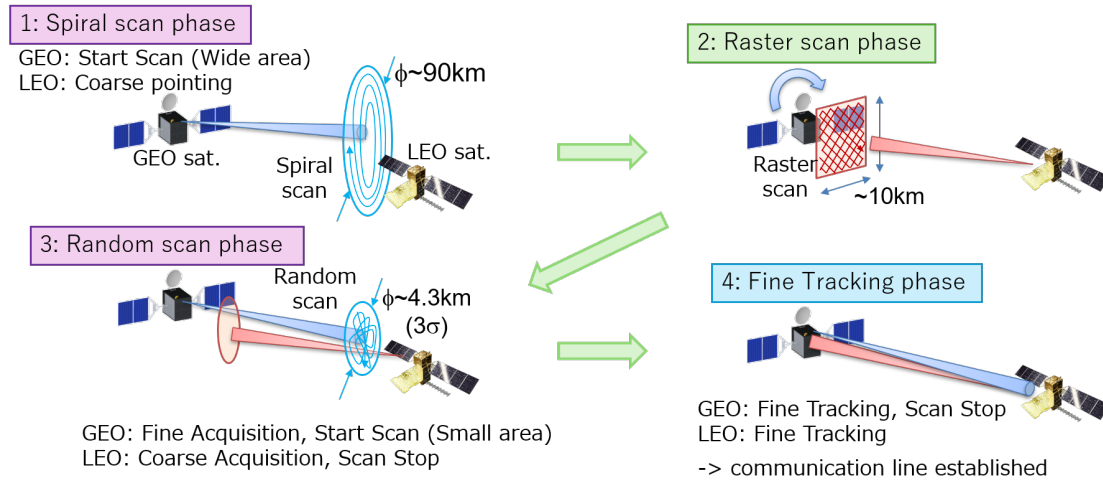


Figure 6 . PAT sequence of LUCAS

However, as only a limited number of OGSs possess such a scanning function, JAXA established an alternative PAT procedure for OGSs. In this procedure, the spiral-scan and random-scan phases are omitted, and the process begins directly from the random-scan phase.

The original design concept of LUCAS is to ensure reliable acquisition of the counterpart terminal by first performing a spiral-scan over an angular region wider than the open-pointing uncertainty. The uncertainty region is then progressively reduced through successive acquisition phases. In contrast, the sequence developed for OGSs relies solely on a random-acquisition scan, whose scanning coverage is narrower than the expected open-pointing uncertainty. Consequently, it is necessary to repeatedly adjust pointing offsets through manual operations in order to locate and acquire the counterpart terminal.

For this reason, characterization of the open-pointing performance of the LUCAS terminal is of critical importance for establishing and optimizing this operational procedure. Although the procedure had previously been validated for OGSs within Japan, it was applied for the first time to OGSs located outside Japan in the present experiment. This provided an opportunity to acquire valuable data regarding the open-pointing characteristics of LUCAS under such conditions. The results obtained are presented in the following subsection.

4.2.2 Pointing Offset Data of LUCAS

Figure 7 shows the offset variation data of LUCAS during operations with the Greek optical ground station (OGS). The blue solid circles and gray dashed circles indicate the random-scan areas. A blue circle denotes that optical signals were detected at the OGS, whereas a gray circle indicates that no signal was received. Since the offset direction was manually adjusted to search for the OGS, six distinct scan areas were examined during this trial.

The red circle represents the estimated region within which the OGS was located. When illuminated by the random-scan beam, the OGS receives the signal transmitted from LUCAS as a sequence of optical pulses. Because the random-scan pattern was designed such that the beam-presence probability follows a Gaussian distribution, the radius of the red circle was estimated from the signal reception frequency observed at the OGS. This estimation provides an indication of the pointing offset between the nominal line of sight of LUCAS and the actual direction toward the OGS.

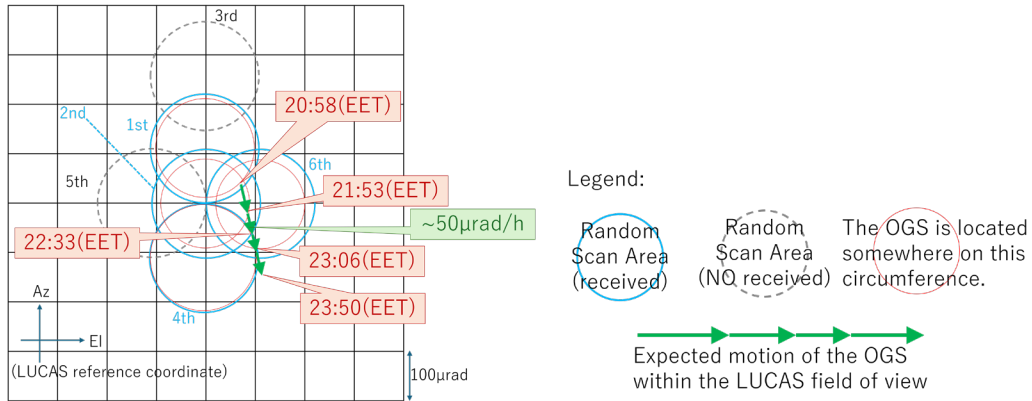


Figure 7 Example of offset drift evaluation results during LUCAS open loop

The experimental results can be consistently explained by assuming that the pointing direction of LUCAS drifted monotonically in a single direction at a rate of approximately $50 \mu\text{rad/h}$ during the experiment. Notably, this drift rate is also consistent with the maximum pointing variation expected from the thermal design characteristics of the LUCAS optical terminal. It should be noted that no such drift was observed during previous experiments conducted with optical ground stations (OGSs) in Japan. Although the underlying mechanism has not yet been identified, the following two possible causes are currently under investigation:

1) Difference in gimbal orientation:

From the perspective of LUCAS, the Japanese OGSs are located in the upper-right region of the Earth disk, whereas the Greek OGS is located in the upper-left region. As a result, the azimuth angle of the gimbal mechanism differs by approximately 10 degrees between these observation geometries. This difference in gimbal orientation may contribute to the observed discrepancy in drift characteristics.

2) Difference in thermo-optical conditions:

Although the experiments with the Japanese and Greek OGSs were conducted at approximately the same local time, they took place in different seasons. Consequently, the thermo-optical environment experienced by the LUCAS optical system differed between the two experiments. Such differences in thermal conditions may have resulted in the observed variation in pointing behavior.

In addition to the current acquisition procedure, another approach under consideration is to perform an initial spiral scan and estimate the offset direction from the temporal intervals between signal detections at the OGS. If successfully established, this method would eliminate the need for iterative random scans based on manual offset adjustments, thereby significantly improving operational efficiency and practicality.

With the cooperation of the Greek OGS team, several datasets were acquired for this purpose, and a number of trials were conducted to estimate the offset direction using the spiral-scan reception patterns. However, the estimation accuracy achieved thus far has not been sufficient for operational application. Once the cause of this limitation has been clarified and effective mitigation measures have been identified, the results will be reported in a future publication.

5. CONCLUSION

The experimental campaign demonstrated acquisition and tracking of the 1550-nm LUCAS optical signal at elevations below 9° . It also confirmed the capability of the LUCAS terminal to support site diversity within a single experimental session by repointing its laser communication terminal between the Athens and Thessaloniki OGSs. Furthermore, the experiments showed that the raster-scan phase can be omitted from the LUCAS pointing, acquisition, and tracking sequence. Finally, JAXA validated an operational approach based on multiple random scans with systematically varied pointing-direction offsets to extend the effective search coverage. During the campaign, this procedure enabled the OGSs

to acquire the random-scan laser signals. Further campaigns are planned for Q4 2026 and throughout 2027 using more advanced ground-station equipment. The objective is to collect more data and pave the way for low-elevation optical links.

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REFERENCES

- [1] J. Romba, Z. Sodnik, M. Reyes, A. Alonso and A. Bird, “ESA’s bidirectional space-to-ground laser communication experiments,” Proc. SPIE 5550, 287–298 (2004)
- [2] J. M. Perdigues et al., “The ESA’s optical ground station for the EDRS-A LCT in-orbit test campaign: upgrades and test results,” Proc. SPIE 10562, 105622V (2017)
- [3] N. Perlot et al., “Results of the optical downlink experiment KIDDO from OICETS satellite to Optical Ground Station Oberpfaffenhofen,” Proc. SPIE 6457, 645704 (2007)
- [4] C. Fuchs et al., “Update on DLR’s OSIRIS program and first results of OSIRISv1 on Flying Laptop,” Proc. SPIE 10910, 109100S (2019)
- [5] Yohei S., Takamasa I., Yutaka T., Shiro Y., “Operational results of JAXA’s optical data relay system LUCAS as of Oct. 2025,” IEEE Journal of Selected Topics in Quantum Electronics Vol.: 32 Issue: 1 DOI 10.1109/JSTQE.2026.3659124
- [6] Hideaki K., YUMA A., Dimiter R. K., Yoshihiko S., Yasuhiro T., Tetsuharu F., Yohei S., Takamasa I., Shiro Y., Hiroyuki T., and Morio T., “Experimental analysis of atmospheric channel model with misalignment fading for GEO satellite-to-ground optical link using “LUCAS” onboard optical data relay satellite,” Vol. 31, No. 13 / 19 Jun 2023 / Optics Express 21351
- [7] Hideaki K., Yohei S., Eiji O., Dimitar R. K., Yasuhiro T., Takamasa I., Shiro Y., Amane M., and Morio T., “Experimental and numerical analysis of data transmission with advanced FEC code and interleaving for GEO satellite-to-ground laser links,” Optics Express Vol. 34, Issue 12, pp. 22310-22329 (2026).
<https://doi.org/10.1364/OE.596932>
- [8] <https://www.noa.gr/en/public-outreach/visitor-centers/visitor-center-penteli/>
- [9] <https://www.celestron.com/products/cpc-deluxe-1100-hd-computerized-telescope>
- [10] <https://www.baader-planetarium.com/en/baader-multi-purpose-vario-finder-10x60-single-or-with-mqr-iv-finder-holder.html>
- [11] <https://andor.oxinst.com/products/c-red-series/c-red-3>