Direct and full-scale experimental verifications towards ground-satellite quantum key distribution

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Quantum key distribution (QKD) provides the only intrinsically unconditional secure method for communication based on the principle of quantum mechanics. Compared with fibre-based demonstrations, free-space links could provide the most appealing solution for communication over much larger distances. Despite significant efforts, all realizations to date rely on stationary sites. Experimental verifications are therefore extremely crucial for applications to a typical low Earth orbit satellite. To achieve direct and full-scale verifications of our set-up, we have carried out three independent experiments with a decoy-state QKD system, and overcome all conditions. The system is operated on a moving platform (using a turntable), on a floating platform (using a hot-air balloon), and with a high-loss channel to demonstrate performances under conditions of rapid motion, attitude change, vibration, random movement of satellites, and a high-loss regime. The experiments address wide ranges of all leading parameters relevant to low Earth orbit satellites. Our results pave the way towards ground-satellite QKD and a global quantum communication network.

Secret information exchanges are essential for both fundamental aspects and practical applications of secure communication. Quantum key distribution (QKD)1–2 has emerged as the first important application within the evolving field of quantum information technology. Although fibre-based implementations have been demonstrated, in general their maximum communication distances have only been ≈100 km (refs 3–5). Free-space links could provide an attractive way to achieve much larger distances, because of the low atmospheric absorption for certain ranges of wavelength. Despite the efforts made in developing free-space QKD6–13, so far all realizations have relied on stationary communication sites. For significantly longer applications of large-scale quantum communication via satellites and ground stations14–17, and in a realistic environment taking into account all possible satellite modes of motion and huge losses, experimental verifications are absolutely crucial, so that secret keys can be established between any two sites globally.

There has been significant theoretical progress in determining the feasibility of ground-satellite quantum communications, as well as some preliminary experimental tests. Hughes et al. demonstrated daylight and night-time operation of practical free-space QKD over a 10 km path14, and the first experimental quantum entanglement distribution over 13 km has been reported15. Recently, an experiment over a distance of 144 km has been performed successfully by Zeilinger’s group16–17, demonstrating that long-distance atmospheric turbulence has little effect on quantum communication. Entanglement QKD has also been illustrated for a free-space optical link over 1.5 km (ref. 9), and quantum teleportation has been realized in real-world atmospheric conditions over 16 km (ref. 13) and 100 km (refs 18,19). These experiments have led to the accumulation of indispenable technical advances and have formed a solid basis for the development of free-space-based quantum communication. Some theoretical aspects have also been derived14–16,20,21 regarding the feasibility of ground-satellite QKD.

In a real-life scenario, quantum communication using satellites needs to be able to handle several critical issues: (i) the satellite may have rapid relative angular motion with respect to the ground stations; (ii) the satellite may have unwanted random motion; and (iii) atmospheric turbulence must be overcome and secret keys generated under the condition of a high-loss regime. For a typical low Earth orbit satellite (LEOS) at an altitude of ≈400–800 km, the motion parameters are generally as follows: maximum angular velocity of 20 mrad s$^{-1}$ and maximum angular acceleration of 0.23 mrad s$^{-2}$. When the orbit is higher, the angular velocity and angular acceleration will be smaller. For an LEOS equipped with a receiving telescope with a diameter of ≈1 m, rough estimation in relation to telescope size and atmospheric attenuation shows that the loss is ≈30–50 dB in a channel linking it to a ground station. To put satellite-based QKD into practice, comprehensive verifications are therefore of paramount importance in overcoming these challenges and to successfully extract secret keys from rapidly moving and vibrating sites, under high-loss conditions. This would allow a steady quantum channel link to be built, while maintaining maximum channel efficiency, reducing quantum bit error rate (QBER), and achieving a high signal-to-noise ratio. However, it is currently impossible to combine all three issues (i) to (iii) in a single experiment except by using a real satellite. It would be challenging to find a platform that had a large angular velocity and angular acceleration simultaneously, and combining these conditions with high loss, random motion and attitude change is not feasible on any platform. An aircraft, for example, cannot provide sufficient angular acceleration in...
combination with a big angular velocity, nor can it provide a high-loss environment, random motion and attitude change to the same level as a satellite, and certainly not at the same time.

To address every aspect of the abovementioned crucial issues, we report direct and comprehensive verifications for establishing successful quantum cryptography communication via satellites in three independent experiments conducted at night. Quantum communication experiments using a turntable and a hot-air balloon were performed to simulate a platform in a rapidly moving orbit as well as the vibration, random motion and attitude change associated with a satellite in such orbit. We then illustrate the generation of secret keys for a 96 km free-space channel with loss of $\sim 50$ dB, which is more severe than the $\sim 30–50$ dB loss associated with links between ground stations and a LEOS\textsuperscript{15,16}. A high-speed QKD\textsuperscript{22–28} system based on a decoy scheme was developed and tested under each real-life scenario, and an acquisition, tracking and pointing (ATP) system was also designed to carry out coarse and fine tracking to establish a steady and accurate connection of the optical links.

High-speed optical sources and controlling electronics were developed to operate at 100 MHz, and tailored transmitters and receivers were engineered and integrated to be lightweight and portable terminals. Low background counts and high temporal precision were maintained to achieve a high signal-to-noise ratio. As well as compensating for polarization-basis deflection, a three-dimensional platform was set up for the transmitter terminal, another critical ingredient for simulating communications via satellite based on polarization encoding. The system successfully maintained a QKD process based on the turntable via a public free-space channel of length 40 km, a floating hot-air balloon at 20 km, and over a 96 km link with about 50 dB loss, respectively. The secure distances achieved here are significantly greater than the effective thickness of the atmosphere (equivalent to $\sim 8–10$ km of ground atmosphere).

Our verification environment has not only incorporated all possible motion modes, but also applied more extreme situations in relation to vibration, random movement and attitude change by using a hot-air balloon. Accordingly, our implementations, for the first time, provide comprehensive and direct verifications for secure key exchanges via fast-moving platforms such as satellites or aircraft, and bring global-scale quantum communication closer to fruition.

**Experimental designs and demonstrations**

A schematic layout of the moving and floating platform experimental set-up is shown in Fig. 1. Our experiment uses the decoy-state protocol proposed by Hwang\textsuperscript{22}, developed by Wang\textsuperscript{23} and by Lo et al\textsuperscript{24,25} independently and systematically, to achieve unconditional security for practical applications. We designed and integrated the optical

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**Figure 1 | Schematic of experimental set-up.** The signal states and decoy states emitted from the polarization-encoding module pass through a reflecting Cassegrain telescope before transmitting to the receiver side. Once received by another telescope, they are directed to the detection module for polarization analysis. The 532 nm and 671 nm beacon light passes through the same channel for tracking, and the 532 nm light also acts as a synchronization signal. A1 (A2) and B1 (B2) represent the transmitter and receiver sites for the moving (floating) platform experiments, respectively. Red lines represent light at 850 nm, green lines and violet lines represent the tracking beacon light of receiver and transmitter, respectively, and dotted lines represent electric cable. PBS, polarizing beam splitters; BS, beam splitter; HWP, half-wave plate; MON, monitor window; MIR, mirror; ATT, attenuator; DM, dichroic mirror; 532LD, 532 nm laser; FSM, fast steering mirror; 671LD, 671 nm laser; 532D, 532 nm detector; IF, interference filter; APD, avalanche photodiode. Inset: rising and erupting hot-air balloon in the floating platform experiment.
components, electronics and the telescope such that the transmitter and receiver were lightweight and portable terminals. In the transmitter terminal, the optical source contains four laser diodes that emit 1 ns optical pulses centred at 850 nm. The offset of the wavelength from these laser diodes is well controlled to be less than 0.05 nm (limited only by the resolution of the wavemeter used) via temperature control, and the linewidth of the light is ≏ 0.3 nm. All light from the laser diodes is guided into the same single-mode fibres for spatial filtering. The divergence angle of the light was measured to be 500 μrad, and we carefully aligned the output beams from the single-mode fibres to obtain both concentricity and coaxiality better than 95%. Once the light from the laser diode overlaps at the beam splitter (BS), we use irises for further spatial filtering. Finally, we ensure there is no difference in the detection of light originating from the different laser diodes by using a checking collimator at the output of the transmitting telescope.

A polarization-encoding module is connected to the optical source via single-mode fibres and consists of two polarizing beam splitters (PBS), one BS and one half-wave plate (HWP). The optical pulses emitted from the polarization-encoding module are in four polarization states, \(|H\rangle, |V\rangle, |+\rangle\) and \(|-\rangle\) (where \(|H\rangle, |V\rangle\) represent horizontal and vertical polarization, respectively, and \(|+\rangle = (1/\sqrt{2})(|H\rangle + |V\rangle)\) and \(|-\rangle = (1/\sqrt{2})(|H\rangle − |V\rangle))\), comprising the four states for the standard BB84 protocol. The type and amplitude of random pulsed signals emitted from the four diodes are all controlled according to high-speed random numbers generated beforehand by random physical noise (RND). To ensure that the amplitudes of the optical pulses are identical and to monitor the deviation of optical power in real time, another exit port of the BS in the polarization-encoding module is connected to a power meter to provide a monitor window (MON).

After the polarization-encoding module, an attenuator (ATT) is used to attenuate the average photon number per pulse to the experimental level. To obtain the correct mean photon number, we first accurately measured the loss in the attenuators in the laboratory with an auxiliary laser at 850 nm, and then accurately calculated and measured the relations between the optical power of the sources and the mean photon number. We could then get the appropriate mean photon number by adjusting the loss in the attenuators in the optical path. Our home-built electric control device triggers the laser diodes with different voltages corresponding to the signal states, decoy states and vacuum states. We checked that there was an average photon number of less than 0.002 per pulse for the vacuum state in the operating phase. A BS, a fast steering mirror (FSM) and a complementary metal–oxide semiconductor (CMOS) are used to create a fine tracking system. The BS channels the 671 nm beacon light from the receiver to the fine tracking CMOS, and the FSM dynamically adjusts the optical path according to a correction program in response to image information obtained by the fine tracking CMOS. Between the BS and fine tracking CMOS, a dichroic mirror (DM) transmits 671 nm beacon light into the CMOS and reflects 532 nm pulsed synchronization light emitted from the 532 nm laser. The 532 nm pulsed light (optical power of 100 mW and divergence angle of 1 mrad) also acts as the beacon light for the receiver system. All the abovementioned optical components were engineered such that they fit into a portable knapsack. The primary mirror of the transmitter terminal is a reflecting Cassegrain telescope with an aperture of 200 mm, focal length of 1,250 mm, and ×10 magnification; this has a small volume and fits our experimental requirements well. The coarse tracking CMOS is located at the top of the telescopic tube. This system contains coarse and fine tracking, the principles and performances of which are described in the Methods.

At the receiver terminal, the primary mirror is a reflecting Cassegrain telescope with an aperture of 300 mm, focal length of 1,500 mm and ×12 magnification. The optical components of the
receiver are located on a small optical box (Fig. 2). The tracking system also contains coarse and fine tracking (performance parameters are listed in the Methods). The collected light contains 532 nm beacon light, 850 nm signal and 850 nm decoy light. We note that part of the 532 nm beacon light is reflected directly to the coarse tracking CMOS, but the 671 nm beacon light (optical power of 300 mW) goes to the telescope before flying to the transmitter (Fig. 1). Light from the telescope first passes through the fine tracking system (consisting of a FSM, a DM and a BS). The FSM is used for fine tracking feedback, and the DM (transmitting at 850 nm and reflecting at 532 nm) is used to separate the 532 nm light from the 850 nm light. The 532 nm component is then divided into two parts by the BS for fine tracking and synchronization, respectively. Transmitted light after the DM passes through a closed receiver module for polarization analysis. In contrast to the encoding module using single-mode fibre, the connector here uses multimode fibre with a core diameter of 105 μm. Before the entrance of the receiver module there is an interference filter (IF) (centre wavelength at 850 nm; 5 nm full-width at half-maximum (FWHM)), which can greatly reduce the effects of stray light. Collected light from the multimode fibre is directed to the avalanche photodiodes (APDs). The receiver electronics acquires channel and timing data from the APD and also timing data for the synchronization light before transferring these data to a personal computer (PC) for further processing. For synchronization, after using the global positioning system (GPS) for initial coarse synchronization, we used an external synchronization approach using 532 nm pulsed light and achieved an accuracy of 1 ns between the distant transmitter and receiver.

Verification for a moving platform
In the first experiment, the satellite orbiting simulation experiment, we chose the Administration Bureau of Qinghai Lake National Nature Reserve (37º21′6″ N, 99º44′33″ E) for the transmitter (Alice) and Heimahe Nature Reserve Station for the receiver (Bob) (36º42′1″ N, 99º52′16″ E), with a straight-line distance between transmitter and receiver of ~40 km. The experiment was performed at the end of August 2010. We placed the transmitter terminal on a turntable (Fig. 2). This turntable provides a complex nonlinear-motion relative motion between transmitter and receiver, providing motion with a maximum angular velocity of 21 mrad s⁻² and a maximum angular acceleration of 8.7 mrad s⁻². The motion regime completely covers the possible range of motion parameters for a ~400–800 km LEOS. At the receiver site, the APDs (total background counts of 800 s⁻¹) can collect a rate of ~5,000 s⁻¹ (total loss of ~40 dB). Of this, 19 dB is due to geometric attenuation, 6 dB is from atmospheric loss, 13 dB from the optical systems of the receiver (3 dB from optical elements, 3 dB from detector efficiency, and 7 dB from the coupling efficiency of the receiver module), and an extra ~1–5 dB from the decrease in efficiency arising from the moving channel link maintained by the ATP.

Verification for a floating platform
To further demonstrate the applicability of our experimental set-up and verify the feasibility of satellite QKD in a vibrating and floating platform, we also implemented the QKD system in a floating hot-air balloon, for the first time conducting a QKD experiment with random motion, attitude change and vibration simulations. In September 2010 we set up the transmitter terminal on a hot-air balloon tethered on Qinghai lakeside (36º49′43″ N, 99º44′18″ E). The receiver was located at Bird Island Hotel (37º2′16″ N, 99º44′31″ E) at Qinghai Lake, at a straight-line distance of ~20 km from the hot-air balloon. The essential part of the experiment was to build a steady optical link between the transmitter and the receiver. When the hot-air balloon rises it undergoes random motion including rotating, jolting and shaking; this is more violent than the possible random motions (attitude change and vibration) experienced by satellites. Following monitoring and recording, an estimate gave an average angular velocity of 10.5 mrad s⁻¹ and an average angular acceleration of 1.7 mrad s⁻² for the random motion of the hot-air balloon. The fine tracking accuracy was better than 5 μrad, which exceeds the requirement of 10 μrad for a typical LEOS. We set the hot-air balloon in captive status so that coarse tracking worked within the entire field of view. This was achieved by adjusting and fastening ropes from four directions when the rising hot-air balloon underwent drastic motion. Therefore the ATP’s ability to recapturing contact is very important. In our experiment, when the balloon underwent dramatic motion, the system had no line of sight. However, the system could still recapture the target and generate keys rapidly, typically within ~3–5 s. A successful link could therefore be reconstructed rapidly, demonstrating the superior ability of the ATP, and indicating that our ATP could satisfy the requirements for satellite-based QKD.

To ensure the entire system worked well, we first carried out a ground test of free-space decoy-state QKD before raising the balloon. A further factor in this experiment that reduced the effective experimental time was the requirement for the balloon to flame every few seconds. The flame would cause more stray counts, reducing the amount of valid time data. This experiment set-up is viable under good weather conditions (no rain, good atmosphere and wind speed less than 3 m s⁻¹).

Verification for a high-loss environment
To verify whether it is possible to achieve a high signal-to-noise ratio and overcome the obstacle of a high-loss environment for satellite QKD, we also implemented an experiment to assess long-distance free-space QKD with ~50 dB loss between stationary sites. The experiment was performed in October 2010. The transmitter (Alice) was located in Qinghai, Hainan Autonomous Prefecture, at Qinghai Lake Observatory (36º33′17″ N, 100º28′30″ E, elevation of 3,585 m) and the receiver (Bob) in Qinghai, Haibei Autonomous Prefecture, Quanji village (37º16′44″ N, 99º53′4″ E, elevation of 3,255 m). The straight-line distance between the transmitter and receiver was ~96 km. The main difference from the moving and floating platform experiments was the receiver, which was a reflecting Cassegrain telescope with an effective aperture of 600 mm, focal length of 6,900 mm, and magnification of x5.6. We chose APDs from PerkinElmer (SPCM-AQRH-16) that had dark counts of 25 s⁻¹ and a detection efficiency of >45% to reduce the dark counts. All other devices were the same as those used in the other experiments. The average photon numbers per pulse of the signal and decoy states were 0.6 and 0.2, respectively. We received about 500 c.p.s. with a total background count of 120 c.p.s. (the dark counts of the four APDs were ~100 c.p.s. and the stray counts amounted to only 20 c.p.s.), so our experimental total loss was as high as 50 dB. We then analysed the attenuation of the link and found the divergence angle of the transmitter telescope is 80 μrad (it is amplified by the atmosphere from a measured value in the laboratory of just 40 μrad), the geometric attenuation of 96 km of free space is ~22 dB, the atmospheric attenuation of 96 km of free space is ~8 dB, the transmittance of the receiving telescope is 50%, the efficiency of the receiver optical component is 80%, the detector efficiency is 45%, the receiver coupling efficiency is 10%, the attenuation of these items is ~17.5 dB, and the effects from the ATP and atmospheric turbulence are ~2–5 dB, so the total loss is over 50 dB, which matches the counts we received.

Experimental results
In all three experiments, we successfully extracted secure keys by follow the decoy methods and by Lo et al. for generating unconditional secure keys. By considering finite key length as well as...
statistical fluctuations, we have achieved performances as listed in Table 1. Detailed explanations of the experimental data and analysis including formula for extracting secure keys, key generating rates, as well as QBERs are provided in the Supplementary Information.

**Discussion**

We have achieved significant experimental results that will contribute to the realization of QKD in free space via a quantum channel between satellites and ground stations. Three independent experiments have been performed successfully: one for a rapidly moving platform over a distance of 40 km, one for a floating platform over a distance of 20 km, and one over 96 km of air with huge losses. Our results provide complete and comprehensive verifications relevant to real-life scenarios of quantum communication via satellite or aircraft, including moving and vibrating terminals, with possibly random motion as well as attitude change. We also show that atmospheric turbulence and conditions of huge loss can be overcome in satellite QKD, as confirmed by our demonstrations under much more severe conditions than would be encountered with real, typical LEOS. Various techniques, particularly precise tracking using our home-made ATP system, and the integrated communication terminals, have been developed to maintain the smooth distribution of secret keys. Emitted from moving objects, high-quality quantum signals are successfully extracted after traversing a significant distance through the air. In both moving platform and floating platform cases, key rates greater than 150 bit s$^{-1}$ are achieved, with low QBER less than 2.8%. When the QKD distance is increased to 96 km, it is possible to maintain key rates of 48 bit s$^{-1}$ associated with a low QBER of $\approx 4\%$. The distance between our communicating parties exceeds by several times the effective thickness of the atmosphere. Our results represent the first milestone on the road to direct and full-scale experimental verifications of satellite-based quantum communication, and in particular have solved the key issues of building steady optical links with rapidly moving, attitude-changing, vibrating terminals, as well as in a high-loss environment. The technical advances are readily applicable to the satellite-based distribution of quantum keys, and suggest methods for achieving global-scale quantum communication network in real-life scenarios.

**Note added in proof:** After submission of our manuscript we became aware of a similar experiment$^{31}$ using an aeroplane for QKD transmission using the BB84 protocol.
that, in Fig. 3, the time axis (\(Q_\alpha\)) achieved disturbance rejection bandwidth was linked rapidly. When stabilized, the tracking accuracy was about \(10^{-6}\) rad (r.m.s.). Experiments showed that the hot-air balloon would sometimes experience severe movements, removing the laboratory for the polarization-encoding module of the 850 nm optical source, experimental results. In the satellite orbiting simulation, the turntable brought additional disturbance, whereas the fine tracking error was 4.5 mrad (r.m.s.), as calculated in Table 2. Methods ATP. The ATP system was necessary for achieving free-space QKD. The ATP system is composed of two control loops: coarse control and fine control. The coarse control loop comprises a coarse pointing mechanism (CPM), a coarse controller and a coarse camera, and the fine control loop is composed of a fine pointing mechanism (FPM), a fine controller and a fine camera. The coarse camera has a wide field of view, whereas the fine camera has a small field of view. Based on open pointing of the CPM, the coarse camera captures beacon light from the target. The CPM corrects its pointing direction based on the position of the light spot in the coarse camera, and guides the beacon light into the fine camera. The FPM then corrects its pointing direction based on the light spot position from the fine camera. The coarse control loop has a tracking accuracy of several hundred microradians, and the fine control loop decreases the tracking error to several microradians. The performance of our ATP system is described in Table 2. In the satellite orbiting simulation, the turntable brought additional disturbance, in particular when it turned in another direction during the movement, so the ATP had some obvious return errors. The coarse tracking error could be brought below \(5 \times 10^{-6}\) rad (r.m.s.), as shown in Fig. 4. The control bandwidth for fine tracking was \(2 \times 10^{-5}\) Hz, whereas the achieved disturbance rejection bandwidth was \(10^{-6}\) Hz (ref. 18). It should be noted that, in Fig. 3, the time axis (\(Q_\alpha\)) seems not to be continuous, which is due to the processing of a combination of several sets of data. Thus, the period of the time axis is not exactly the turntable period of 15 s. This phenomenon only arises from limitations in the data storage of the CMOS and does not influence the experimental results. Key factors for successful running of the experiments. To maintain smooth running of the experiment several more essential factors should be addressed. The first is the coaxiality of the optical elements. We first achieved coaxiality in the laboratory for the polarization-encoding module of the 850 nm optical source, CMOS for fine tracking, CMOS for coarse tracking, and pulsed synchronization light, with the help of the auxiliary mirror and optical source. One also has to maintain stability before field experiments. In the receiver, the coaxiality of the optics is maintained in the same way. The second factor is the transmitter divergence angles of the 850 nm and 332 nm light. In the experiment we managed to keep the divergence angle of the 850 nm light as small as possible (restricted by the diffraction limit), and so kept the divergence angle of the 332 nm light at a suitable level (~1 mrad), thereby ensuring simultaneous operation for synchronization and ATP. Third, by means of a three-dimensional platform between the optics and the transmitter telescope, not only can we instantly roughly adjust the transmitter angle to keep the beacon light of the ATP within the effective field of view in the hot-air experiment, but by combining the camera set-up on the platform, we compensate, in real time, the polarization-basis mismatch to restrict the QBER below an acceptable threshold during the moving and floating experiments. Furthermore, polarization stability is a very demanding parameter when we design the system. We have developed and used the following methods to improve our system: (i) polarization matching in polarization deflection; and (ii) we use two mirrors for phase matching in polarization deflection; and (iii) other optical elements (PBS and so on) are custom-made with a high extinction rate. By considering all the above features when setting up the optical system, we managed to achieve a polarization visibility of the transmitter and receiver systems of about 200:1, and when transmitter and receiver were connected together during an experiment, the total polarization visibility was as high as 100:1. In the satellite orbiting simulation, the turntable brought additional disturbance, in particular when it turned in another direction during the movement, so the ATP had some obvious return errors. The coarse tracking error could be brought below \(5 \times 10^{-6}\) rad (r.m.s.), as shown in Fig. 4. The control bandwidth for fine tracking was \(2 \times 10^{-5}\) Hz, whereas the achieved disturbance rejection bandwidth was \(10^{-6}\) Hz (ref. 18). It should be noted that, in Fig. 3, the time axis (\(Q_\alpha\)) seems not to be continuous, which is due to the processing of a combination of several sets of data. Thus, the period of the time axis is not exactly the turntable period of 15 s. This phenomenon only arises from limitations in the data storage of the CMOS and does not influence the experimental results.

| Components | Transmiter terminal | Receiver terminal |
|------------|---------------------|-------------------|
| Telescope diameter | Coarse pointing mechanism | Fine pointing mechanism |
| Coarse camera field of view | Coarse tracking error | Fine tracking error |
| Fine camera field of view | Size & frames per second | Size & frames per second |
| Type | Tracking range | Type | Tracking range |
| 200 mm | +0.7 mrad | Two-axis gimbal mount | Two-axis gimbal mount |
| 2 pixels | 512 x 128 & 2,300 Hz | 640 x 480 pixels | 1 mrad |
| 2 pixels | 512 x 128 & 2,300 Hz | Fast steering mirror | Fast steering mirror |
| 2 pixels | 512 x 128 & 2,300 Hz | +0.7 mrad | +200 rad |

Table 2 | Performance of the ATP system.
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Author contributions

C-Z.P and J-W.P. conceived the idea for the experiments. J-Y.W., C-Z.P. and J-W.P. designed the experiments. B.Y., S-K.L., Q.S., X-F.H., J-C.W., H.L., J.Y., J-G.R., G-S.P. and C-Z.P. designed the QKD devices. J-Y.W., S-K.L., I.Z., J-C.W., S-J.Y., H.L., Y-H.H., Y-M.H., R.Q., J-J. and C-Z.P. designed the ATP devices. S-K.L., I.Z., X-F.H., Y-L.T., B.Z. and W-Y.L. designed the software. All authors performed the experiments. B.Y., W-Y.L., K.C., Y-A.C., C-Z.P. and J-W.P. analysed the data. B.Y., K.C., Y-A.C., C-Z.P. and J-W.P. wrote the paper. J-W.P. supervised the entire project.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C-Z.P. and J-W.P.

Competing financial interests

The authors declare no competing financial interests.