World's first demonstration of space quantum communication using a microsatellite

July 11 2017, by Sachiko Hirota

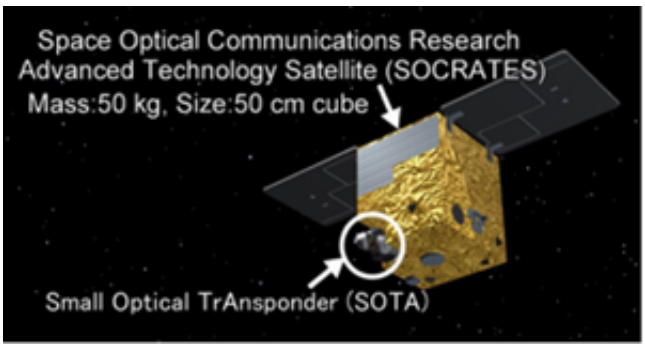

Fig. 1. Image of SOTA onboard SOCRATES. Credit: NICT

NICT developed the world's smallest and lightest quantum communication transmitter (SOTA) onboard the microsatellite SOCRATES. We succeeded in the demonstration of the first quantum communication experiment from space, receiving information from the satellite in a single-photon regime in an optical ground station in Koganei city. SOTA weighs 6 kg and its size is 17.8 cm length, 11.4 cm width and 26.8 cm height. It transmits a laser signal to the ground at a rate of 10 million bits per second from an altitude of 600 km at a speed of 7 km/s. We succeeded in correctly detecting the communication signal from SOTA moving at this fast speed. This is a major step toward building a global long-haul and truly secure satellite communication network.

As a result of this research, NICT demonstrated that satellite quantum communication can be implemented with small low-cost satellites, which makes it possible to use this key technology. It is an achievement that opens a new page in the development future global communication networks and a big boost to the space industry.

The results of this research were accepted for publication in *Nature Photonics*.

The technologies required to launch small satellites at a low cost have progressed immensely during this century, and significant efforts are being made to develop satellite constellations to achieve a global communication network covering the entire Earth. However, there is a need for a technology that can transmit large amounts of information from space to the ground in short periods of time, and the current RF bands are already congested, creating a bottleneck of communication capacity.

By using lasers, satellite optical communication has a readily available frequency band and can transmit with higher power efficiency and with smaller and lighter terminals. Thus, it is expected to be a key technology to support the future satellite communication networks. Quantum communication, and more specifically, quantum key distribution (QKD) is another key technology to guarantee the information security of the next global communication networks. Current QKD links are limited to several hundreds of km, thus implementing satellite-to-ground QKD is a fundamental step in this endeavor. QKD research is actively conducted in Japan, China, Europe, Canada and the United States (see supplementary information on recent research and development trends). In August of 2016, the University of Science and Technology of China launched a large (635 kg) quantum communication satellite and performed a quantum-entanglement experiment with two ground stations.

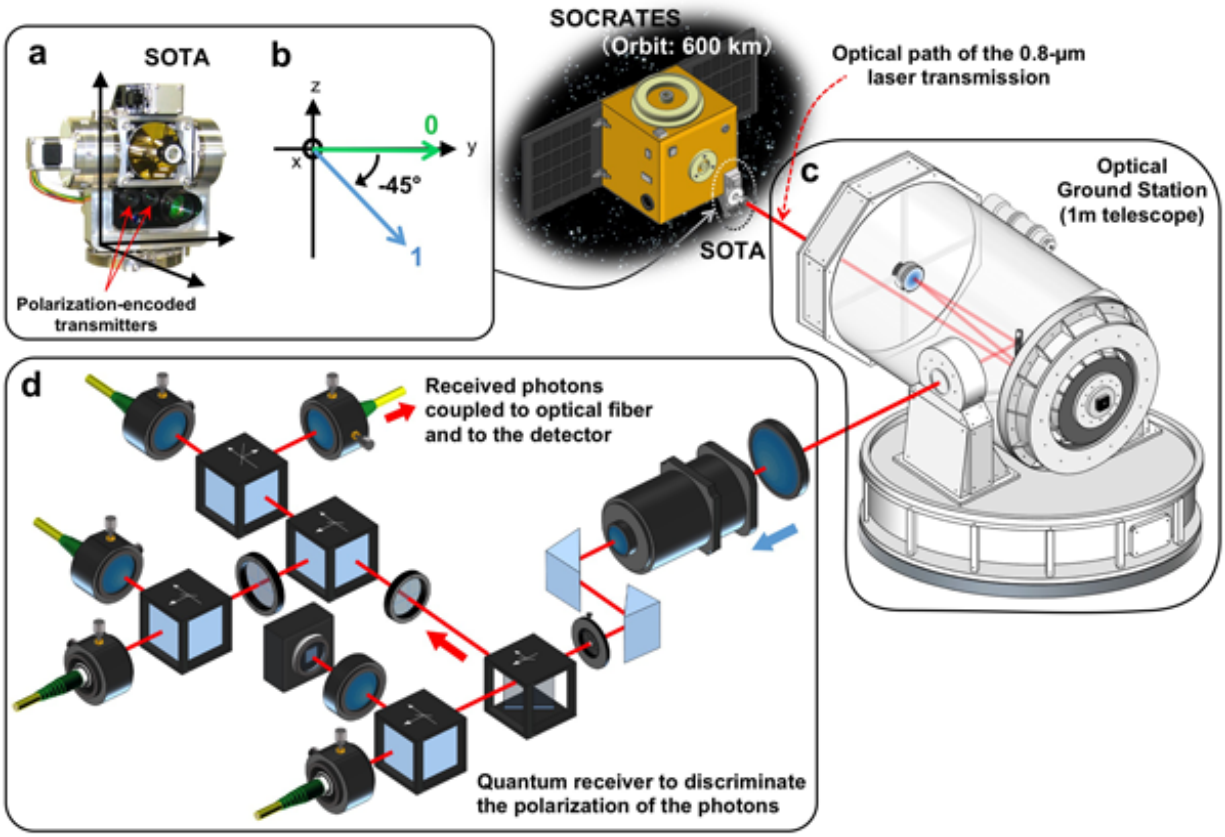

Fig. 2. Outline of the microsatellite SOCRATES and the NICT optical ground station located in Koganei city. (a) Picture of the lasercom terminal SOTA. (b) Polarization states that encode the bits of the transmitted information. (c) Optical ground station. (d) Configuration diagram of the quantum receiver. Credit: NICT

SOTA is the world's smallest and lightest quantum communication transmitter (6 kg weight, 17.8 cm length, 11.4 cm width, and 26.8 cm height) embarked on the microsatellite SOCRATES (see Fig. 1). SOTA transmitted two polarization states, encoding zeroes and ones (see Fig. 2a, b) to the ground at a rate of 10 million bits per second. The signals from SOTA were received at the NICT optical ground station in Tokyo's Koganei city using a 1 m telescope (see Fig. 2c) to collect the

transmitted photons and guide them to the quantum receiver (see Fig. 2d), which decoded the information using a QKD protocol.

The signal that arrives at the 1 m telescope is extremely weak, with an average of 0.1 photons per received pulse. NICT developed the technology to perform the time synchronization and polarization reference frame matching between the satellite and the ground station directly from the QKD signals, as well as a quantum receiver capable of detecting such a weak signal with low noise. We demonstrated the world's first quantum communication from a 50-kg microsatellite. This will enable the development of future secure links from space via quantum cryptography to completely prevent information leakage.

The technology developed in this project demonstrated that satellite quantum communication can be implemented by using low-cost lightweight microsatellites. Therefore, it is expected that many research institutes and companies interested in this technology will accelerate the practical application of quantum communication from space. In addition, since it was proved that long-distance communication is possible with very low electric power, this will open up a path to speed up deep-space optical communication with exploration spacecraft.

In the future, we plan to further increase the transmission speed and improve the precision of the tracking technology to maximize the secure key delivery from space to ground by using quantum cryptography enabling a truly secure global communication network, whose confidentiality is currently threatened by the upcoming development of quantum computers.

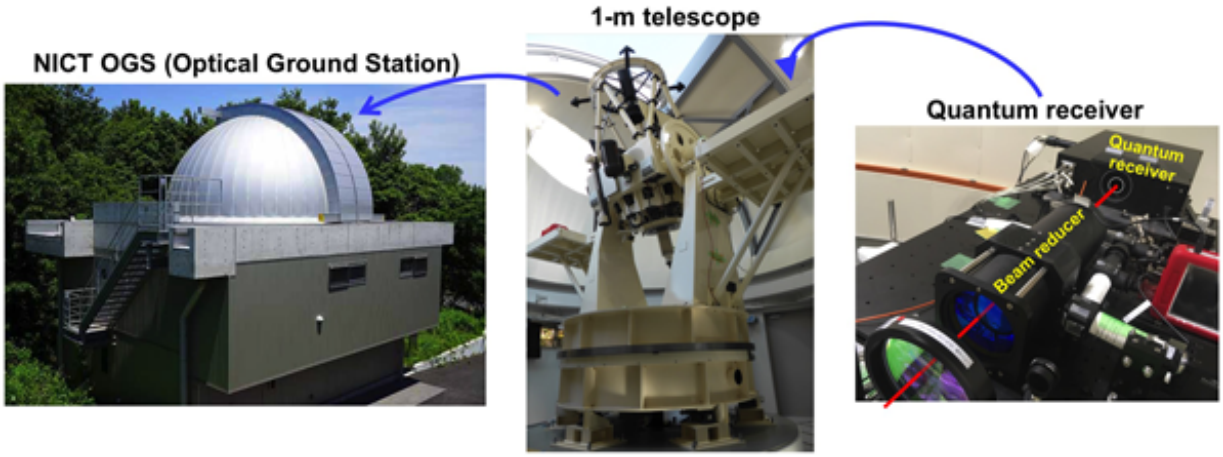

Fig. 3. Images of the NICT Optical Ground Station, the 1-meter telescope and the quantum receiver. Credit: NICT

The technologies necessary to launch small satellites at low cost have advanced immensely in the last few years, and by launching a high number of satellites into low Earth orbit, global communication networks covering the entire Earth in the form of satellite constellations are becoming a reality. These constellations will have to deal with a huge amount of data to be transferred to the Earth in short periods of time (since the typical pass of a LEO satellite is several minutes). Additionally, the RF technology is becoming obsolete and the radio spectrum congested. Satellite optical communication has a readily available spectrum and the potential to increase the amount of transmitted data while reducing the power, mass and weight of the terminals.

Space laser communication has been demonstrated in many missions, mainly in Japan, Europa and the U.S. In May 2014, NICT developed a small laser communication terminal (SOTA) and launched it onboard the microsatellite SOCRATES into a 600-km sun-synchronous orbit. NICT

successfully performed a variety of laser communication experiments, and since 2016, a new campaign of quantum communication experiments was carried out.

Quantum communication is an essential technology for realizing quantum cryptography, which can completely protect the cryptographic key exchange from any information leakage. Satellites can significantly increase the range of QKD links since the losses are smaller than when using optical fibers, which is typically limited to around 200 km, allowing intercontinental secret key exchanges.

In August of 2016, the University of Science and Technology of China launched a large (635 kg) quantum communication satellite and performed a quantum-entanglement experiment with two ground stations (J. Yin et al., Science, 356(6343), June 2017). The Chinese team is also conducting experiments on intercontinental-scale quantum cryptography using this satellite (E. Gibney, *Nature*, 535, 2016).

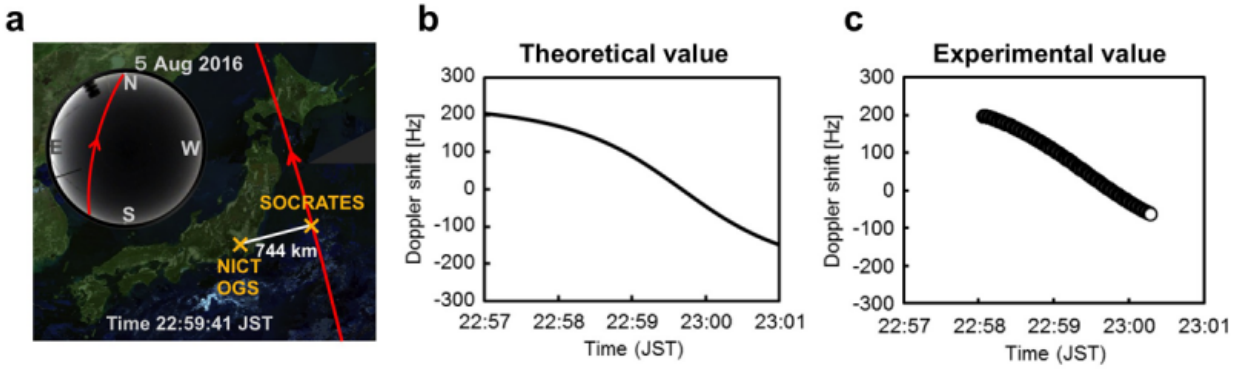

Fig. 4. (a) SOCRATES orbit and link distance between SOCRATES and the NICT OGS at its closest approach. (b) Theoretical value of the Doppler shift received from SOCRATES in the OGS. (c) Experimental measured value. Credit: NICT

Satellite laser communication and quantum communication are emerging technologies with great potential in future global-scale communication networks, and they are attracting a great deal of attention from many important research institutions all over the World.

Most of the transmitted SOTA photons are lost before reaching the receiver because of the divergence of the laser beam and the limited aperture of the telescope to gather the photons. Additionally, many photons are scattered and absorbed in the atmosphere. As a result, the signal arriving at the OGS is extremely weak, carrying an average of fewer than 0.1 photons per pulse. Since such weak signals cannot be detected via conventional photodetectors, the quantum receiver used extremely sensitive detectors known as photon counters that can detect single photons. This enables more highly efficient communication than conventional satellite optical communication. Also, by using signals with less than one photon per pulse, quantum cryptography can detect the presence of an eavesdropper, which makes it possible to deliver secret keys in a confidential way.

In order to realize quantum communication and quantum cryptography with such a weak signal, a key step is to accurately time-stamp the signals so that they are clearly recognized in the quantum receiver. Therefore, it is necessary to accurately synchronize the signals between SOCRATES and the OGS to detect the transmitted bits without errors. It is also necessary to carry out a polarization-axis matching, because the reference frames change due to the relative motion between the satellite and the ground station. Only Japan and China have been able to demonstrate these technologies in space, but China did it by using a 600 kg-class satellite, while Japan did it by using a 50 kg-class satellite.

Since the satellite moves at high speed relative to the OGS (about 7 km/s), the wavelength of the laser signal Doppler shifted to a shorter wavelength when approaching the OGS, and to a longer wavelength

when moving away from the OGS. Because of the Doppler effect, it is necessary to carry out an accurate time synchronization to correctly detect the long sequences of bits without errors. In the China quantum communication experiment, this synchronization was realized by using a dedicated laser transmitting a synchronization signal. By contrast, NICT was able to carry out this synchronization by using the quantum signal itself. A special synchronization sequence of about 32,000-bits was used in the quantum communication signal for this purpose, and the quantum receiver was able to perform not only the quantum communication, but also the synchronization and the polarization axis matching directly, by using only the weak quantum signal. In this experiment, NICT succeeded in demonstrating for the first time that quantum communication technology can be implemented in small satellites.

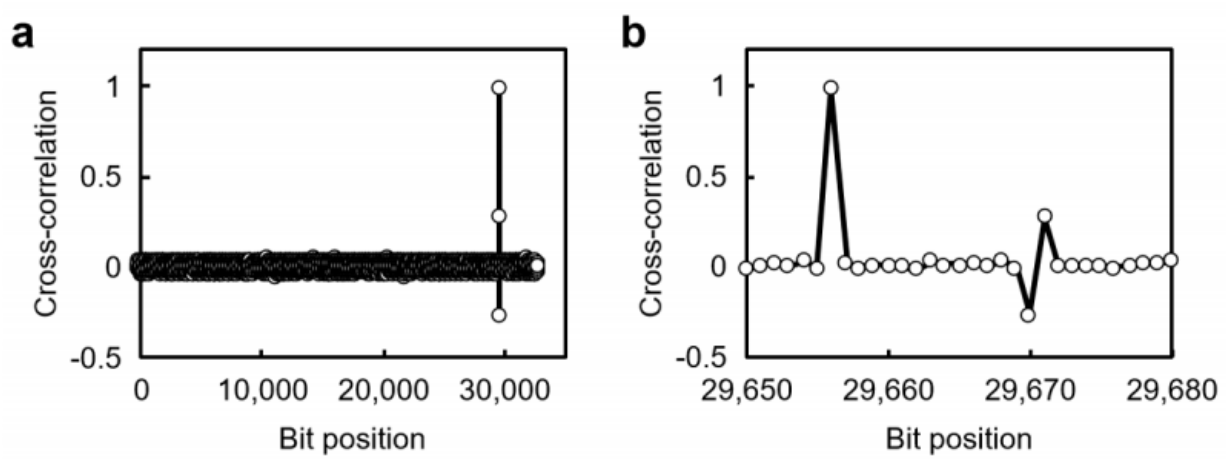

Fig. 5. (a) Result of the correlation analysis using the synchronization sequence. (b) Magnified view near the correlation peak at the 29,656th bit position. Credit: NICT

Fig. 4 shows the SOCRATES orbit, as well as the Doppler-shift

calculation and measurement of the experiment conducted on August 5, 2016. As shown in Fig. 4a, SOCRATES flew over the Pacific Ocean from the south to the north and reached the closest distance of 744 km to the NICT optical ground station at 22:59:41 Japan time. A communication link was established for two minutes and 15 seconds around that time. Fig. 4b shows the theoretical value of the Doppler shift predicted from the SOCRATES orbit information, and Fig. 4c shows the experimental value. The observed value of the Doppler shift showed a good agreement with the theory, and the change of frequency due to the Doppler shift could be accurately corrected. Based on this frequency correction, the time synchronization between the satellite and the ground station was established while accurately correcting the change of the time interval of photons coming from SOCRATES every second.

After establishing the time synchronization, the photon signal is transformed into digital zeroes and ones. However, due to the bit-position shift, it is still necessary to match the bit sequence transmitted from SOTA with the bit sequence received at the OGS. As shown in Fig. 5, by analyzing the cross-correlation of the synchronization sequence of about 32,000 bits, this match could be successfully performed. Fig. 5b shows the correlation peak at the 29,656th bit position, which means that this is regarded as the origin in the OGS, so that the sequence can be correctly decoded.

Fig. 6 shows an example of a histogram of the series of detected photons by the quantum receiver. The Tx2 and Tx3 signals show the transmitted photons by SOTA and the histogram shows how the detected photons are related to the original signal. This demonstrates that the synchronization could be accurately established by directly using the quantum signal, even in the presence of significant losses.

Since SOCRATES is moving in relation to the ground station, the polarization reference frame between SOTA and the OGS is constantly

changing. For a quantum communication link to be established correctly, the polarization reference frame must be the same. If this relative change is not corrected, the polarization states corresponding to zeroes and ones cannot be accurately identified. Fig. 7 shows the predicted polarization angle of the photons transmitted from SOTA for zeroes and ones, as well as the measured angles, reaching a good agreement between both. The theoretical prediction was calculated by using the orbital information of SOCRATES, as well as its attitude change during the pass over Japan. By matching the reference frame, a quantum bit error rate as low as 3.7 percent could be measured. This demonstrates that quantum communication is feasible from space, since it is below 10 percent, frequently used as a condition for quantum cryptography to be secure. This represents the first such demonstration using a 50 kg-class microsatellite.

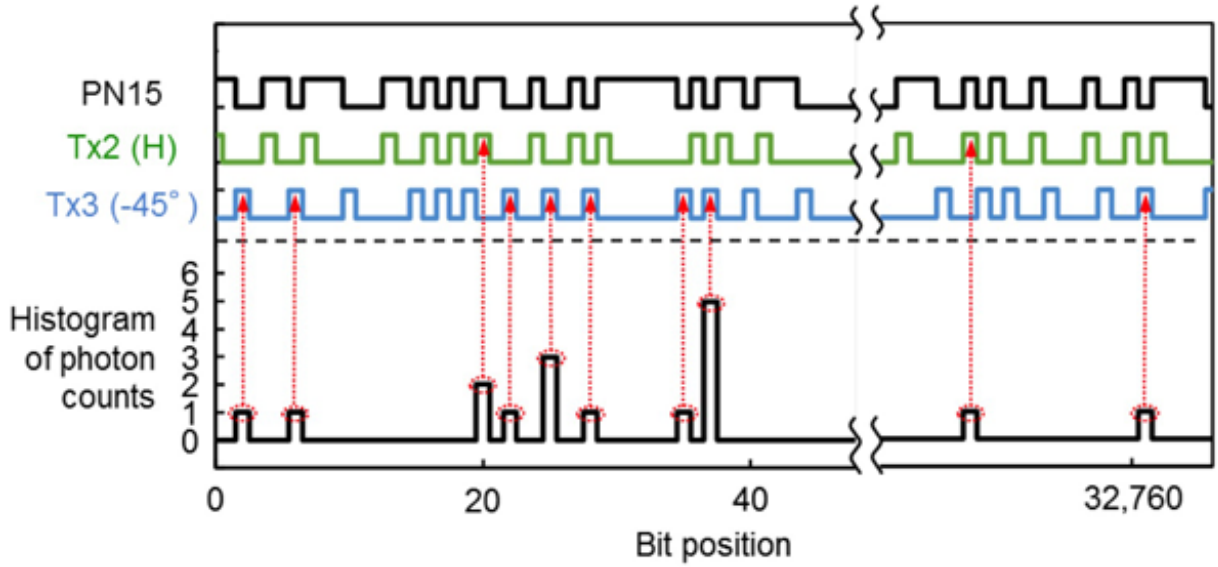

Fig. 6. Sequence pattern of the synchronization signal and the pulses transmitted from SOTA, and histogram of detected photons at the ground station. Credit: NICT

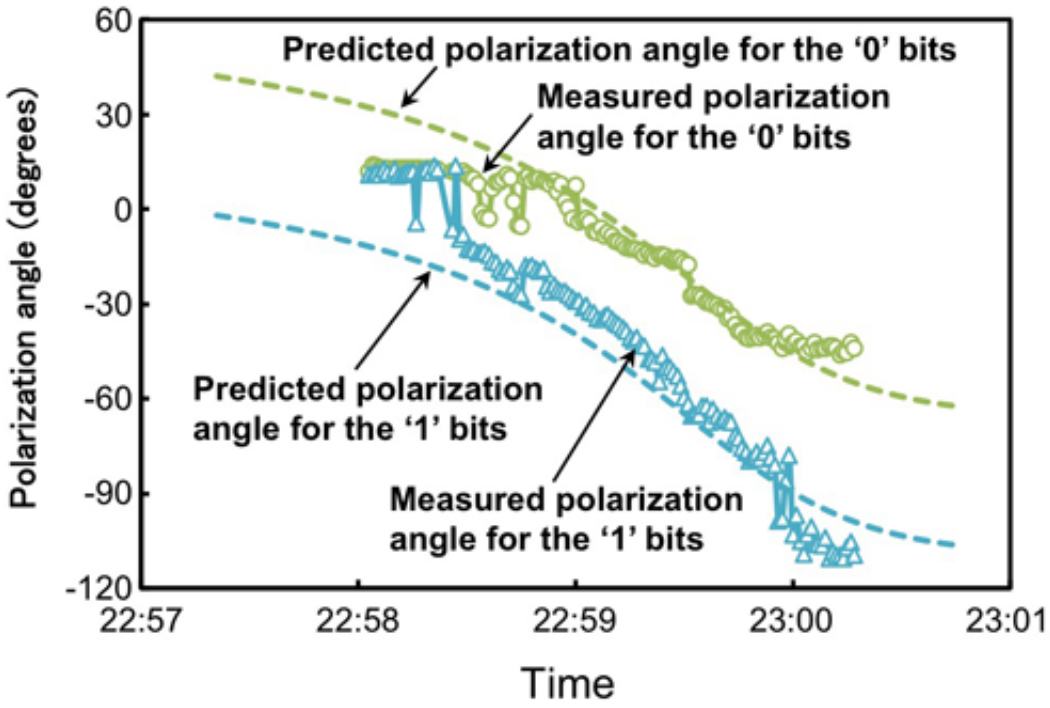

Fig. 7. Experimental result of the polarization-axis matching.

More information: Hideki Takenaka et al. Satellite-to-ground quantum-limited communication using a 50-kg-class microsatellite, *Nature Photonics* (2017). DOI: 10.1038/nphoton.2017.107

Provided by NICT