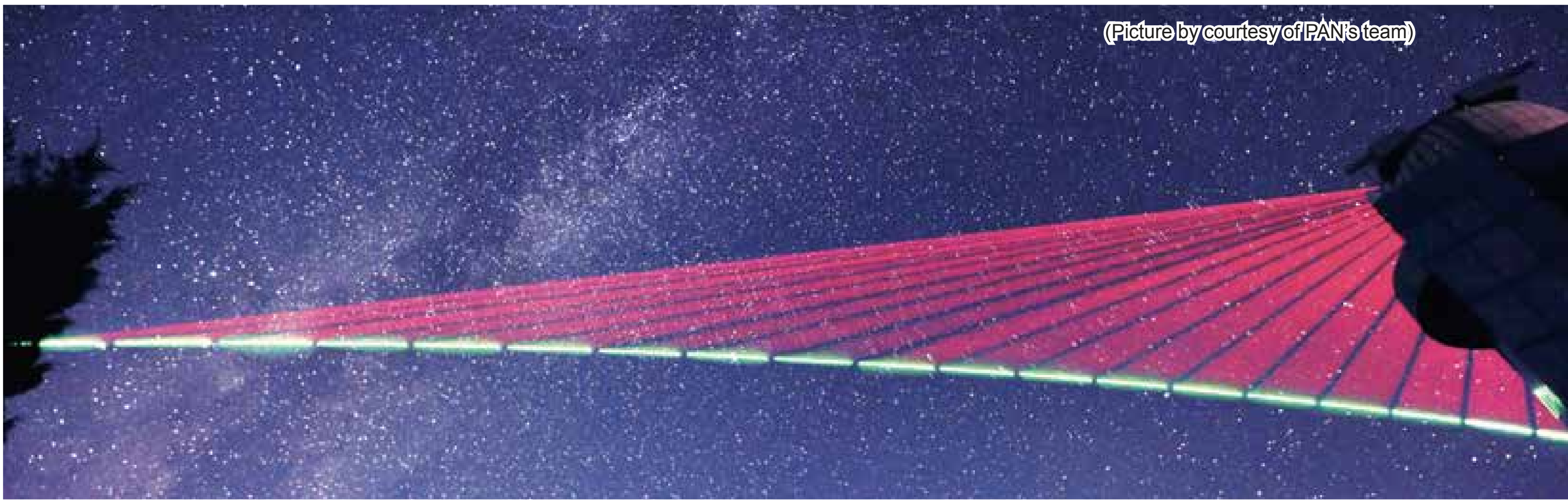
New Results from *Micius* Pave Way for Global Quantum Communications

By SONG Jianlan (Staff Reporter)



(Picture by courtesy of PAN's team)

Hardly had the elation in the wake of the 1,200 km-survival of quantum entanglement subsided before we again had news from *Micius*. On August 10, the joint team reported online in *Nature* the results from the other two major experiments aboard the satellite: Both the encrypted quantum key distribution (QKD) and quantum teleportation (QT) successfully passed through a distance of approximately 1,200 km, and did so less than two months after the success of the first *Micius* experiment – quantum entanglement distribution (QED) – made headlines in June with its publication in *Science* as a cover article.

The success of the two recent experiments add further luster to the achievement, marking the accomplishment of all three major preset tasks aboard the satellite *Micius*, ahead of schedule.

Nicknamed after *Mozi* (*Mo-tse*), an ancient Chinese scientist who explored pin-hole imaging nearly 2,500 years ago, the satellite *Micius* has been designed to perform quantum physics experiments in outer space to establish a satellite-ground channel for quantum communications. As one of the four science satellites sent into space under the Strategic Priority Research Program on Space Science sponsored by the Chinese Academy of Sciences (CAS), *Micius* was jointly developed by the University of Science and Technology of China (USTC) and the CAS Shanghai Institute of Technical Physics (SITP). The joint research force working on the satellite is led by the chief scientist team from USTC consisting of Profs. PAN Jianwei, PENG Chengzhi, ZHANG Qiang and their colleagues, together with scientists from other CAS institutes, including Prof. WANG Jianyu and his colleagues from the Shanghai Institute of Technical Physics (SITP), the Institute of Microsatellite Innovation (IMI), the Institute of Optics and Electronics (IOE), the National Astronomical Observatories (NAOC), the Purple Mountain Observatory (PMO), and the National Center of Space Science (NCSS).

With the success in QED, QKD and QT over a ~1,200 km distance, *Micius* has helped remove major obstacles in performing encrypted quantum communication at a space scale. It has demonstrated the feasibility of connecting segments of networks for encrypted quantum communication via satellites to build a global-scale network for ultra-safe quantum communication, protected by theoretically unbreakable encryption.

"Code Book" Sealed by Law of Quantum Physics

In the QKD experiment, the team successfully implemented decoy-state QKD from *Micius* to a ground station in Xinglong County, Hebei Province, over a distance of approximately 1,200 km, achieving an efficiency 20 orders of magnitude, better than what is expected using an optical fiber (with 0.2 dB/km loss) of the same length.

The team members who obtained these results have been working for 13 years to go into space. They initially demonstrated in a terrestrial experiment as early as in 2004 the feasibility of sending loophole-free quantum keys from a satellite orbiting in outer space to a receiver at a ground station.

Even longer, however, has been the pursuit of loophole-free encryption.

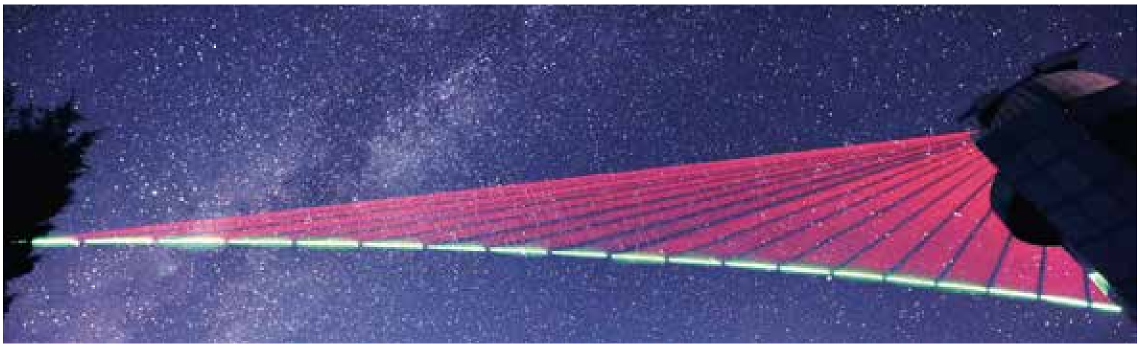
Humans have long pursued the dream of absolutely safe communication. Various techniques have been developed to protect information from hacking. However, with the greatly strengthened capacity and performance of computers, conventional encryption, including techniques based on factorization of large prime numbers thought to be very difficult to crack, has become vulnerable.

Answering this challenge, QKD emerged in the mid-1980s as a radical new approach to encryption. This new technique allows the sender and receiver of the message to share a randomly produced string of secret bits, which can be much shorter than the message body itself, via an unconditionally safe way secured by a principle of quantum physics called "no-cloning theorem". Secret information can be encoded in the superposition states of quanta at a single-quantum level, which will make it absolutely free from any interception or spying, as any effort to copy the information will change the quantum state and hence be easily detected by the sender or the receiver.

This random string will be shared and used only once in the communication as a "code book" (the secret key) to decode the message, which is encrypted and can be sent separately through conventional communication networks without worry. This method was proven by Claude Elwood Shannon to be an ultra-safe means to encrypt and decrypt a message.

Taking advantage of this approach, scientists found they were able to achieve fast and secure encrypted communication. Information can be encoded to the photons in a beam of polarized light and sent to the receiver; if any wiretapping or spying occurs, the system would respond to it immediately as an interference and the encoded information would be changed and lost. Therefore, absolutely secure quantum communication can be achieved if we send the key or the "code book" of a piece of encrypted message via quantum particles.

However, this information will not go far if carried by photons and transmitted in optical fibers or terrestrial free-space. Due to the collisions between the photons and the fiber molecules, energy will decay exponentially with distance. Even worse, following the no-cloning theorem again, this decay termed "channel loss" cannot be compensated for by signal amplification. As a result,



To establish a reliable space-to-ground link for quantum state transfer, the experiment of quantum key distribution aboard *Micius* adopted a downlink protocol. Illustrated here is an image of overlaid time-lapse photographs tracking the laser beams to and from the satellite over the Xinglong station. The red laser is sent from the ground as a beacon for the satellite to follow and lock on; and the green one, the one carrying quantum keys, is sent from the satellite for the ground station to pick up. (Picture by courtesy of PAN's team)

the maximal distance for secure QKD is limited to a few hundred kilometers.

Going into Space

One way to solve this problem is to use quantum repeaters. Despite remarkable progress in this field, it remains difficult to combine entanglement swapping, entanglement purification and quantum memories.

Another solution is to go into space. Given that the effective thickness of the atmosphere is about 10 km, most of the photons' journey would occur in the quasi vacuum of outer space, where the absorption and turbulence of photons are negligible. Therefore, the overall channel loss could be greatly reduced and the distance over which the photons can travel would be significantly increased.

By distributing the quantum keys from space and using a constellation of satellites as relays, a global network for secured quantum communication can be built by joining the segments of metropolitan-area networks together. This rosy future is exactly what PAN's team has been working towards and why *Micius* was designed and built.

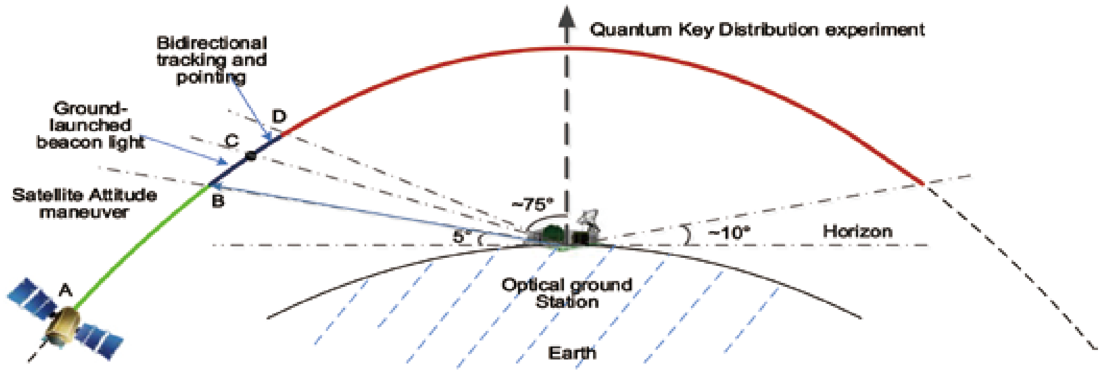
As early as 2004, in an experiment over the Qinghai Lake on the Qinghai-Tibet Plateau, the team showed the world that quantum keys could be sent safely over a distance beyond 13 km through noisy ground atmosphere, a distance larger than the valid thickness of the atmosphere from the surface to outer space (measuring about 10 km, as noted), hence removing a fundamental theoretical obstacle for the distribution at a space scale. Following that experiment, this safe distance was repeatedly updated by PAN's team as well as by other teams around the world, and eventually in 2012, they extended the distance to beyond 200 km in a "measurement-device-independent quantum key distribution" experiment; in 2016, they achieved a record 400 km.

In 2011, CAS and the State became sufficiently convinced by the team's many scientific breakthroughs and innovative project proposal to support the development and building of *Micius* under a special project termed the "Strategic Priority Research Program on Space Science". After years of development, the satellite was successfully launched from the Jiuquan launching site in northwestern China in August 2016.

While preparing for the experiment in outer space, the team further verified the feasibility of the satellite-based QKD, sending the quantum keys under simulated outer space conditions, including serious signal attenuation and various turbulence; through different spans of distance; and to/from rapidly moving platforms. In addition, they also used satellite corner cube retroreflectors in ground experiments of quasi-single-photon transmission and quantum communication to make sure the experiments proceeded smoothly in outer space.

Establishing Ground-Satellite Channel

As noted before, by taking advantage of the quasi vacuum in outer space the safe distance of distribution can be greatly increased. Some obstacles still exist, however. For example, photon wandering caused by atmospheric turbulence can introduce channel loss.



A schematic illustration showing how *Micius* works in the experiment. (Picture by PAN's team)

To reduce its influence, the team adopted a downlink protocol rather than an uplink. By this means the wandering occurred only at the very end of the transmission when the beam, after travelling all the way from space to Earth's surface, significantly expanded due to diffraction; hence the influence of wandering can be largely reduced relative to the beam size.

To improve the accuracy of distribution, the team also took measures to control the beam diffraction itself, which mainly depends on the size of the telescope used. The team used a 300-mm aperture Cassegrain telescope aboard the satellite, optimized to eliminate chromatic and spherical aberrations, to send the light beam downwards. As a result, the beam divergence was narrowed to a satisfactory level, and the diameter of the beam was limited to about 10 m when it arrived at the ground surface, after travelling 1,200 km.

Meanwhile, a high-bandwidth and high-precision acquiring, pointing and tracking (APT) system was developed and installed on both the transmitter and the receiver to accurately lock onto the light beam securely, despite the fast-moving satellite and the narrowed beam size from it. In addition, the team eliminated the error induced by the relative motion between the satellite and the ground station as well as all the birefringent elements in the optical path, by calculating the offset and making dynamic compensation for the rotation angle.

While circling the Earth along a sun-synchronous orbit, the *Micius* passes the Xinglong ground station once a night, remaining in view of the receiver telescope for 5 minutes. During this period, the APT systems aboard the satellite and installed at the receiver need to point to and track each other accurately to establish and maintain a robust downlink channel throughout the orbit. When the satellite reached an elevation angle of 15°, the transmitter sent randomly modulated signal and decoy photons together with a beam beacon laser for timing synchronization, and the receiver picked it up from the ground station. The transmission did not end until the satellite had passed by and dropped to an elevation angle of 10° on the other side. After the transmission, error correction and privacy amplification were conducted to obtain final keys.

As reported by the team in their paper published online in *Nature*, they have obtained stable results from the quantum key distribution experiments since last September. After repeated experiments and data analysis, they compared the performance of the satellite-based QKD with what was expected from the conventional method of direct transmission through telecommunication fibers.

"At 1200 km, the satellite-based QKD within the 273-s coverage time demonstrates a channel efficiency that is ~20 orders of magnitudes higher than using the optical fiber," the team concluded in the paper. "Through a 1,200 km fiber, even with a perfect 10-GHz single-photon source and ideal single-photon detectors with no dark count, one would obtain only 1-bit sifted key over six million years," they added.

Quantum Teleportation: New Hope for Encrypted Communication

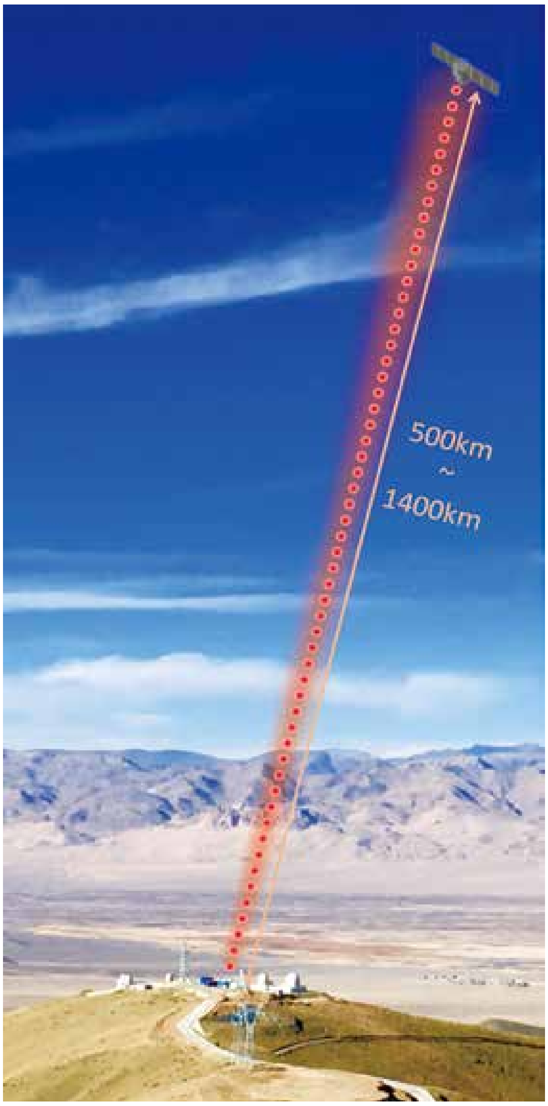
PAN's team has frequently been in the spotlight since their early pursuit of quantum teleportation over ten years ago. According to quantum mechanics, two entangled photons always strictly remain synchronized in terms of their quantum state – in other words, from the state of one of the photon pair, one can read the state of another. Taking advantage of this mysterious spooky "empathy" between the pair of photons, scientists can "send" a quantum state from one to the other without sending the carrier photon of the state itself. Due to the "no-cloning theorem" as noted, encrypted data communication based on quantum entanglement can be achieved at a very high level of security via teleportation.

Quantum teleportation aims to send the quantum state of a single quantum (A) to another (B) at a distance via some interference exerted on a quantum nearby (C), which is entangled with the latter. Given that the two quanta in the entangled pair (namely B and C) always stay in a synchronized state, theoretically the state of either of them can be read from another, no matter how far away it is. Taking advantage of this, information carried by A can be encoded in the quantum state of C through some interference, and "sent" to B via the spooky empathy. In quantum teleportation experiments, after sending the encoded information, the sender measures the quantum state of C, and this immediately causes the collapse of the quantum state of B, due to the "no-cloning theorem". However, the receiver can still fully recover the encoded information via some quantum calculation, based on the measurement of the quantum state sent by the sender and the collapsed quantum state of B. In this case, the measurement can only be sent through a conventional channel, in accordance with the quantum uncertainty and the no-cloning theorem.

Driven by its great potential in encrypted communication, scientists around the world have been striving to overcome technical bottlenecks to achieve quantum teleportation over long distances. Since the first successful experimental demonstration of quantum teleportation of a single degree of freedom in 1997, many groups have committed to the pursuit; results have been encouraging. However, owing to channel loss and quantum de-coherence in ground-surface atmosphere and optical fibers, the span of distance at which the previous experiments achieved success was limited to the order of 100 km.

PAN's team resorted to space technology to extend the teleportation distance. Before taking this step, however, the team conducted a series of ground-based experiments to guarantee a successful space-scale endeavor.

In August 2012, at a time when *Micius* was under development, PAN's team achieved the first 100-km scale teleportation in free space, erecting a "spring board" to space-scale experiments. Further, in 2015, the team achieved the first quantum teleportation of the composite quantum states of a single photon encoded in both spin and orbital angular momentum.



In the *Micius* experiment of quantum teleportation, a ground-to-satellite channel was successfully established, and the quantum state of single-level photons successfully exceeded a distance of 1,400 km. (Picture by courtesy of PAN's team)

At this point, with help from *Micius*, PAN's team members were able to conduct their ambitious test. Unlike the QKD experiment, however, the teleportation experiment adopted an uplink protocol: To facilitate the complicated manipulation of quantum particles involved in teleportation, as well as the use of both conventional and quantum channels of communication, the transmitter system was compressed into a compact desktop setup situated in a ground station located in Nigari, Tibet Autonomous Region, China, and the receiver was installed aboard the satellite *Micius*.

In the *Micius* teleportation experiment, the team successfully achieved the first quantum teleportation over a distance up to 1,400 km, sending independent single-photon qubits from the ground station in Nigari to a low-Earth-orbit satellite via an uplink channel. To optimize the link efficiency and overcome the atmospheric turbulence in the uplink, a compact ultra-bright source of multi-photon entanglement was developed and used; some techniques adopted in the quantum key distribution experiment, including those for narrow beam divergence and APT systems, were also used in this experiment.

"In summary, our work has established the first ground-to-satellite uplink at a ~500–1,400-km scale with 41–52 dB loss, and accomplishes the faithful transfer of the superposition state of a single-photon qubit using the quantum teleportation", the authors concluded. They successfully demonstrated quantum teleportation for six input states in mutually unbiased bases with an average fidelity of 0.80 ± 0.01, well above the classical limit.

Catching Quanta in Daylight

The two successful experiments were both limited to night-time operation to avoid sunlight, whose brightness "overshadows" the photons used in quantum communications and makes it much more difficult for the receivers to pick them up. In a space quantum network for practical use, however, it will be inevitable to transmit and receive signals in daylight, as the much higher altitude of the orbit to be used in future global quantum communication will make it impractical to take shelter from the sun – the Earth synchronous orbit is about 36,000 km above sea level, much higher than the sun synchronous orbit (about 500 km above sea level) used in the *Micius* experiments. Moving at such an altitude the satellites can take shelter from the sun only 1% of the time, and this short time span would greatly reduce the efficiency of the communication, should information be transmitted only when the satellite is in the shadow of the Earth.

Encouragingly, PAN's team broke through this bottleneck issue just before publication of the results from the QKD and QT experiments. Choosing to send information encoded in photons with a wavelength of 1,550 nm (near-infrared light), the team successfully demonstrated quantum key distribution in daylight over a distance of 53-km in free space over the Qinghai Lake on the Qinghai-Tibet Plateau. They published their results online in *Nature Photonics* on July 24, 2017. With novel spectral and spatial filtering technologies they had developed themselves, the team overcame one more obstacle on the way to satellite-satellite quantum communications. Moreover, given that the working wavelength is located in the optical telecom band, the experimental system is naturally compatible with existing ground fiber networks and thus represents an essential step toward a satellite-constellation-based global quantum network.

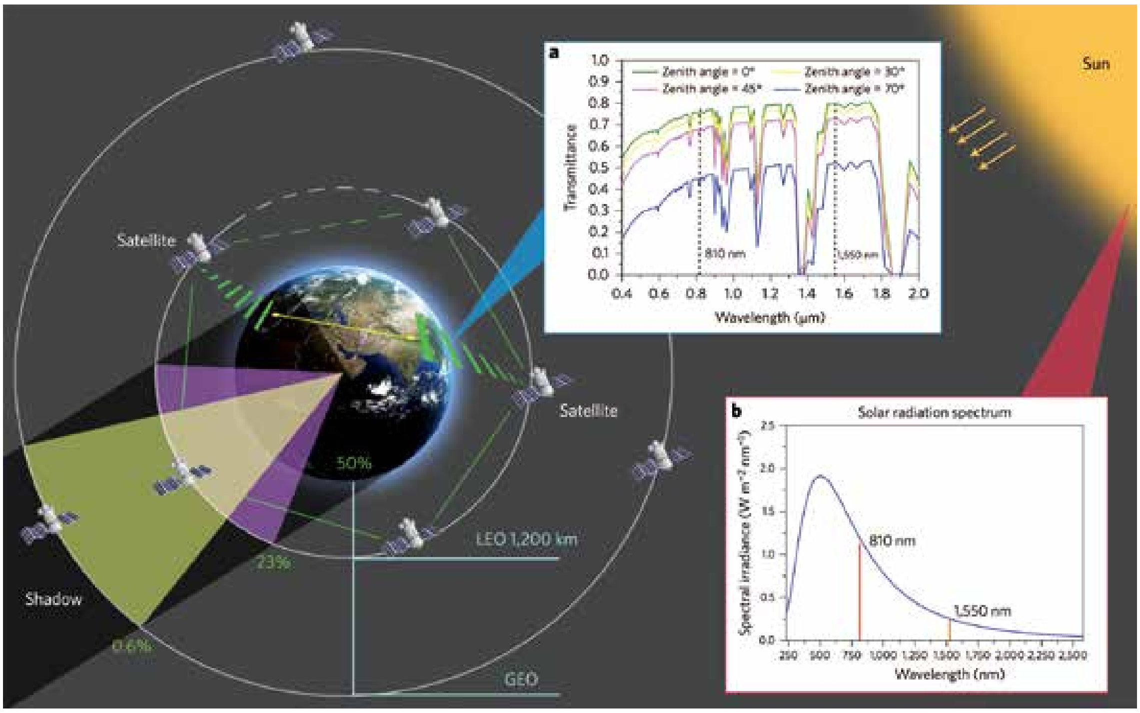
Outlook of Global Coverage of Quantum Communication Networks

The success of these experiments is expected to help remove some technical obstacles to joining the existing segments of quantum communication networks into one, bringing us closer to a global-scale network for quantum communication.

"The satellite-based QKD can be linked to metropolitan quantum networks where fibers are sufficient and convenient to connect numerous users within a city at ~100 km scale. We can thus envision a space-ground integrated quantum network, enabling quantum cryptography – most likely the first commercial application of quantum information – useful at a global scale", the authors said.

As early as 2008, the team had already succeeded in building the first general quantum communication network in Hefei, the capital city of east China's Anhui Province, and built up a special "quantum communication hotline" between important nodes to help secure smooth communication for the military parade celebrating the 60^{th} anniversary of the founding of the People's Republic.

PAN's university has been working to build a trunk line for encrypted quantum communications connecting Beijing and Shanghai; recently this project passed the technical evaluation given by panel experts. This 2,000-km information highway marks the first backbone network for encrypted quantum communications in the



Schematic illustration of a global quantum network based on a constellation of satellites. (Picture by PAN's team)

world. The successful establishment of a satellite-ground channel for quantum communications will undoubtedly further upgrade the performance of the networks.

According to PAN, China will send the second and the third quantum satellites into space if *Micius* works well. In late September, an experiment on intercontinental secure key exchanges between China and Austria proved successful, and further cooperative experiments with Italy and Germany are in the pipeline.

This grand plan, if successful, will make China one step closer to its ambitious goal of establishing the first global quantum communication network by 2030, with aid from a satellite array consisting of dozens of quantum satellites and numerous ground-based quantum communication networks.

Based on this network, China will be able to establish an ultra-safe quantum Internet, a quantum communication industry and a new generation of information security systems, scientists say.

At a news conference held in Beijing on August 10, 2017, the new results from *Micius* were released and CAS President BAI Chunli expressed his congratulations to the entire *Micius* team on their successful experiments, commenting that their innovative endeavor has opened a door to global quantum communications, space quantum physics and the experimental examination of quantum gravity.

So far, Austria has joined with CAS in the research aimed at global quantum communications, and teams from other countries, including Germany and Italy, have also filed proposals to participate.

As for *Micius*, following the achievement of its goals it has acquired new tasks, which involve further exploration of scientific issues concerning entanglement-based quantum keys and all-time quantum communications. "Within its designed lifetime," remarked BAI, "we can anticipate more scientific results from *Micius*."

For more information please refer to:

1. Liao, S. *et al*. Satellite-to-ground quantum key distribution. *Nature* http://dx.doi.org/10.1038/nature23655 (2017).
2. Ren, J.-G. *et al*. Ground-to-satellite quantum teleportation. *Nature* http://dx.doi.org/
3. Liao, S. *et al*., Long-distance free-space quantum key distribution in daylight towards inter-satellite communication, *Nature Photonics* 11, 509–513 (2017).