I. INTRODUCTION

In the last few years, free-space optical communications have gained significant importance as higher and higher amounts of data are being produced onboard all kinds of spacecraft. The potential of increasing the bitrate while reducing the volume, mass and energy of the space terminals, and taking advantage of a license-free spectrum [1] are attracting the attention of many researchers from both the public and the private sector.

The long-awaited promise of revolutionizing space communications has started to materialize with an increasing number of projects all over the world. Lasercom demonstrations have been carried out in a wide variety of scenarios, e.g. deep space-to-ground [2], ground-to-deep space [3], LEO-to-ground [4][5], LEO-to-LEO [6], GEO-to-ground [7][8], GEO-to-LEO [9][10], GEO-to-aircraft [11], aircraft-to-ground [12][13], aircraft-to-aircraft [14] and balloon-to-balloons [15], and a number of projects are projected for future demonstrations [16][17][18][19][20][21].

The National Institute of Information and Communications Technology (NICT) in Japan has been engaged in research-and-development activities related to free-space optical communications for over 30 years. During this time, NICT has performed numerous demonstrations, including in-orbit validations such as ETS-VI in the 1990s [7] and OICETS in the 2000s [4]. The last one (in the 2010s) is the SOTA (Small Optical TrAnsponder) mission, conceived to prove for the first time the feasibility of high-bitrate lasercom from a microsatellite platform.

II. SOTA MISSION

The maximum data rate achievable from space scales with the mass of the spacecraft. Even nowadays, the Gbps-class lasercom systems need very big space platforms, and the same thing happens with high-throughput RF systems. Small satellites have a strong limitation in the available bandwidth when using RF, as this technology is reaching its limits. For example, the maximum achievable bandwidth for cubesats is currently in the order of several tens of Mbps from LEO [22]. For the same kind of platform, data rates in the order of the Gbps will be achieved soon by lasercom [23][18].

Furthermore, the crowded radio-frequency spectrum and regulatory difficulties to get the necessary authorizations are other issues that prevent many small satellites to get enough bandwidth, even if it is technically feasible using RF. Optical Communications do not require any authorization in terms of spectrum allocation, which is a big advantage, especially for small satellites with shorter development time frames.

In the late 2000s, NICT identified the potential of lasercom applied to this kind of satellites. With this idea in mind, SOTA was designed to demonstrate an optical communication system in a microsatellite platform for

The final version of this manuscript is accessible through the Acta Astronautica website:
http://www.sciencedirect.com/science/article/pii/S0094576516313194
the first time. Furthermore, the goal was using COTS parts mainly, in order to demonstrate a simple yet effective communication system. This tendency has gained a great deal of interest in the last few years, taking the concept even further with the application of lasercom in cubesats platforms [24].

SOCRATES was embarked on SOTA (Space Optical Communications Research Advanced Technology Satellite), which was launched on May 24th, 2014, as a hosted payload on a Japanese H-II A rocket from the Tanegashima Space Center, in Japan. On July 11th, 2014, the first light of SOTA was received in the Optical Ground Station (OGS) of NICT Headquarters, in Koganei, Tokyo (Japan).

III. SOTA SPECIFICATIONS

The mass of SOTA is 48 kg and its size 496x495x485 mm when the solar panels are folded. The mass of SOTA is only 5.9 kg and the maximum power consumption during operation is below 40 W. It is articulated using an alt-azimuth gimbal with micro-stepping motors with a reduction ratio of 100 to get a resolution of 20 µrad/pulse and a speed of 3°/s.

Fig. 1 shows the main elements of the receiving and the transmitting subsystems of SOTA. The receiving system is responsible of supporting the uplink and has two functions: ATP (Acquisition, Tracking and Pointing) and communications. ATP is performed in two levels: coarse (using a 2.3-cm lens with a FOV of 80 mrad) and fine (using a 5-cm Cassegrain telescope with a FOV of 4 mrad). The fine-detector provides a control signal for a fine-steering mirror in order to fine-point the transmitted communications laser.

Fig. 1: Receiving and transmitting subsystems onboard SOTA including their main elements.

The transmitter subsystem is made up by four different lasers: Tx1 at 976 nm, Tx2 & Tx3 at 800-nm band and Tx4 at 1549 nm. Tx1 and Tx4 are communication lasers which can transmit at 1 or 10 Mbit/s with NRZ-OOK (Non-Return to Zero On-Off Keying) modulation from different selectable sources (an image from an onboard camera, a preloaded sample image or a pseudorandom binary sequence PRBS-15). This data can be coded against transmission errors using LDGM or Reed Solomon.

IV. TYPICAL SOCRATES PASS

SOCRATES is inserted in a Sun-synchronous near-circular orbit at an altitude of ~600 km, with an inclination of 97.9° and a period of 97.4 minutes. In a typical SOCRATES pass, the sequence to establish a link goes in the following way: the experiment parameters are transmitted to the satellite by a RF link from a TT&C (Telemetry, Tracking and Control) ground station; the sequence of data to transmit through the optical link is prepared adding the error-correcting code; the OGS starts tracking the satellite according to the predicted orbital information and transmits a high-power beacon towards that position; when SOTA detects the beacon signal, it starts transmitting the laser or lasers set for that experiment until the end of the communications.

Fig. 2: An example of a typical 3-day sequence of SOCRATES passes. Above, a summary image of the three passes. Below, the variation of the OGS elevation angle and the distance SOCRATES-OGS for the three passes.

The characteristics of the orbit of SOCRATES allow the Koganei OGS to perform a lasercom experiment with SOTA in sequences of three days, with sequences of other three days without experiments. These links are always performed during the night around 23:00 (local time) because of SOTA design constraints. Fig. 2 shows an example of a typical three-day sequence of passes, including the satellite image of the passes (above) with the minimum SOCRATES-OGS distance (which happens at the maximum OGS elevation) and an image of the all-sky camera at that moment. Below, the figure
shows the variation of the OGS elevation angle and the distance SOCRATES-OGS during these passes. Generally, lasercom experiments occur when the OGS elevation angle is above ~30° and below ~80°. This can be observed in Fig. 2 for the links of August 5th and 6th in red colour. On August 7th, no experiment could be performed due to bad weather conditions. In these 3-day sequences, the intermediate pass requires an OGS high-elevation angle, which makes the link stop briefly until it is re-acquired by the ATP system.

![Fig. 3: Footprint of the SOTA lasers on the OGS of Koganei (Tokyo, Japan) for the minimum (~600 km, below) and maximum (~1400 km, above) distance range.](image)

Table 1: Main specifications of SOTA Tx1 and Tx4.

|          | Tx1       | Tx4       |
|----------|-----------|-----------|
| Wavelength | 976 nm    | 1549 nm   |
| Transmitted power | 0.89 MW/sr | 0.57 MW/sr |
| Divergence angle | 500 µrad   | 223 µrad   |
| Aperture size | ~1 cm     | ~5 cm     |
| Polarization | Linear    | Circular  |
| Pointing loss | -3.4 dB   | -5.7 dB   |

The Fig. 4 shows an example of a SOTA downlink on December 9th, 2015. This experiment was chosen for being a typical low-elevation pass (no interruption around the 90° elevation) with a clear sky (no clouds) and long duration (around 200 s). Tx4 (λ = 1549 nm) was used in this downlink at a 10-Mbit/s constant bitrate. The figure also shows the measured BER (Bit Error Rate) associated to the PRBS-15 transmitted sequence, with an average value of 6·10⁻³, after FEC (Forward Error Correction) decoding using a Low-Density Generator-Matrix/Low-Density Parity Check (LDGM-LDPC) code. Since the SOTA receiver sensitivity is -55 dBm, a BER increase can be observed when the received power falls below the sensitivity. The decrease in the measured power around the middle of the experiment is associated with alignment issues related to the higher speed the telescope must move to track SOCRATES at higher elevation angles.

![Fig. 4: Predicted and measured received power and BER measurement using the 1-m telescope in Koganei (Tokyo) on 9 Dec. 2015 in a Tx4 (1549 nm) downlink experiment at 10 Mbit/s.](image)

In the link budget calculation, the atmospheric loss was simulated with MODTRAN, and it depends on the telescope elevation angle (the optical path is longer at lower elevation angles), varying between 3.2 dB at the longest distance (1300 km, at a 25° elevation angle) and 1.8 dB at the shortest distance (875 km, at a 42° elevation angle). The elevation angle also determines the free-space loss, as the optical path is longer for lower elevation angles, producing a bigger footprint, as was shown in the Fig. 3. The beam scintillation, i.e. the power fluctuation due to atmospheric turbulence, depends on the telescope elevation angle as well. An in-depth analysis of the power scintillation using SOTA measurements can be found at [25].

V. SOTA ACHIEVEMENTS

SOCRATES was launched on May 24th, 2014. A general verification of the satellite was performed during ~2 months, followed by a start-up period of the OGS and SOTA. The lasercom experiments officially started in November, 2014, and they have continuously been performed up to the present date. With nearly 300
planned passes, around 45% of the experiments were carried out. The rest have been cancelled due to bad-weather forecast or due to maintenance work on the satellite or the lasercom terminal. Almost 30% of the performed experiments were carried out successfully with a stablished uplink and downlink, and the rest were unsuccessful due to bad weather or abnormal operation. The SOTA mission ended on November 2016 [26], doubling the 1-year initial lifetime design.

In SOTA mission, several success criteria are defined. The minimum success was achieved after the verification of the correct behavior of all the components of SOTA. The success level consisted of the verification of the ATP system after receiving the uplink beacon and BER measurements of the Tx1 and Tx4 signals in the OGS. Full success was achieved when the different data sources (the camera image, the preloaded image and the pseudorandom binary sequence) could be transmitted to the OGS, including error correcting codification (see Fig. 5).

![Fig. 5: SOCRATES artistic illustrations. Left: Lasercom between SOTA and NICT OGS in Koganei, Tokyo. Top right: SOCRATES imaging the Earth with a visible camera. Bottom right: International campaign with other ground stations (in the image, MeO OGS, France).](image)

An extra-success phase was carried out since May 2015, consisting of interoperability tests with other international OGSs (see Fig. 6). Four different space agencies participated in the campaign: ESA (European Space Agency), CNES (National Centre for Space Studies), DLR (German Aerospace Center) and CSA (Canadian Space Agency). Two passes were assigned to ESA in April 2015 using the 1-m OGS in Tenerife (Spain), but the uplink beacon hit SOTA only for a short time and with low power, thus no link was established. CNES performed five successful links detecting Tx1 and Tx4 signals from SOTA during June, July and October 2015 using the 1.54-m MeO OGS in Caussol (France) [267]. DLR hit SOTA with the uplink beacon in July 2015 and they performed one successful link in May 2016 receiving the Tx4 signal from SOTA using a 40-cm and 60-cm OGS in Oberpfaffenhofen (Germany) [28]. Lastly, CSA used a 40-cm OGS in Montreal (Canada) to perform a partially-successful link in August 2016, hitting SOTA with the uplink beacon in one pass.

![Fig. 6: SOTA interoperability campaign: the international OGSs which participated in the campaign are shown.](image)

VI. SITE DIVERSITY

The main impediment of free-space optical communications is the propagation of laser signals through the atmosphere. An effective solution to mitigate this problem is site diversity. This technique consists of replicating the ground segments in several uncorrelated sites in order to increase the probability of link success. Within this endeavor, NICT is developing a network of OGSs throughout Japan (Fig. 7), with autonomous-operation capabilities in order to be operated remotely from a control center according to the link availability, decided using meteorological data in each location.

This network is called INNOVA (IN-orbit and Networked Optical ground stations experimental Verification Advanced testbed) [29] and it consists of three different OGS locations: NICT Headquarters (Koganei, Tokyo prefecture), Kashima Space Technology Center (Kashima, Ibaraki prefecture) and Okinawa Electromagnetic Technology Center (Okinawa, Okinawa prefecture). All these OGSs include a telescope with a 1-m aperture and a focal length of 12 m, with LEO-tracking capabilities (accuracy better than 10 arcsec), and five available focus (Cassegrain, 2×Nasmyth and 2×Coudé) in the case of Koganei and one Nasmyth focus in the case of Kashima and Okinawa.
INNOVA also includes a total number of ten locations with different meteorological sensors to take long-term weather statistics.

![Map of Japan with the three NICT 1 m-class Optical Ground Stations for site diversity.](image)

Fig. 7: Map of Japan with the three NICT 1 m-class Optical Ground Stations for site diversity.

As an example of the potential improvement of the site diversity, an estimation of the link availability was made taking into account all the possible SOCRATES passes over the three NICT OGS locations during the period of June 5th to July 18th. During the SOTA mission, the Kashima and Okinawa OGSs were still not in operation, thus only the Koganei OGS was used for SOTA experiments. The following study presents a theoretical estimation using the SOTA mission as a study case assuming that all the NICT OGSs could have been used during the mission.

Table 2: Statistics of the possible passes over the three NICT OGSs during the 2016 rainy season.

| Period (Baiu) | Koganei | Kashima | Okinawa |
|--------------|---------|---------|---------|
| No. of days  | 44      | 44      | 44      |
| Possible passes | 21      | 21      | 21      |
| Total link time | 7156 s  | 7161 s  | 7143 s  |
| Link probability | 50%     | 49%     | 31%     |
| Real link time | 3607 s  | 3473 s  | 2193 s  |
| Using 2 OGS  | 5508 s (77%) | -       |         |
| Using 3 OGS  | 7174 s (100%) | -       |         |

According to the Japan Meteorological Agency, the 2016 rainy season occurred in this period in Kanto prefecture, where the NICT headquarters is located with the Koganei OGS. All of Japan (except Hokkaido island) experiences this rainy season, called Tsuyu, every year in early summer (from early June to late July, and one month earlier in Okinawa). Although Tokyo registers an average of 12 rainy days during the whole rainy season, just 120 hours of sunshine are recorded on average. The following figures illustrate the strong impact this cloudy season has on the link availability: if the annual clear-sky rate in Koganei OGS is 56.5%, the one for the 2016 rainy season was only 11.2%. Therefore, this period can be used as a worst-case scenario in terms of link availability.

INNOVA meteorological data can be used to predict the OGS availability for lasercom. A simple predictive algorithm was designed taking into account the atmospheric transmittance and the cloud coverage. The atmospheric transmittance is estimated using the solar radiation, and the cloud coverage is estimated using temperature measurements and all-sky camera images. In general, the algorithm predicts good conditions for lasercom if atmospheric transmittance is over 60% and the cloud coverage is less than 10%. The current predictive algorithm is in a preliminary version of this on-going project.

![Link probability for each SOTA pass in the 2016 rainy season using each single NICT OGS (red) and applying site diversity with 2 OGSs (orange) and 3 OGSs (green).](image)

Fig. 8: Link probability for each SOTA pass in the 2016 rainy season using each single NICT OGS (red) and applying site diversity with 2 OGSs (orange) and 3 OGSs (green).

During the 2016 rainy season, each OGS had 21 available passes according to the usual constraints for SOTA experiments: the experiment has to be at nighttime and at an OGS elevation over 45°. The table 2 shows the statistics for this period. If only one OGS was used, the best link probability would be 50% (at Koganei). Assuming a weather decorrelation between the three sites, if two OGS (Koganei or Kashima) could be selected in each pass, the link probability would increase up to 77%, and if the three OGS could be selected, the link probability would become 82% on average in every SOTA pass.

The previous calculations are average values assuming that each pass occurs on the same day and one out of two or three OGSs can be selected in each pass to avoid the cloud coverage. This is a realistic assumption in the case of selecting between Koganei and Kashima because the SOTA passes occur almost at the same
time. As shown in the Fig. 8, for Okinawa the SOTA passes usually occur on different days, thus different passes than the Koganei/Kashima ones. Therefore, the combined link probability for 2 OGSs was calculated only for Koganei and Kashima.

![Fig. 9: Individual link probability for every NICT OGS, and link probability applying site diversity with 2 OGSs (orange) and 3 OGSs (green).](image)

The fact that the Okinawa passes occur on different days than the Koganei/Kashima ones in practice increases the total available link time, reaching the 100% of the foreseen link time for one OGS. This means that even in the rainy season (worst-case scenario for Japan) the three NICT OGSs allow to download the same data as having a single OGS with a cloud coverage of 0%. The link probabilities for each individual OGS as well as the probabilities for 2-OGSs and 3-OGSs site diversity are summarized in the Fig. 9.

VII. QKD EXPERIMENT

Free-space optical communications can allow other applications besides the high-speed transmission of data from a satellite. One important application is the information security, and specifically quantum communication can be carried out using lasercom terminals with some modifications. One of the most important applications of quantum communication is Quantum Key Distribution (QKD). This technique allows the transmission of encryption keys in a theoretically secure way by using fundamental laws of physics, in particular the Heisenberg uncertainty principle. QKD is a relatively-mature technique in its guided version, using optical fibers. However, the transmission distance is limited to ~200 km [30] because of the lack of reliable quantum repeaters. Space-to-ground links, being a key step towards a global QKD network remain to be demonstrated [31].

A basic QKD experiment was designed as part of the extra-success phase of the SOTA mission. This experiment makes use of the Tx2 and Tx3 lasers (see Fig. 1) in the 800-nm band. They are non-orthogonally linearly polarized laser sources, since the most important QKD protocols are based on polarization-encoded photons. In the first phase of this experiment, a characterization of the polarization behavior after the atmospheric propagation was carried out [32]. For this, a 1.5-m Cassegrain telescope was used to gather the signal from SOTA and couple it to a polarimeter (Fig. 10, left). These experiments were performed from January to March 2016 measuring the polarization of the Tx1 (\(\lambda = 976\) nm, linear polarization) and Tx4 (\(\lambda = 1549\) nm, circular polarization) signals when transmitting a PRBS-15 sequence at 10 Mbit/s.

The Stokes parameters, the received optical power and the Degree Of Polarization (DOP) were measured in these experiments. The polarimeter system has a strong dependence between the DOP and the received power: If the power is high enough, a DOP \(\approx 100\%\) can be measured from a well-polarized signal, but for low power, a decrease in the DOP as well as a bigger variability in the measurement is observed for the same signal. In the SOTA experiments, the power is not high enough for the polarimeter to measure the DOP with high accuracy, so the characterization of this dependence is important, and it was explained in detail in [32].

![Fig. 10: Left: Receiving system for measuring the polarization of SOTA laser sources. Right: Normal distribution of the degree of polarization received in the NICT OGS from SOTA Tx1 (\(\lambda = 976\) nm, linear polarization) in blue, and Tx4 (\(\lambda = 1549\) nm, circular polarization) in red.](image)
source in space was measured, as well as the polarization of a source at $\lambda = 1549$ nm. This wavelength and polarization are good candidates to become the standard in future QKD links from space: this spectral region is the preferred in terms of atmospheric transmission and turbulence, and linear polarization is used in the most extended protocols, such as BB84.

After the verification of the polarization preservation through the atmosphere, other experiment was performed, consisting of demonstrating for the first time some basic principles of quantum communication from space. Currently, the data obtained in this experiment is being analysed and the results will be reported soon. In this experiment, the non-orthogonal Tx2 and Tx3 signals were received at a near single-photon regime using a QKD-like receiver in the 1-m OGS. For this experiment to be accomplished successfully, a key step was being able to track and correct the polarization of the received signals due to the motion of the satellite in relation to the OGS. This motion makes the reference frame change with time, which has to be aligned. This can be achieved with a rotating half-wave plate before the receiver. Since the orbital information of the satellite is well known, it is possible to predict the angle of the linear polarization when received in the OGS. A simulation was carried out taking into account the relative motion between the SOCRATES satellite and the OGS, as well as the OGS elevation (which also makes the angle change when using the Nasmyth bench of the telescope). Fig. 11 shows this prediction for previous SOTA passes and a good agreement is observed with measured data using the polarimeter for the same passes. The two examples of the Fig. 11 show the prediction for Tx1 as well as Tx4 (the polarization angle for a circular polarization like Tx4 is possible to be measured since the signal is not perfectly circular, but elliptical). For both experiments, an interruption of the reception can be observed for high elevation angles, as was explained in the section IV.

**VIII. CONCLUSION**

The SOTA lasercom terminal onboard the SOCRATES satellite was operated by NICT for more than two years. During this time, all the goals of the mission were achieved, including up to 10-Mbit/s downlinks using two different wavelengths and apertures, verification of coarse and fine tracking of the OGS beacon, space-to-ground transmission of pseudo-random sequences and images from the on-board-camera as well as preloaded samples, and experiments with different error correcting codes. Other two extra-success experiments were carried out within SOTA mission: interoperability with other international OGS and basic experiments on space QKD. In this paper, the basic characteristics of SOTA and the fundamentals of its operation were described, along with an overview of the achievements of the mission.

**IX. REFERENCES**

[1] H. Hemmati et al., “Comparative study of optical and radio-frequency communication system for a deep-space mission,” The Telecommunications and Data Acquisition Progress Report TDA PR 42-128 (1996).

[2] D. M. Boroson et al., “Overview and results of the Lunar Laser Communication Demonstration,” Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI, 89710S (March 6, 2014).

[3] K. E. Wilson et al., “GOPEX: a laser uplink to the Galileo spacecraft on its way to Jupiter,” Proc. SPIE 1866, Free-Space Laser Communication Technologies V, 138 (August 6, 1993).

[4] T. Jono et al., “OICETS on-orbit laser communication experiments,” Proc. SPIE 6105, Free-Space Laser Communication Technologies XVIII, 610503 (March 1, 2006).

[5] M. Gregory et al., “Three years coherent space to ground links: performance results and outlook for the optical ground station equipped with adaptive optics,” Proc. SPIE 8610, Free-Space Laser Communication and Atmospheric Propagation XXV, 861004 (March 19, 2013).

[6] R. Fields et al., “NFIRE-to-TerraSAR-X laser communication results: satellite pointing, disturbances,
and other attributes consistent with successful performance,” Proc. SPIE 7330, Sensors and Systems for Space Applications III, 73300Q (May 6, 2009).

[7] K. Araki et al., “Performance evaluation of laser communication equipment onboard the ETS-VI satellite,” Proc. SPIE 2699, Free-Space Laser Communication Technologies VIII, 52 (April 22, 1996).

[8] A. Alonso et al., “Performance of satellite-to-ground communications link between ARTEMIS and the Optical Ground Station,” Proc. SPIE 5572, Optics in Atmospheric Propagation and Adaptive Systems VII, 372 (November 11, 2004).

[9] G. D. Fletcher et al., “The SILEX optical interorbit link experiment,” Electronics & Communication Engineering Journal 3(6), pp. 273-279 (1991).

[10] H. Zech et al., “LCT for EDRS: LEO to GEO optical communications at 1.8 Gbps between Alphasat and Sentinel 1a,” Proc. SPIE 9647, Unmanned/Unattended Sensors and Sensor Networks XI; and Advanced Free-Space Optical Communication Techniques and Applications, 96470J (October 29, 2015).

[11] V. Cazaubiel et al., “LOLA: A 40000 km Optical Link between an Aircraft and a Geostationary Satellite,” Sixth International Conference on Space Optics, Proceedings of ESA/CNES ICSO 2006 (June 27-30, 2006).

[12] F. G. Walther et al., “Air-to-ground lasercom system demonstration design overview and results summary,” Proc. SPIE 7814, Free-Space Laser Communications X, 78140Y (August 24, 2010).

[13] F. Moll et al., “Demonstration of high-rate laser communications from fast airborne platform: flight campaign and results,” IEEE Journal on Selected Areas in Communications 33(9) (May 13, 2015).

[14] E. D. Miller et al., “A prototype coarse pointing mechanism for laser communication,” Proc. SPIE 10096, Free-Space Laser Communication and Atmospheric Propagation XXIX, 100960S (February 24, 2017).

[15] B. Moision et al. “Demonstration of free-space optical communication for long-range data links between balloons on Project Loon,” Proc. SPIE 10096, Free-Space Laser Communication and Atmospheric Propagation XXIX, 100960Z (February 24, 2017).

[16] Thomas Dreischer et al., “Functional System Verification of the OPTEL-μ Laser Downlink System for Small Satellites in LEO,” International Conference on Space Optical Systems and Applications (ICSOS) (May 7-9, 2014).

[17] W. J. Siegfried and R. P. Welle, "The NASA Optical Communication and Sensor Demonstration Program," Proceedings of the 27th AIAA/USU Conference (August 10-15, 2013).

[18] C. Schmidt et al., “OSIRIS Payload for DLR’s BiROS Satellite,” International Conference on Space Optical Systems and Applications (ICSOS) (May 7-9, 2014).

[19] Y. Chishiki et al., “Overview of optical data relay system in JAXA,” Proc. SPIE 9739 (2016).

[20] B. Edwards et al. “A Day in the Life of the Laser Communications Relay Demonstration Project,” Proc. SpaceOps Conference (May 16-20, 2016).

[21] Z. Sodnik et al., “Multi-purpose laser communication system for the asteroid impact mission (AIM),” IEEE International Conference on Space Optical Systems and Applications (ICSOS) (October 26-28, 2015).

[22] National Academies of Sciences, Engineering, and Medicine, “Achieving Science with CubeSats: Thinking Inside the Box,” The National Academies Press, Washington, DC (November 23, 2016).

[23] National Aeronautics and Space Administration, “Optical Communications and Sensor Demonstration. Technologies for Proximity Operations and Data Transmission,” NASA Facts FS#2015-03-20-ARC (2015).

[24] T. S. Rose et al., “LEO to ground optical communications from a small satellite platform,” Proc. SPIE 9354, Free-Space Laser Communication and Atmospheric Propagation XXVII, 93540I (March 16, 2015).

[25] D. Kolev and M. Toyoshima, “Received-Power Fluctuation Analysis for LEO Satellite-to-Ground Laser Links,” IEEE Journal of Lightwave Technology 35(1), 103–112 (2017).

[26] National Institute of Information and Communications Technology (NICT), Official announcement of the completion of SOTA mission, http://www.nict.go.jp/info/topics/2016/12/161202-1.html

[27] E. Samain et al., “First free space optical communication in europe between SOTA and MeO optical ground station,” IEEE International Conference on Space Optical Systems and Applications (ICSOS) (October 26-28, 2015).

[28] C. Fuchs et. al., “SOTA optical downlinks to DLR’s optical ground stations”, International Conference on Space Optics ICSO (October 18-21, 2016).

[29] M. Toyoshima et al., “Introduction of a terrestrial free-space optical communications network facility: IN-orbit and Networked Optical ground stations experimental Verification Advanced testbed (INNOVA),” Proc. SPIE 8971, Free-Space Laser Communication and Atmospheric Propagation XXVI, 89710R (6 March, 2014).

[30] V. Scarani et al., “The security of practical quantum key distribution,” Rev. Mod. Phys. 81(3), 1301–1350 (2009).
[31] C. Bonato et al., “Feasibility of satellite quantum key distribution,” New J. Phys. 11(4), 045017 (2009).

[32] A. Carrasco-Casado et al., “LEO-to-ground polarization measurements aiming for space QKD using Small Optical TrAnsponder (SOTA),” Optics Express, vol. 24, issue 11, p. 12254 (2016).

[33] M. Toyoshima et al., “Polarization measurements through space-to-ground atmospheric propagation paths by using a highly polarized laser source in space,” Opt. Express 17(25), 22333–22340 (2009).