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Satellite-Relayed Intercontinental Quantum Network

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We perform decoy-state quantum key distribution between a low-Earth-orbit satellite and multiple ground stations located in Xinglong, Nanshan, and Graz, which establish satellite-to-ground secure keys with ~kHz rate per passage of the satellite *Micius* over a ground station. The satellite thus establishes a secure key between itself and, say, Xinglong, and another key between itself and, say, Graz. Then, upon request from the ground command, *Micius* acts as a trusted relay. It performs bitwise exclusive OR operations between the two keys and relays the result to one of the ground stations. That way, a secret key is created between China and Europe at locations separated by 7600 km on Earth. These keys are then used for intercontinental quantum-secured communication. This was, on the one hand, the transmission of images in a one-time pad configuration from China to Austria as well as from Austria to China. Also, a video conference was performed between the Austrian Academy of Sciences and the Chinese Academy of Sciences, which also included a 280 km optical ground connection between Xinglong and Beijing. Our work clearly confirms the *Micius* satellite as a robust platform for quantum key distribution with different ground stations on Earth, and points towards an efficient solution for an ultralong-distance global quantum network.

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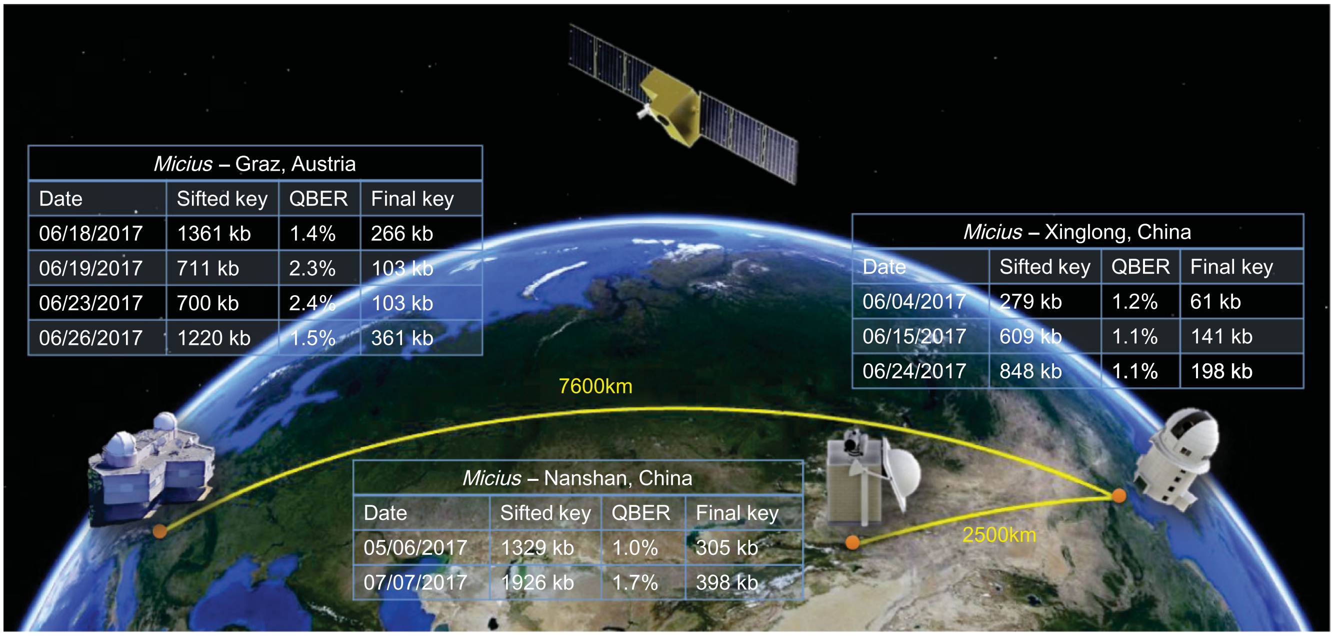
With the growth of internet use and electronic commerce, a secure global network for data protection is necessary. A drawback of traditional public key cryptography is that it is not possible to guarantee it is information theoretically secure. It has been witnessed in history that every advance of encryption has been defeated by advances in hacking. In particular, with the advent of Shor's factoring algorithm [1], most of the currently used cryptographic infrastructure will be defeated by quantum computers.

On the contrary, quantum key distribution (QKD) [2] offers unconditional security ensured by the law of physics. QKD uses the fundamental unit of light, single photons, encoded in quantum superposition states which are sent to a distant location. By proper encoding and decoding, two distant parties share strings of random bits called secret keys. However, due to photon loss in the channel, the secure QKD distance by direct transmission of the single photons in optical fibers or terrestrial free space was hitherto limited to a few hundred kilometers [3–7]. Unlike classical bits, the quantum signal in the QKD cannot be noiselessly amplified owing to the quantum no-cloning theorem [8], already contained at the core of Wiesner's proposal of quantum money that is physically impossible to counterfeit [9], where the security of the QKD is rooted.



Micius – Graz, Austria

Date	Sifted key	QBER	Final key
06/18/2017	1361 kb	1.4%	266 kb
06/19/2017	711 kb	2.3%	103 kb
06/23/2017	700 kb	2.4%	103 kb
06/26/2017	1220 kb	1.5%	361 kb

Micius – Xinglong, China

Date	Sifted key	QBER	Final key
06/04/2017	279 kb	1.2%	61 kb
06/15/2017	609 kb	1.1%	141 kb
06/24/2017	848 kb	1.1%	198 kb

Micius – Nanshan, China

Date	Sifted key	QBER	Final key
05/06/2017	1329 kb	1.0%	305 kb
07/07/2017	1926 kb	1.7%	398 kb

FIG. 1. Illustration of the three cooperating ground stations (Graz, Nanshan, and Xinglong). Listed are all paths used for key generation and the corresponding final key length.

The main challenge for a practical QKD is to extend the communication range to long distances, ultimately on a global scale. A promising solution to this problem is exploiting satellite and space-based links [10,11]. That way, one can conveniently connect two remote points on Earth with greatly reduced channel loss because most of the photons' propagation path is in empty space with negligible loss and decoherence. Very recently, QKD from a low-Earth-orbit satellite, *Micius*, to the Xinglong ground station close to Beijing has been demonstrated with a satellite-to-ground-station distance of up to 1200 km [12].

In this Letter, we use the *Micius* satellite as a trusted relay to distribute secure keys between multiple distant locations in China and Europe. The *Micius* satellite, launched in August 2016, orbits at an altitude of about 500 km. As illustrated in Fig. 1, the three cooperating ground stations are located in Xinglong (near Beijing, 40°23′45.12″N, 117°34′38.85″E, altitude of 890 m), Nanshan (near Urumqi, 43°28′31.66″N, 87°10′36.07″E, altitude of 2028 m), and Graz (47°4′1.72″N, 15°29′35.92″E, altitude of 490 m). The distances from Xinglong to Nanshan and Graz are 2500 and 7600 km, respectively.

In this work, QKD is performed in a downlink scenario—from the satellite to the ground. One of the payloads in the satellite is a space-qualified QKD transmitter [12], which uses weak coherent laser pulses to implement a decoy-state Bennett-Brassard 1984 (BB84) protocol that is immune to the photon-number-splitting attack [13,14]. Eight tunable fiber lasers, emitting light pulses with a wavelength of ~850 nm at a repetition rate of 100 MHz, are used to generate the signal, decoy, and vacuum states. After being collected into single-mode fibers and collimated, the laser pulses enter a BB84-encoding module. It consists of a half-wave plate (HWP), two polarizing beam splitters (PBSs), and one nonpolarizing beam splitter (BS). The photons emitted and sent to the ground station are randomly prepared in one of the four polarization states: horizontal, vertical, linear 45°, and linear −45°. In the three ground stations, corresponding BB84-decoding setups are used, consisting of a BS, a HWP, two PBSs and four single-photon detectors [15].

For secure QKD, the average intensity per pulse sent over the channel has to be at the single-photon level. As the photons travel from the fast-moving satellite (~7.6 km/s) through the atmosphere to the ground station over typically ~1000 km, several effects contribute to the channel loss, such as beam diffraction, pointing errors, atmospheric turbulence, and absorption. As is typical for photonic communication, decoherence can be ignored. To obtain a high signal-to-noise ratio in the QKD protocol, one cannot increase the signal power but only reduce the channel attenuation and background noise. In order to optimize the link efficiency, we combine a narrow transmitting beam divergence (~10 μrad) with high-bandwidth acquisition, pointing, and tracking technique that ensures a typical tracking accuracy of ~1 μrad (Ref. [12] and extended data Table I). To reduce the background noise, the BB84-decoding setups in the optical ground stations are designed with a small field of view and employ low dark-count rate single-photon detectors.

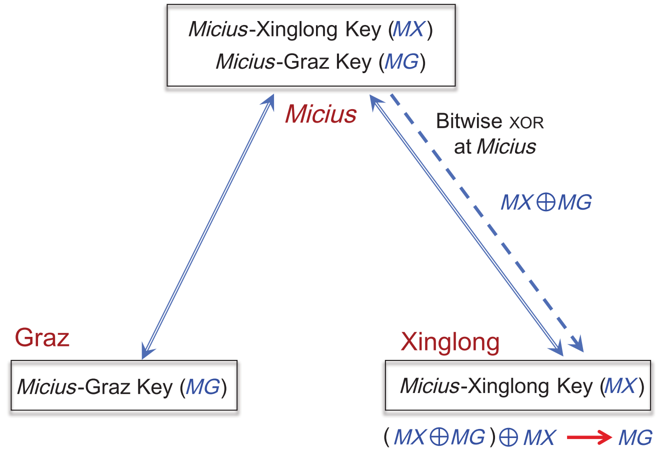


FIG. 2. Schematic of key exchange procedure between Graz and Xinglong with the satellite as a trusted relay. After *Micius* distributed a key with Graz (MG) and Xinglong (MX), it performs a bitwise exclusive OR between those keys (MX ⊕ MG) and sends this combined key via a classical channel towards Xinglong station. Combining the XORed key at Xinglong with MX leads to the same key (MG) on both sides.

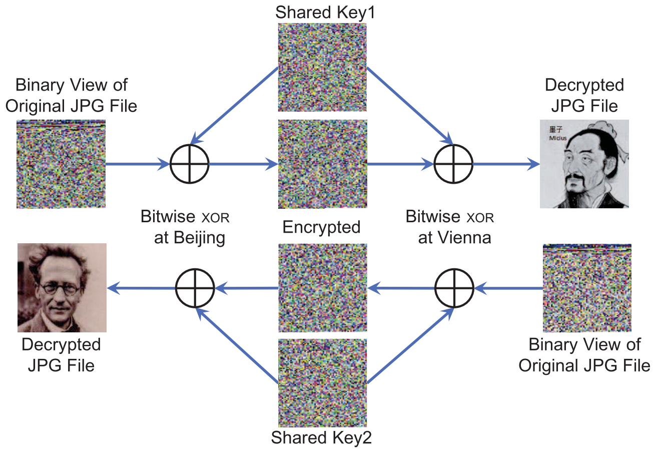


FIG. 3. One-time-pad file transfer. A picture of *Micius* or Schrödinger was transferred between Beijing and Vienna one-time-pad encrypted with a secure key with a length of 5.34 or 4.9 kB, ensuring unconditional security. Binary view of pictures and keys are depicted where each pixel represents one byte of data or key encoded in a 256 color scale. Each side encrypted or decrypted the picture with a simple bitwise XOR operation.

The satellite flies along a Sun-synchronized orbit which circles Earth every 94 min. Each night starting at around 0:50 a.m. local time, *Micius* passes over the three ground stations allowing for a downlink for a duration of ~300 s. Under reasonably good weather conditions, we can routinely obtain a sifted key rate of a ~3 kb/s at ~1000 km physical separation distance and ~9 kb/s at ~600 km distance (at the maximal elevation angle), respectively. Note that the distance can be greater than the satellite height when the satellite does not fly exactly on top of the ground stations. The observed quantum bit error rates are in the range of 1.0%–2.4%, which is caused by background noise and polarization errors. The satellite is equipped with an experimental control box [15] that is able to exchange classical data with dedicated ground stations through radio frequency channels, with uplink and downlink bandwidth of 1 and 4 Mbps, respectively. This allows us to implement the full QKD protocol including sifting, error correction, and privacy amplification [15], to obtain the final keys between the satellite and the three ground stations. Typical satellite-to-ground QKD performances between May and July 2017 are summarized in Fig. 1, with the final key length ranging from 400 to 833 kb.

Next, we rely on the satellite as a trusted relay to establish secure keys among the ground stations on Earth. Figure 2 shows the example of exchanging keys between the Xinglong and Graz stations. We denote the random keys shared between *Micius* and Xinglong as MX, and between *Micius* and Graz as MG. *Micius* can simply perform a bitwise exclusive OR operation (⊕) between MX and MG of the same string length, which then yields a new string: MX ⊕ MG. The new string can then be sent through a classical communications channel to Xinglong or Graz, who can decode the other's original key by another exclusive OR (i.e., MG = (MX ⊕ MG) ⊕ MX). This process can be easily understood as *Micius* uses MX to encrypt MG and Xinglong decrypts the cipher text to recover MG, shared with Graz. Such a key is known only to the two communicating parties and the satellite, but not any fourth party. In this work, we establish a 100 kB secure key between Xinglong and Graz. Similarly, secure keys between Nanshan and Xinglong, and between Nanshan and Graz, can also be established.

For a real-world application of the space-to-ground integrated quantum network, we transmitted a picture of *Micius* (with a size of 5.34 kB) from Beijing to Vienna, and a picture of Schrödinger (with a size of 4.9 kB) from Vienna to Beijing, using approximately 10 kB from the 100 kB secure quantum key for one-time-pad encoding (Fig. 3).

On Sep. 29, 2017, an intercontinental video conference was held between the Chinese Academy of Sciences and the Austria Academy of Sciences. The satellite-based QKD network is combined with fiber-based metropolitan quantum networks, in which fibers are used to efficiently and conveniently connect many users inside a city with a distance scale of within 100 km. The Xinglong ground station is connected to the conference venue, Zhongguancun Software Park in Beijing, via a 280-km optical fiber link involving six trusted relays [19,20]. We employed the Advanced Encryption Standard (AES)-128 protocol that refreshed the 128-bit seed keys every second. The video conference lasted for 75 min with a total data transmission of ~2 GB, which consumed

~70 kB of the quantum key generated between Austria and China.

In summary, using the *Micius* satellite as a trusted relay, we have demonstrated intercontinental quantum communication among multiple locations on Earth with a maximal separation of 7600 km. Our work already constitutes a simple prototype for a global quantum communications network. To increase the time and area coverage for a more efficient QKD network, we plan to launch higher-orbit satellites and implement daytime operation using telecommunication wavelength photons and tighter spatial and spectral filtering [21]. One limitation of the current implementation of the QKD protocol is that we have to trust the satellite itself, which can be overcome in the future using entanglement-based systems [22–24]. Other future developments will include multiparty connections from satellites to various ground stations in parallel, and the connection to large ground networks [20], at first in China and Europe and then on a global scale.

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S.-K. L. and W.-Q. C. contributed equally to this work.

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