Satellite-to-ground quantum-limited communication using a 50-kg-class microsatellite

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The recent rapid growth of satellite-constellation programmes for remote sensing and communications, enabled by the availability of small-sized and low-cost satellites, has provided impetus for the development of high-capacity laser communication (lasercom) in space. Quantum-limited communication can enhance the performance of lasercom and is also a prerequisite for the intrinsically hack-proof secure communication known as quantum key distribution. Here, we report a quantum-limited communication experiment between a microsatellite (48 kg, 50 cm cube) in low Earth orbit and a ground station. Non-orthogonal polarization states were transmitted from the satellite at a 10 MHz repetition rate. On the ground, by post-processing the received quantum states with a receiver with four photon counters, with a quantum bit error rate below 5%, validating the applicability of our technology to satellite-to-ground lasercom and quantum key distribution.

Recently, the increasing availability of small-sized satellites as well as low-cost launches has led to a rapid growth of satellite-constellation programmes, in which thousands of satellites orbiting in low Earth orbit (LEO) work in concert with each other for remote sensing and communications, with coordinated ground coverage. Data-intensive satellite sensors mounted in such a constellation produce a large amount of information to be transmitted to the ground in a short time, which requires high-capacity communications. However, conventional satellite communications based on microwave frequency bands will struggle to provide the needed capacity because these bands are already congested and severely regulated and hence the frequency licensing process is lengthy. In the past decade, laser communication (lasercom) has evolved as a promising alternative for high-capacity data links from space, surpassing microwave communication in providing high-capacity power-efficient transmission, as it is able to use an unregulated spectrum, has ultralow inter-channel interference and features smaller and lighter terminals. In fact, the feasibility of satellite lasercom has been demonstrated by many space missions. However, they were based on dedicated bulky satellites of large size, typically several hundred kilograms, with a lasercom terminal mass of over 10 kg (see Supplementary Section ‘Recent optical satellite communication demonstrations’).

Information security is also becoming an urgent issue in satellite constellations, because the amount of critical and valuable data to be communicated is increasing. Space lasercom, when combined with a quantum receiver, provides a requisite platform for intrinsically hack-proof secure communication, namely quantum key distribution (QKD). Satellite QKD technology enables QKD on a global scale. This cannot be provided by Earth-bound networks alone due to the inevitable losses in optical fibres. There have been significant diverse efforts to develop the basic technologies required for QKD in space, including terrestrial free-space quantum communications, demonstrations with moving terminals to emulate the motion of a satellite, experiments using passive corner-reflector satellites to receive single photons at a ground station, a programme to miniaturize QKD technologies for future microsatellites and an experiment focusing on quantum-limited coherent communication from a geostationary satellite to a ground station. Recently, a 600 kg quantum-communication satellite has been launched into orbit for QKD and quantum teleportation experiments. However, an outstanding challenge has been to demonstrate the feasibility of quantum-limited communication and QKD in space using a small and low-cost satellite instead. If this could be done using a microsatellite, the paradigm of satellite communications would change.

Here, we report the first ever microsatellite-based quantum-limited communication experiment in an LEO-to-ground link. The link consists of the microsatellite SOCRATES (Space Optical Communications Research Advanced Technology Satellite: a cube with a side length of 50 cm and mass of 48 kg) and the Optical Ground Station (OGS) at the NICT headquarters in Tokyo, Japan. Pseudo-random binary sequences (PRBSs) of non-orthogonal linearly polarized states at a wavelength of 0.8 μm were transmitted at a 10 MHz repetition rate from the SOTA (Small Optical Transponder) terminal (5.9 kg) on board SOCRATES. On the ground, the polarized quantum states were received by the quantum receiver and discriminated in an unambiguous way with a quantum bit error rate (QBER) of <5%. The SOTA lasercom terminal was designed to carry out feasibility studies on optical downlinks and quantum communications with a low-cost platform on board the microsatellite SOCRATES inserted in LEO at an altitude of ~650 km. Optical downlinks of imaging sensor data at different wavelengths (980 and 1,550 nm) were successfully carried out using on-off keying (OOK) modulation at 10 Mbits s⁻¹ from the SOTA and with the 1-m-diameter telescope in the OGS. An experiment on the effect of atmospheric propagation on the polarization was performed using circular and linear polarizations transmitted from the SOTA. CNES (the National Centre for Space Studies) was also able to successfully receive the signals from the SOTA in the 1.54 m MeO OGS in Caussol (France), demonstrating satellite-to-ground links with adaptive optics to compensate atmospheric effects.

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Table 1 | Specifications of the SOTA and loss characteristics of the link and the OGS.

| Specifications of SOTA                      | Tx2       | Tx3       | Comments                                      |
|--------------------------------------------|-----------|-----------|-----------------------------------------------|
| Polarization                               | Linear    | Linear    | Ellipticity <0.1°                             |
| Wavelength (μm)                            | 0.8       | 0.8       | At 25 °C, centre wavelength varies at 0.1 nm °C⁻¹ |
| Wavelength width (nm)                      | 0.2       | 0.2       | Measured at ~3 dB full width                  |
| Clock frequency (MHz)                      | 10 or 1   | 10 or 1   | Selectable                                    |
| Intensity (MW sr⁻¹)                        | 2.68 × 10⁻³ | 3.30 × 10⁻³ | Average power at 10 Mbps                      |
| Mean photon number per pulse               | 2.34 × 10⁸ | 3.30 × 10⁸ | Measured at ~3 dB full width                  |
| Beam divergence (μrad)                      | 970       | 880       | Owing to small misalignment of Tx2/3 from the direction of pointing beam from Tx4 |
| Transmit aperture (mm)                     | <5        | <5        |                                               |
| SOTA optical loss (dB)                     | −1.5      | −1.9      |                                               |

Loss characteristics of the link and the receiver for a 53° elevation angle

|                        | Tx2       | Tx3       | Comments                                      |
|------------------------|-----------|-----------|-----------------------------------------------|
| Atmospheric attenuation (dB) | −3.55     | −3.55     | Estimated with the code MODTRAN (Spectral Sciences) |
| Space coupling loss to the receiver telescope (dB) | −57.8     | −56.9     | Evaluated for a SOCRATES-OGS distance of 802 km at 22:59:00 JST |
| Receiver’s telescope loss (dB) | −2.68     | −2.68     | −1 dB due to primary mirror and 1.68 dB due to secondary and tertiary mirrors |
| Quantum receiver loss (dB) | −14.5     | −14.5     | Evaluated by using star light (Supplementary Table 1) |
| Total loss budget (dB)  | −78.5     | −77.7     |                                               |

Figure 1 | Transmitter and receiver systems. a, Picture of the SOTA (18 cm width × 11 cm depth × 27 cm height). b, Configuration of the two linearly polarized laser diodes Tx2 and Tx3 in the SOTA. c, Receiver telescope. d, Quantum receiver. DM, dichroic mirror; PD, photodetector; IR, infrared; BS, beamsplitter; PBS, polarizing beamsplitter; HWP, half-wave plate; SPCM, single-photon counter module. In the NICT OGS, incident light reflected by the primary and secondary mirrors passes through a tertiary mirror (made of aluminium to minimize linear polarization deterioration). The beam after the tertiary mirror has a width of 3 mm and is guided towards the quantum receiver installed at the Nasmyth bench of the telescope. A 1.5-μm-wavelength circularly polarized beam from the SOTA was used for satellite tracking and was separated from the 0.8-μm-wavelength light using a dichroic mirror in the quantum receiver. This 1.5 μm beam was then guided to a PD and monitored using an IR camera. The quantum receiver consists of BSs, PBSs and a HWP, ending with four ports, where four SPCMs based on Si avalanche photodiodes were used as detectors after coupling the beams to multimode optical fibres using converging lenses. Received photon counts were then time-tagged by a time-interval analyser (timing resolution of 1 ps), generating a time-tagged photon-count sequence for each SPCM.
After the success of these experiments we moved on to the quantum-limited communication experiment to emulate the B92 QKD protocol. The purpose of this experiment was to verify the feasibility of the polarization-encoded on-board transmitter in orbit and quantum state discrimination with photon counting on the ground through a space-to-ground slant atmospheric path (Supplementary Movie). Transmission of the 0.8-μm-wavelength polarized signals is based solely on a coarse-tracking gimbal system with stepping motors instead of a fine-pointing mechanism, which usually requires an additional bulky payload. To track the OGS more reliably with this coarse pointing, the laser beam divergence was widened, and brighter laser pulses (on the order of 10^8 photons per pulse at the exit of the SOTA, Table 1) than those required in QKD were used, although the optical signals received at the entrance of the OGS were photon-limited in the range of ~0.145–6.696 photons per pulse.

Polarization encoding is a reasonable option for QKD from space thanks to its stable propagation through the atmosphere, whereas time-bin encoding is widely used in fibre networks. A big challenge in this kind of system is polarization reference-frame synchronization between the fast-moving LEO satellite and the OGS to implement the QKD protocol reliably. Another challenge is clock data recovery using the received sequences of quantum states directly, which will enable compact and low-cost transmitter and receiver implementations. For a slant-atmospheric downlink from a LEO satellite, the Doppler shift is also an important factor to be evaluated for precise clock data recovery. In this Article, we solve these two main issues to demonstrate the discrimination of polarized quantum states and finally to evaluate the QBER.

We thus transmitted repeating PRBSs generated by a linear feedback shift register, with a period of 2^{15} – 1 = 32,767, the so-called pseudo-random noise-15 (PN15) sequences, encoding it into a signal sequence of binary non-orthogonal polarization states. Using this known bit pattern, we performed the necessary tasks for quantum-limited communication, including clock data recovery, timing offset identification, bit pattern synchronization, polarization reference-frame synchronization and the discrimination of polarized quantum states.

Figure 1a presents a picture of the SOTA, in which two linearly polarized laser diodes (Tx2 and Tx3) are mounted. Their linear polarizations are aligned with a difference of −45° (the actual separation angle is −44°, Fig. 1b). Tx2 and Tx3 are driven by the PN15 PRBSs, based on a clock frequency of 10 MHz and with a unit time interval (UTI) of T_0 = 100 ns. Tx2 emits a horizontally...
polarized pulse (H) synchronized with every rising edge of the PRBS, and Tx3 emits a $-45^\circ$-polarized pulse ($-45^\circ$) synchronized with every falling edge. The transmitted signal thus consists of sequences of H- and $-45^\circ$-polarization states. Note that the pulse-emission rate of each Tx2 or Tx3 is 2.5 MHz. The NICT OGS consists of a 1-m-diameter Cassegrain telescope (Fig. 1c) and a polarization-based quantum receiver (Fig. 1d).

Table 1 summarizes the specifications of the SOTA and the loss characteristics of the link and OGS for a 53° elevation angle under the conditions of the optical link campaign on 5 August 2016. Because the beam divergences at Tx2/3 were widened for reliable tracking with coarse pointing, the footprint spread over an area with a diameter of $\sim$600 m to 1 km depending on the SOCRATES–OGS distance. This caused a large space-coupling loss to the 1-m-diameter receiver telescope.

Clock data recovery and timing-offset identification

In the OGS, the clock data were first recovered by post-processing a part of the received photon-count sequence from the quantum receiver. Due to heavy attenuation in the atmospheric path of the optical downlink and in the quantum receiver, which totals approximately $\sim$78 dB, many optical pulses emitted at the SOTA did not arrive at the single-photon counter modules (SPCMs) in the quantum receiver. A 10 Mbit block of the transmitted PRBSs at the SOTA was therefore used for clock data recovery. Because SOCRATES was moving fast (velocity of 7 km s$^{-1}$), with propagation distances to the OGS ranging from 744 km to 1,032 km, the Doppler shift through each optical link campaign was expected to be within $\pm$200 Hz around the clock frequency $f_0 = 10$ MHz, with a shifting rate (frequency drift) of 3 Hz s$^{-1}$. The UTI at the OGS, denoted as $T$, also deviates from that at SOTA ($T_0 = 100$ ns). To take into account the Doppler shift, we analysed a received photon-count sequence for 1 s (time to acquire a 10 Mbit block of PRBSs), from 22:59:00 to 22:59:01 JST on 5 August 2016, by using various possible clock frequencies $f$ (equivalently UTIs $T = 1/f$) to fit the values that best fit the received photon-count sequence (see Methods, ‘Clock data recovery and timing-offset identification’).

The total count from all four SPCMs in this sequence was 7,119. This corresponds to the signal with 0.0744 photons per pulse at the entrance of the OGS telescope, because the total pulse-emission rate from Tx2 and Tx3 was 5 MHz and the OGS loss (receiver telescope loss + quantum receiver loss) was $\sim$17.18 dB.

The clock frequency and frequency drift at the OGS that best fit the received photon-count sequence were identified to be $f = 10,000,096.5$ Hz and $-2.25$ Hz s$^{-1}$, respectively. This precision is essential for dealing correctly with the long sequence of received signals. The timing offset of the received photon-count sequence from the transmitted PRBSs could be found as 0.64 T (in seconds) in the UTI (the sharp peak in Supplementary Fig. 3). Appropriate time-gating around this timing offset can then be used to suppress the noise counts, down to $\sim$10 counts s$^{-1}$ per photon-counting channel, which is $\sim$10% of the intrinsic SPCM dark count rate.

Figure 2 presents the Doppler shift (Fig. 2a,b) and frequency drift (Fig. 2c,d) evaluated for an optical link campaign with a duration of 2 min 15 s from 22:58:03 to 23:00:18 on 5 August 2016. Figure 2a,c shows the calculated curves for the SOTA orbit on that date, and Fig. 2b,d presents the observed data. The observed Doppler shift was less than 200 Hz. Given that the SOTA clock frequency could possibly differ slightly from 10 MHz, the time when the frequency drift reached its minimum is considered to be the time when SOCRATES approached closest to the OGS. These results
demonstrate that clock data recovery and timing-offset synchronization could be carried out successfully using data extracted directly from the received quantum states.

Bit pattern synchronization
The time-tagged photon count sequence in the time domain thus turns into a simple bit sequence in the bit domain. The next task is to establish the synchronization of bit patterns between the transmitted and received sequences. This could be done by calculating the cross-correlation between these sequences for the period of the PN15 PRBS (32,767 bit length). For a description of the detailed procedure, see Methods, ‘Bit pattern synchronization’. Figure 3a,b presents the experimental results for the cross-correlation between the transmitted and received sequences. This has a peak at 29,656, which corresponds to the bit pattern offset.

By compensating this offset, we could finally synchronize the photon count histogram in the bit domain with the transmitted bit patterns. Figure 3c, bottom, shows a histogram of photon counts summed for 1 s (the time span of a 10 Mbit sequence) after the bit patterns were synchronized. Also shown are the PN15 PRBS (Fig. 3c, top), the on–off sequences of Tx2 (Fig. 3c, second top) and Tx3 (Fig. 3c, third top). As indicated by red vertical arrows, one can see that whenever the quantum receiver registered finite counts, the SOTA had always emitted optical pulses.

Polarization reference-frame synchronization
It should be possible to track the polarization between the SOTA and the OGS by adaptively rotating a half-wave plate at the entrance of the quantum receiver, based on the orbital and telemetry information from the satellite. However, in the campaign on 5 August 2016, this polarization-tracking system was not used, and shortly after that the satellite operation of SOCRATES was terminated. In addition, the alignment of the receiver was not optimal because the quantum-limited communication experiment was carried out in parallel with other experiments within the SOTA mission. We therefore performed polarization reference-frame synchronization by post-processing part of the photon counts registered at the SPCMs (see Methods, ‘Post-calibration of the quantum receiver’).

Figure 4a shows (circles for Tx2 and triangles for Tx3, with solid curves) the reconstructed variations of the two polarization states in front of the receiver telescope during the optical link campaign from 22:58:03 to 23:00:18 on 5 August 2016. The two plots for Tx2 and Tx3 were derived independently by the above procedure of polarization reference-frame synchronization (see Methods, ‘Polarization reference-frame synchronization’).
reference-frame synchronization). The dashed curves are theoretical curves calculated by the orbital information from SOCRATES (see Supplementary Section 'Calculation of the received polarization angle'). Figure 4b shows the variations of photon counts received by all four SPCMs for the sequences from Tx2 (circles) and Tx3 (triangles), respectively, as well as the distance from the OGS to the SOTA. Note that the photon counts in Fig. 4b were renormalized to compensate for the imbalance in the efficiencies of the four detection channels (see Supplementary Section 'Post-calibration of the quantum receiver'). In the first half period, ~22:58:03–22:59:00, the received photon counts fluctuated, which may be due to unstable tracking. On the other hand, in the second half period, ~22:59:00–23:00:18, the tracking could be more stabilized, the received photon counts were increasing, and the observed curves of polarization angle variation could be fitted with the theoretical curves much better than during the first half period. The photon count rate from Tx3, for example, ranges from 890 counts s⁻¹ (at 22:59:01) to 46,107 counts s⁻¹ (at 22:59:48) during ~22:59:00–23:00:00. These intensities can be converted to 0.146 photons per pulse and 6.696 photons per pulse, respectively, at the entrance of the OGS, because Tx3 emits pulses at a 2.5 MHz rate and the OGS loss was ~25.6 dB after compensating for the imbalanced detection-channel efficiencies.

Compared with the 1.78 × 10⁸ photons per pulse at Tx3 in the SOTA, the total loss budgets were evaluated to range from ~90.9 dB to ~74.2 dB. These losses are larger than the predicted ones: ~61.4 dB at 22:59:01 and ~60.5 dB at 22:59:48, respectively. So there must be excess losses ranging from ~29.5 dB to ~13.8 dB. These may be attributed to atmospheric scintillation, which typically changes losses by ~10–20 dB in a 10 ms scale in urban areas, and also to pointing and tracking errors. Because atmospheric scintillation is inevitable, the key rate should vary in the same range in practical QKD, and one should take it into account in future QKD key management for practical applications.

Quantum bit error rate

Once the polarization reference frame is established between the SOTA and the OGS, we can estimate an essential parameter for the QKD protocol, that is, the QBER. In the B92 protocol that we emulate here, bit information 0 and 1 is encoded into binary non-orthogonal quantum states. These quantum states are discriminated unambiguously by a receiver that has three outcomes: detection of the 0 or 1 with certainty, or an inconclusive outcome for which both the 0 and the 1 are likely, which is dealt with as a failure event, and discarded. QBER is defined for the 0 and the 1 detected with certainty (see Methods, 'Quantum bit error rate').

Because we did not track the polarization angle of the SOTA, but established the polarization reference frame by post-processing in our experiment, we chose, for the QBER estimation, a 12 s duration of ~22:59:21–22:59:33 on 5 August 2016, in which the polarizations were best aligned. The quantum states that arrived at the OGS were actually at ~45° and ~90°, which were originally emitted at H from Tx2 and at ~45° from Tx3, respectively, at the SOTA. The observed QBER was smaller than 4.9% and reached a minimum value of 3.7% at 22:59:25. The variation of QBER is shown in Fig. 5 for a wider duration of 1 min (~22:59:00–23:00:00). The increase in QBER outside the estimation interval (marked by vertical dashed lines) is attributed to the non-optimal polarization reference-frame configuration, which occurred because we could not use polarization tracking between the SOTA and the OGS.

The contribution to QBER from total noise counts (detector dark and sky background noises) was estimated to be ~1/4–1/5 (see Methods, 'Quantum bit error rate'). The linear polarization state itself can be preserved through atmospheric propagation, as shown in ref. 11. So, the main remaining contribution to QBER might be attributed to residual misalignment of polarization in the quantum receiver.

Discussion

The techniques demonstrated here will enable compact implementation of satellite-to-ground lasercom systems and microsatellite QKD systems and they will also be useful for polarization multiplexing space lasercom and polarization LIDAR (light detection and ranging).

For future microsatellite QKD, several techniques should be developed further. First, coupling loss from a satellite to a receiver telescope needs to be improved by transmitting a diffraction-limited laser beam. By using a fine-pointing mechanism with an appropriate divergence angle, a beam footprint can be as small as 20 m in diameter, which should improve the space coupling efficiency by 30 dB. Second, quantum receiver loss will be improved by 10 dB by careful tuning. Third, the pulse repetition rate should be increased to 1 GHz. Finally, the average photon number per pulse should be reduced to ~0.5 per pulse at the transmitter. Our results (raw signal counts of 3,500 counts s⁻¹) imply that the secure key rate of a few bits per second would be feasible after key distillation. PN sequences should also be replaced with true random number sequences, although PN sequences will be used for clock data recovery, being inserted into true random number transmissions. Real-time polarization tracking should also be used, which could not be done in this work although the scheme was implemented in the OGS. Unfortunately, the SOCRATES mission was terminated before applying this scheme.

If an optical link system with total loss of ~30 dB were available, which requires further challenges for a fine-pointing system with a narrower beam, the secure key rate would reach ~10–100 bits s⁻¹. However, further increases would be very hard. Considering the limited available time in the LEO-to-ground link (<10 min) and atmospheric scintillation, current QKD schemes will face a bottleneck in practical applications that require higher key rates. One alternative is to use physical layer cryptography, which can realize information-theoretically secure communications at a higher rate, by relaxing the assumption on the physical capability of an eavesdropper so as to adapt to a realistic scenario in a line-of-sight optical space channel.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions
M.T., H.T., M.F. and M.S. conceived and designed the experiments. H.T., M.K. and M.F. supervised the experiments.

Additional information
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Competing financial interests
The authors declare no competing financial interests.
Methods

Clock data recovery and timing-offset identification. The received photon count sequence from each of the four SPCMs comprises a ‘1’ when a click is detected and a ‘0’ when no click is detected. Each bit is time-tagged with a resolution of ~1 ns, which includes the timing jitter of the SPCMs and other electronics. For clock data recovery, each sequence was recorded during 1 s to acquire photon counts corresponding to the 10 MHz PRBS transmitted from the SOTA. The four received photon count sequences were summed up by an OR operation, creating the binary time-tagged sequence \( C(t) \) in the time domain. The sequence \( C(t) \) was then divided into blocks \( c_i(t) \), where \( i \) denotes a block index, by an appropriate UTI, say \( T \), which must be around \( T_0 = 100 \) ns, corresponding to a clock rate of \( f_0 = 10 \) MHz. All the blocks, in total ~300–310 blocks depending on \( T \), were summed, producing a histogram over time span \( T \). This histogram \( c_i(t) = \Sigma c_i(t) \) should have a peak at a certain time position if \( T \) is chosen appropriately. The clock data as well as the timing offset can be recovered in this way. The detailed procedure and analysed data are provided in Supplementary Section ‘Clock data recovery and timing-offset identification’.

The characteristics of the SPCM channels in the optical link campaign on 5 August 2016 are summarized in Supplementary Table 1. Note that although the detection efficiencies of the SPCMs themselves are within ~23–46%, there is a large difference of about a factor of ten in the four polarization channels in the quantum receiver (Supplementary Fig. 6 and the relevant paragraphs in Supplementary Section ‘Post-calibration of the quantum receiver’).

Bit pattern synchronization. After clock data recovery and timing-offset identification, the time-tagged sequence \( C(t) \) in the time domain turns into a simple bit sequence \( B \) in the bit domain. The next task is to establish the synchronization of bit patterns between the transmitted signal sequence and the received bit sequence \( B \).

The transmitted signal sequence, denoted \( A \), is made up by a ‘1’ representing an emission and a ‘0’ representing a no emission of either Tx2 or Tx3. Sequence \( A \) is a simple repetition of unit pattern \( a \) of length 32,767 bits (the period of the PN15 sequence). This pattern is given by \( a = a_1 \ldots a_6 \), where \( a_6 \) represents the sequence from Tx2 (Tx3), which emits a pulse with every rising (falling) edge of the PN15. For the later purpose of cross-correlation calculation, pattern \( a \) is converted into a sequence of ‘1’ and ‘0’, denoted by \( a' \), by shifting each ‘0’ to a ‘1’. The relation between these sequences is illustrated in Supplementary Fig. 4.

Received bit sequence \( B \) should also have the same period; although many ‘1’ signals from the SOTA were lost through the lossy quantum channel consisting of the atmospheric path of the optical downlink, the receiver telescope and the quantum receiver. We thus divided \( B \) into blocks of 32,767-bit length, \( b \). All the blocks were summed, producing a histogram of photon counts over the 32,767 bit length, \( b = \Sigma b_0 \). Then, by calculating the cross-correlation between \( a \) and \( b \), we could find the offset. The cross-correlation thus obtained is shown in Fig. 3a,b, showing a peak at 29,656. By compensating this offset, we can correct for the relative sensitivity of each port for various telescope elevation and azimuth angles, by observing the light from different high-luminosity stars as reference point sources. As the light from the stars is not polarized, a rotating linear polarizer was inserted between the telescope and the quantum receiver to prepare linearly polarized light at different azimuth/elevation angles. Then, given a known sequence of polarized states either from Tx2 or Tx3, we analysed photon count sequences from SPCM1, SPCM2 and SPCM4, because this combination maximized the signal-to-noise ratios in the polarization angle evaluation and precisely reconstructed the polarization angle, which varied as the SOTA was moving.

This evaluation was performed for every second during the optical-link campaign from 22:58:03 to 23:00:18 (2 min 15 s) on 5 August 2016. The photon counts at SPCM1, SPCM2 and SPCM4 for 1 s were first normalized, producing the relative count ratios \( N_1, N_2 \) and \( N_3 \). We already had the polarization calibration chart, which is given by a set of normalized optical beamsplitting ratios for SPCM1, SPCM2 and SPCM 4, denoted as \( P_1(\theta), P_2(\theta) \) and \( P_3(\theta) \) for an input polarization angle \( \theta \). We then found the angle \( \theta \) that minimized the mean square:

\[
\Delta = [N_1 - P_1(\theta)]^2 + [N_2 - P_2(\theta)]^2 + [N_3 - P_3(\theta)]^2
\]

where \( \theta \) was swept in \([0°, 360°]\) with a resolution step of 1°. In this campaign, the elevation angle of the OGS was around 50°. So, the polarization calibration chart made with light from Capella was adopted.

Quantum bit error rate. In the B92 protocol, the bit information 0 and 1, denoted as inputs \( x = 0, 1 \), were encoded into binary non-orthogonal quantum states. These quantum states were discriminated unambiguously by a receiver with three kinds of outcome: (1) detection of 0 with certainty; (2) detection of 1 with certainty; and (3) an inconclusive outcome for which both possibilities of 0 and 1 are implied, which is dealt with as a failure event. These outcomes are denoted \( y = 0 \) and \( F \). The inconclusive outcomes, \( y = F \), were discarded. This process is referred to as sifting of the raw data. After sifting, one can obtain the transition statistics \( N(x|y) \), which represents the number of events detecting \( y \) given input \( x \). The QBER is given by

\[
QBER = \frac{N(1|0) + N(0|1)}{\sum_{y=0,1} N(y)}
\]

where \( N(x) = \Sigma_y N(x|y) \).

The three outcomes in the quantum receiver correspond to the clicks at (1) SPCM3 for \( y = 0 \), (2) SPCM2 for \( y = 1 \) and (3) SPCM1 or SPCM4 for \( y = F \) (see Fig. 1 for SPCM positions). For the observed transition statistics \( N(x|y) \), see Supplementary Table 3.

The contribution of QBER from total noise counts (detector dark and sky background noises) was estimated to be ~1/4–1/5. Supplementary Table 1 shows that total noise count rate in SPCM2 and SPCM3 (output signals \( y = 1 \) and 0, respectively) amounts to 380 counts s\(^{-1}\). After time gating, only an ~10% fraction remains (38 counts s\(^{-1}\)). The total counts for the output signals \( y = 1 \) and 0 are ~3,500 counts s\(^{-1}\) (Supplementary Table 3). QBER due to total noise counts is thus ~1%.

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.