Progress of the Quantum Experiment Science Satellite (QUESS) “Micius” Project

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Abstract

By using satellites, ultra-long-distance quantum communication and tests of quantum foundations could be achieved at a global scale. The Quantum Experiment Science Satellite (QUESS for short) in China, also called “Micius”, one of the scientific satellite programs in the Strategic Priority Program on space science, the Chinese Academy of Sciences, was launched on August 16, 2016. There are totally 4 scientific payloads. We give a brief overview of the quantum experiment science satellite project and present most recent science results. The main scientific goal of the quantum experiment science satellite was achieved in 2017. Here, we introduce the latest achievements [1–5] in satellite-based quantum communication and large-scale tests of quantum foundations obtained by *Micius*.

Key words

Quantum science satellite, Quantum communication, Quantum entanglement, Quantum teleportation

1. Brief Overview of Quantum Experiment Science Satellite Project

The scientific objectives of QUESS (see Figure 1) are to carry out satellite-ground experiments of high-speed quantum key distribution, and, based on it, do further experiments on the long-distance quantum key network, in order to make breakthroughs in the realization of space-based practical quantum communications; carry out experiments on quantum entanglement distribution as well as quantum teleportation at the space scale, and fundamental tests of quantum mechanics at space scale.

QUESS was formally approved in December 2011, with PDR completed in November 2012 and CDR in December 2014. The spacecraft and payloads entered flight model phase in December 2014. Besides, the construction of five optical ground stations in Hebei, Xinjiang, Qinghai, Yunnan, and Tibet provinces were respectively completed in 2015–2016. We developed a sophisticated satellite, ‘Micius’, dedicated for quantum science experiments, which was successfully launched on 16 August 2016 from Jiuquan, China, and now orbits at an altitude of about 500 km.

Fig. 1 Launch of QUESS satellite

1.1 Scientific Objectives of China’s QUESS Project

Quantum Science Satellite is one of first space science missions for launch in CAS's forerunner of science and technology plan. The project aims to establish a space platform with long-distance satellite and ground quantum channel and carry out a series test of quantum principles and protocols at space-based large scale.

The scientific objectives are implementing a series of science mission with the quantum channel between Quantum Science Satellite and quantum communication ground stations. The major tasks are as follows:

- Quantum key distribution from satellite to ground[3-4]

For this objective, we establish an ultra-long-range quantum channel between ground and satellite with the assistance of high-precision acquisition, tracking, pointing system, implement quantum key distribution between the satellite and the ground station, and carry out experiments of unconditional secure quantum communications.

- Global scale quantum communication network[5]

For this objective, we set up a real wide-area network for quantum communication by the satellite repeater and two arbitrary quantum ground station and their auxiliary local-area fiber quantum networks.

- Entanglement distribution from satellite to two ground station[1]

For this objective, we distribute quantum entangled photons from the satellite to two distant ground stations whose distance is larger than one thousand kilometers, test properties of entanglement at a larger scale and non-locality of quantum mechanics.

- Teleportation from the ground to satellite[2]

As a whole new way of communication, quantum teleportation lies the fundamental process of quantum networks and quantum computing. A high-quality quantum entanglement source on the ground will be built to achieve ground-to-satellite teleportation experiments based on photon entanglement.

1.2 Timeline and Details of China's QUESS Project

2003: A pre-study project, 'free space quantum communications', was assigned by the Chinese Academy of Sciences (CAS) to test the feasibility of satellite-based quantum communications.

2004: Distribution of entangled photons over 13 km through a noisy near ground atmosphere over Hefei city was achieved, reaching a distance of more than the effective thickness of the aerosphere1.

2007: The 'Quantum Experiments at Space Scale' project, aimed at developing important techniques for performing quantum experiments at the space scale, was supported by CAS.

2007: Quantum teleportation over the Great Wall in Beijing, a distance of 16 km, was achieved.

2010: Direct and full-scale experimental verifications towards ground-satellite QKD were implemented near Qinghai Lake in western China, on a moving platform (using a turntable), on a floating platform (using a hot-air balloon) and with a high-loss channel (96 km, about 50 dB).

2011: Quantum teleportation and bidirectional entanglement distribution over an approximately 100-km free-space channel were achieved over Qinghai Lake. These results demonstrated the technical ability to handle the high-loss ground-to-satellite uplink channel and satellite-to-ground two-downlink channel.

2011: The 'QUantum Experiment Science Satellite' project was officially approved by CAS.

2012: Construction of the first prototype satellite began.

2014: The first prototype satellite was completed. The observatory station in Xinglong was completed.

2015: The flight model of the satellite was completed. The observatory stations in Nanshan and Delingha were completed. QKD and entanglement distribution experiments were conducted between the payloads of the first prototype satellite and the Delingha observatory station, over a distance of 17 km. A quantum teleportation experiment was also conducted between the payloads of the first prototype satellite and a transmitter placed in the Delingha station.

2016: The satellite passed through a series of environmental tests, including thermal vacuum, thermal cycling, shock, vibration and electromagnetic compatibility. The observatory stations in Lijiang and Ngari were completed.

2016: The Micius satellite, weighing 635 kg, was launched at 01:40 Beijing time on 16 August 2016 by a Long March 2D rocket from the Jiuquan Satellite Launch Centre, China. (A full view of the satellite before being assembled in the rocket is shown in Figure 2).

The locations of the five ground stations are shown in the map of Figure 3.

2. Scientific Results for Chinese QUESS Project

On August 16th, 2016, we launched the first quantum science satellite in the world. The satellite is named *Micius* after a Chinese philosopher and scientist lived more than two thousand and five hundred years ago. Almost one month later, a small-sized payload for QKD, was launched together with the Tiangong-2 space lab[4]. After nearly a year of efforts, we have achieved the three major scientific goals. We realized for the first time in the world satellite-based entanglement distribution over 1200 kilometers[1], ground-to-satellite quantum teleportation[2], and satellite-to-ground QKD[3-5]. These results pave the way to global-scale quantum networks and space-scale quantum experiments.

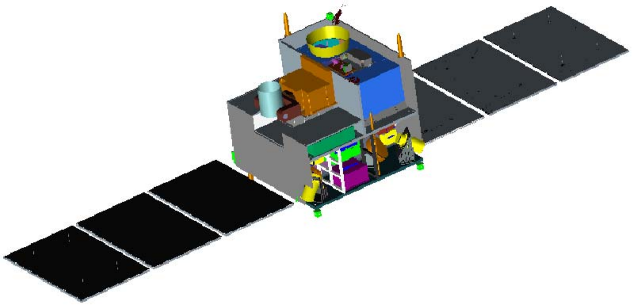


Fig. 2 Payloads of the QUESS satellite

Fig. 3 Ground stations of the QUESS satellite in China

2.1 Quantum Entanglement Distribution

For the mission of entanglement distribution[1], three ground stations are cooperating with the satellite, located in Delingha (37°22’44.43”N, 97°43’37.01”E; altitude 3153 m) in Qinghai, Nanshan (43°28’31.66”N, 87°10’36.07”E; altitude 2028 m) in Urumqi, Xinjiang, and Gaomeigu Observatory (26°41’38.15”N, 100°1’45.55”E; altitude 3233 m) in Lijiang, Yunnan (see Figure 4). The physical distance between Delingha and Lijiang (Nanshan) is 1203 km (1120 km). After passing through satellite-to-ground two-downlink with a sum of length varies from 1600 km to 2400 km, we observed an average two-photon count rate of 1.1 Hz, with a signal-to-noise ratio of ~8:1. Using the distributed entangled photons, we perform Bell test at space-like separation and without the locality and the freedom-of-choice loophole. We run 1167 trials of the Bell test during an effective time of 1059 s.

Finally, we observe a survival of two-photon entanglement with the state fidelity: F=0.87 ± 0.09, and a violation of Bell inequality by 2.37 ± 0.09 under strict Einstein locality conditions. Compared to the previous entanglement distribution method by direct transmission of the same two-photon source using the best-performance (with a loss of 0.16 dB/km) commercial telecommunication fibers, the effective link efficiency of our satellite-based approach within the 275 s coverage time is 12 orders of magnitude higher.

This work is asserted by the reviewers of the Science magazine as “a major technical accomplishment with potential practical applications as well as being of

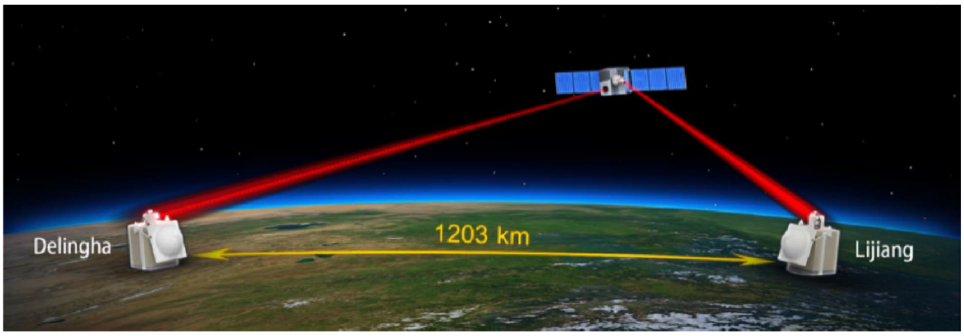


Fig. 4 Illustration of the Micius satellite's two-downlink to two ground stations

fundamental scientific importance." This work is also selected as a cover of the Science magazine.

2.2 Ground-to-satellite Quantum Teleportation

For the mission of quantum teleportation[2], a single qubit was generated at an observatory ground station in Ngari, Tibet (32°19'30.07"N, 80°1'34.18"E; altitude 5047 m), with the aim of teleporting it to the Micius satellite (see Figure 5).

We have established a ground-to-satellite uplink over a distance of 500–1400 km with loss of 41–52 dB and achieved the reliable transfer of the superposition state of a single-photon qubit using quantum teleportation.

Overall, we obtain 911 four-photon counts in 32 orbits, with each orbit corresponding to 350 s of data collection. The measured fidelities of the teleportation state for the six input states are yielding an average of $F = 0.80\pm0.01$, sampling over the whole Bloch sphere all well above the classical limit of 2/3. These results conclusively confirm the quantum nature of teleportation of a single qubit.

The reviewers of the Nature magazine commented this work as, "These results represent an important breakthrough in the quest for quantum communications over long distances" and "This goal is very challenging and new, and it represents a significant advancement of the realization of quantum communications schemes."

2.3 Satellite-to-ground Quantum Key Distribution

For the mission of quantum key distribution[3], two ground stations are cooperating with the satellite, located in Xinglong (near Beijing, 40°23'45.12"N, 117°34'38.85"E; alti

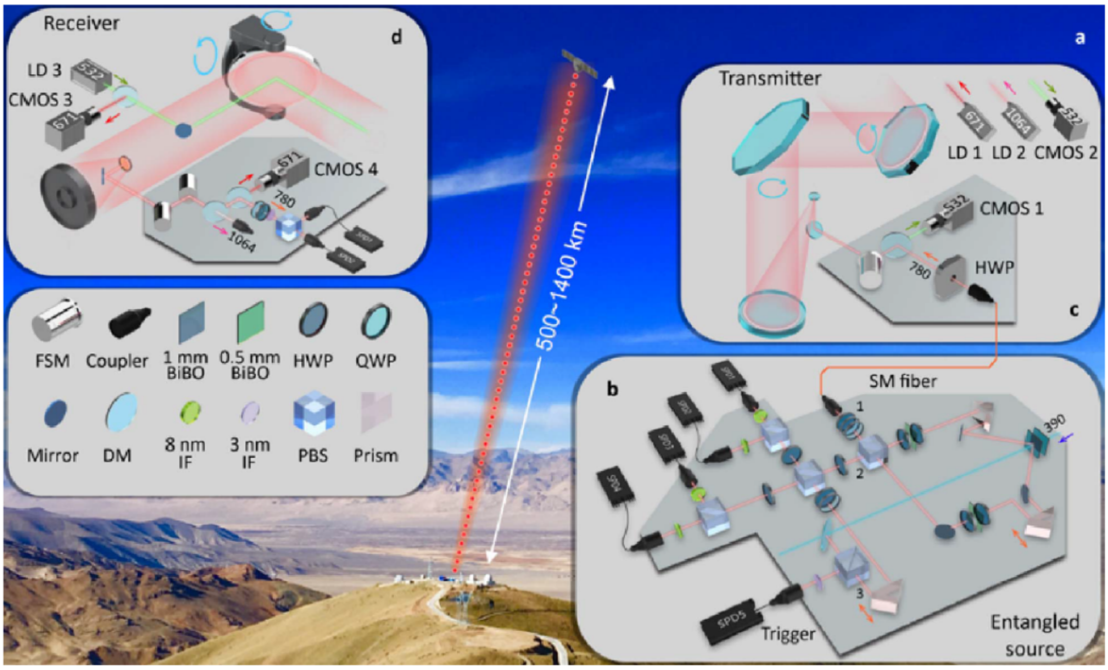


Fig. 5 Quantum teleportation from the ground to satellite

tude 890 m), and Nanshan (43°28’31.66”N, 87°10’36.07”E; altitude 2028 m). Since September 2016, we have routinely been able to successfully perform QKD under good atmospheric conditions (see Figure 6).

In this work, we show the data for the orbit on 19 December 2016, with a minimal (maximal) separation of 645 km (1200 km). Within a duration of 273 s for the QKD data collection, the ground station collected 3 551 136 detection events, corresponding to 1 671 072 bits of sifted keys. The sifted key rate decreases from about 12 kbit s^{-1} at 645 km to 1 kbit s^{-1} at 1200 km, owing to the increase both in the physical separation distance and in the effective thickness of the atmosphere near Earth at smaller elevation angles. The observed quantum bit error rate, with an average of 1.1%, consistent with the expected error rate due to background noise and polarization visibility. We then perform error correction and privacy amplification to obtain the final keys. After randomly shuffling the sifted key, a hamming algorithm is used for error correction.

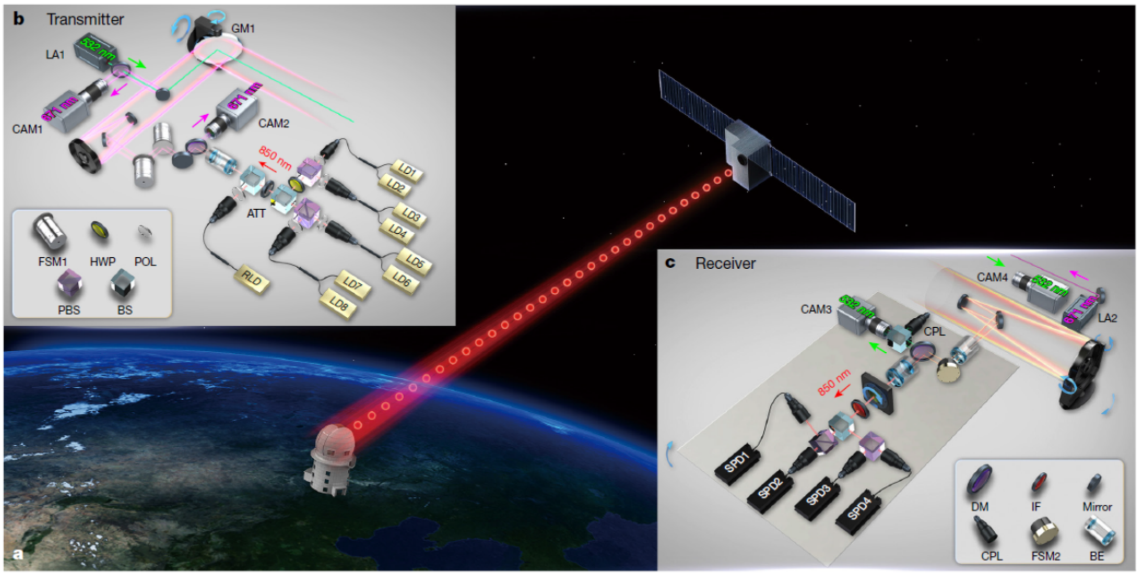


Fig. 6 Satellite to ground quantum key distribution

Finally, we calculate a secure final key of 300 939 bits, corresponding to a key rate of approximately 1.1 kbit s^{-1}. As a comparison with our data, over a distance of 1200 km, even with a perfect 10–GHz single-photon source and ideal single-photon detectors with no dark count, transmission through optical fibers would result in only a 1-bit sifted key over six million years.

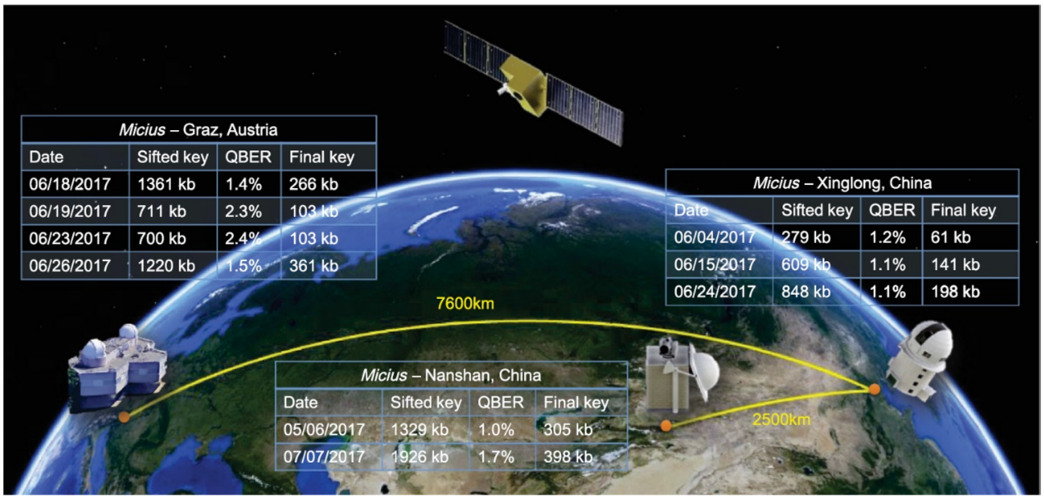
“I have no doubt that it will attract the interest of scientists working in a variety of fields (including quantum information science and space science), the general public, and lead to very extensive media coverage.”, said a reviewer of Nature.

2.4 Global Quantum Key Distribution

Our satellite can be further exploited as a trustful relay to conveniently connect any two points on the earth for high security key exchange[5]. We have already demonstrated this between Xinglong and Nanshan station. We first implement QKD in Xinglong, after which the key is stored in the satellite for 2 hours until it reaches Nanshan station near Urumqi, by a distance of ~2500 km from Beijing (see Figure 4).

By performing another QKD between the satellite and the Nanshan station, and using one-time-pad encoding, the secure key between Xinglong and Nanshan can then be established. There is a fiber channel between Xinglong ground station and Beijing. So, the satellite can also cooperative work with Beijing-Shanghai Quantum Backbone network. The future experimental plan also includes intercontinental secure key exchanges between China and Austria, Italy, and Germany. The international cooperation is underway.

“It will likely be at least a decade before any non-satellite approach (such as a quantum repeater) can come close to the reported result”, said a reviewer of Physical Review Letter. This work is also selected as a Focus story in the website of Physics and an Editors’ Suggestion.



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. 7 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

3. Conclusion

The developed satellite-based technology opens up a new avenue to both practical quantum communications and fundamental quantum optics experiments at distances inaccessible previously on the ground. Further, the distributed entangled photons are readily useful for entanglement-based quantum key distribution and a variant of quantum teleportation protocol for remote preparation and control of quantum states, which can be a useful ingredient in distributed quantum networks.

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