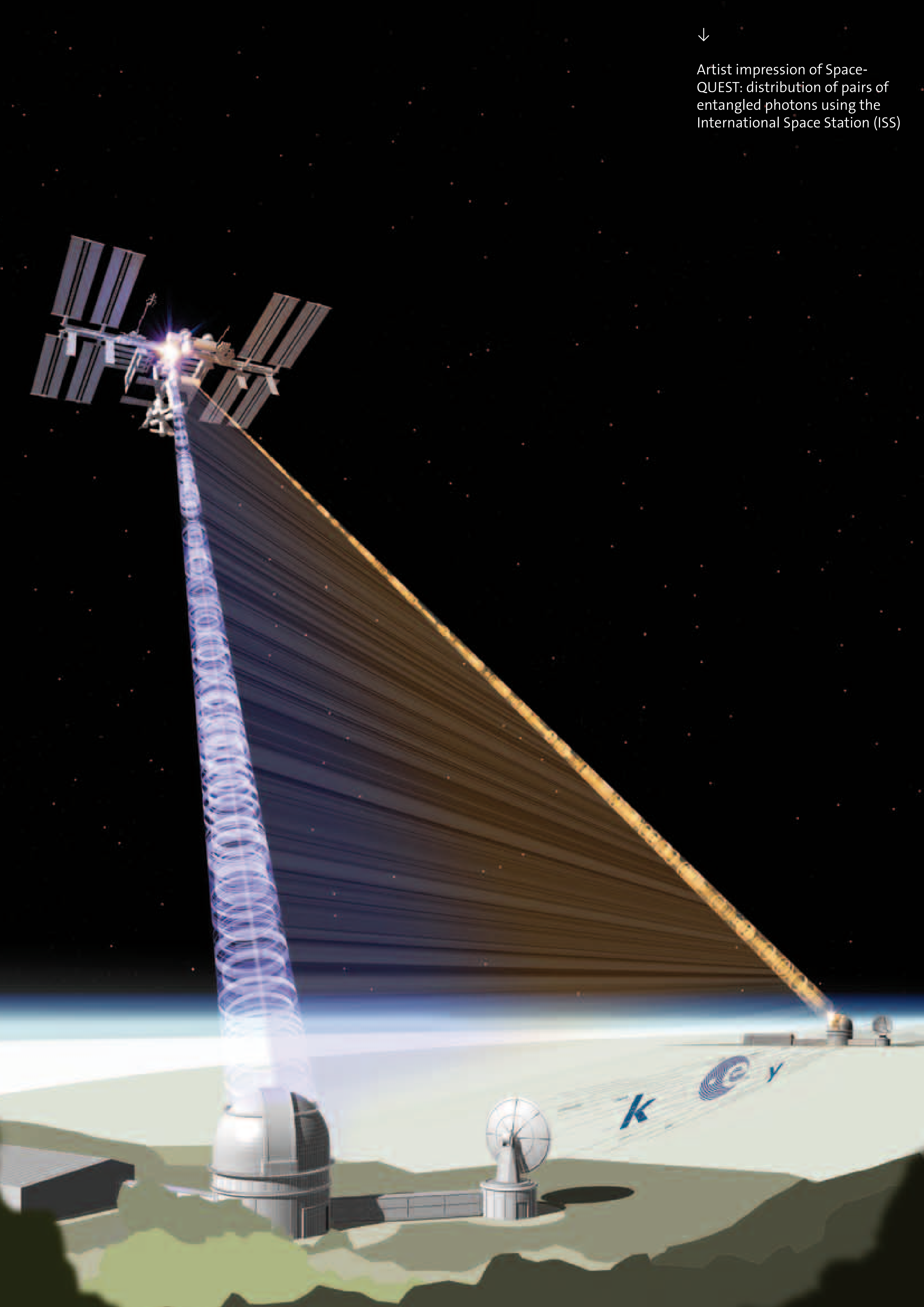

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Artist impression of Space-QUEST: distribution of pairs of entangled photons using the International Space Station (ISS)

→ LEAP AHEAD IN SPACE COMMUNICATIONS

Quantum technologies for space systems

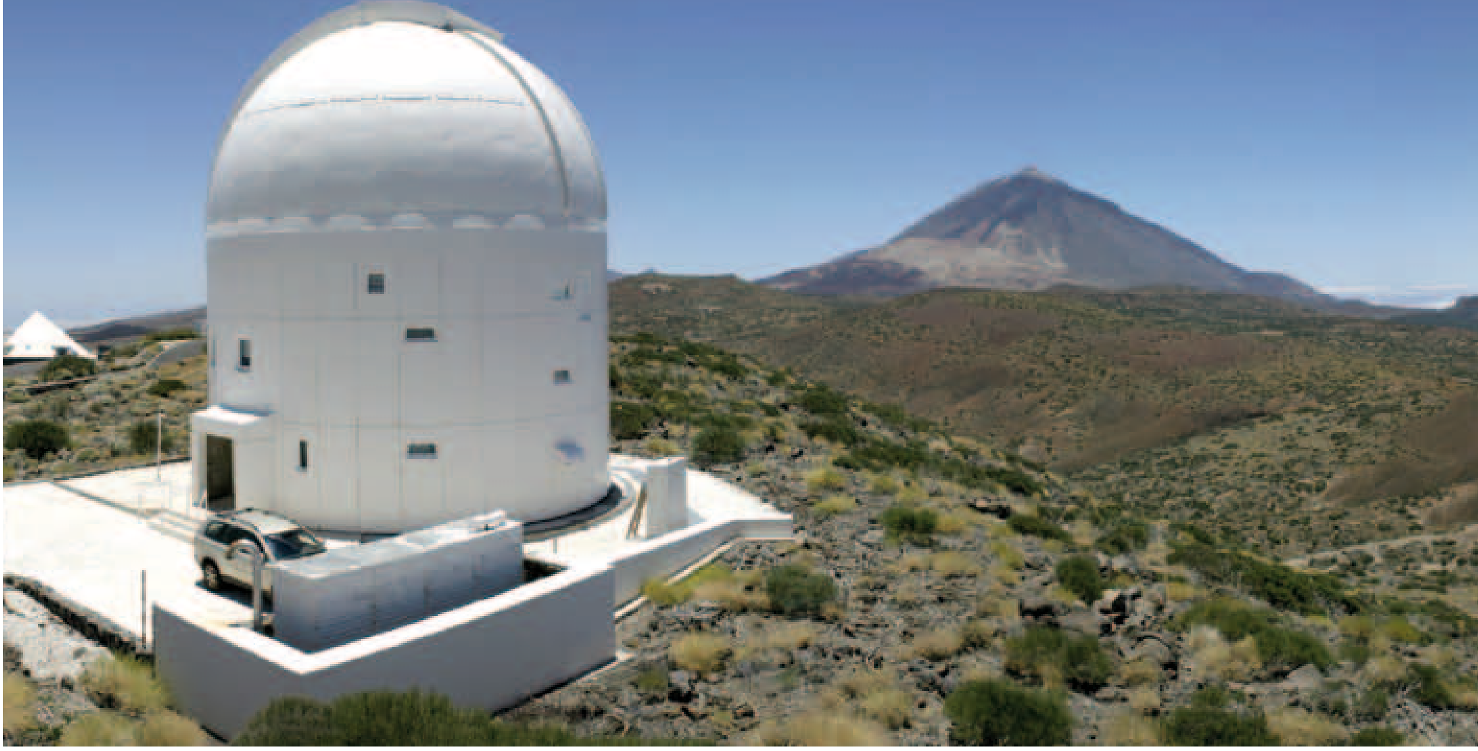
Josep Perdigues-Armengol & Zoran Sodnik
Directorate of Technical and Quality Management
ESTEC, Noordwijk, The Netherlands

Clovis De Matos
Strategic Planning and Strategic Control Office
ESA HQ, Paris, France

Today, spacecraft communicate with Earth using radio waves and laser beams but what about the future? ESA scientists believe that the weird behaviour of nature on its smallest scales may allow spacecraft to send information to Earth more securely and efficiently than ever before.

Quantum physics has changed our understanding of the fundamental principles of nature. Its predictions, although intriguing and counterintuitive, have been verified extensively and have established quantum theory as one of the most successful theories of modern science. Quantum physics has reached a crucial stage where useful commercial and technological applications can be developed, based exclusively on quantum physics principles with no equivalent classical counterpart. These new and innovative technologies are called 'quantum technologies'.

For a number of years, ESA has been examining how quantum technologies may benefit space applications and research. Indeed, it is expected that quantum



technologies will progressively enter the space arena and have a major impact on how we communicate or process information, as well as on how we will use the space environment in scientific missions to enhance our understanding of fundamental physics. One area that looks particularly promising for space application is 'quantum communications'. In the future, this will become a novel type of resource available to a wide variety of space and ground systems.

At nature's tiniest scales, non-intuitive things happen and these are known as quantum effects. For example, a beam of light can behave like an avalanche of particles, known as photons. Single photons cannot be cloned or split and, by measuring them, you change them from their initial state. So a message sent by a quantum communications system can only ever be read once because, as soon as it is read, the original message is automatically scrambled. This means that the receiving station can recognise if a third party has eavesdropped on the message.

These properties make possible the communications protocol called 'quantum key distribution', to distribute keys for data encryption with absolute security. If such a system was included in future versions of European's global navigation system Galileo, for example, it would instantly show if someone had tampered with the signals to and from the satellites.

Another example of quantum communications protocol is called 'quantum dense coding', which uses the weird quantum phenomenon of 'entanglement' to put more than a single piece of information on each photon, increasing the capacity of the communication channel.

→ Why quantum communications?

Security services are critical to modern telecommunications. For instance, they help ensure that a message received is the one that was sent, and that secrets remain secret.

The most sensitive information, such as bank transfers or military communications, can be encrypted very effectively. But some widely used encryption systems could be defeated by powerful computers, and even if information is encrypted, an eavesdropper can still tap into a conventional communications channel and listen to or copy a transmission without being detected.

Quantum mechanics offers the potential for ultra-secure communications because the act of observing an unknown quantum system changes its state. As a consequence, accurate copying is impossible, and changes caused by eavesdropping can be detected. Whereas today's fibre-optic communication systems require bits of information made of thousands of photons, quantum communication uses single photons to transmit unique random secret keys of ones and zeros. These can be used in future secure encryption systems.

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ESA's Optical Ground Station on the island of Tenerife (left), by day and night, with La Palma in distance at right and Mount Teide in background (T.Herbst)

Entanglement is one of the most puzzling quantum effects. If entanglement were possible on everyday scales, imagine having a pair of entangled coins. Give one to a friend and toss your coin. If you obtain a head, then you know immediately that when your friend tosses the other coin, it will fall on a tail. You do not have to wait for your friend to perform the experiment and tell you the result.

Understanding exactly how quantum particles are linked like this is difficult and some physicists never accepted the idea. Even Albert Einstein dubbed this effect as 'spooky action' and proposed that particles 'hide' some of their characteristics from us, which is why they then appear to spontaneously change their known ones.

Even though entanglement has been known about for decades, no one has known whether the entanglement decays over long distance. For example, would a beam of entangled photons remain entangled if it passed through Earth's atmosphere? On their journey, the photons could interact with atoms and molecules in the air. Would this destroy the entanglement? If so, entanglement would be useless as a means of communicating with satellites in orbit, because all signals would have to pass through Earth's atmosphere.

In September 2005, a European team aimed ESA's Optical Ground Station 1 m telescope on the Canary island of Tenerife toward the Roque de los Muchachos Observatory on the neighbouring island of La Palma, 144 km away. On La Palma, a specially built quantum optical terminal generated entangled photon pairs, using the SPDC process, and then sent one photon towards Tenerife, while keeping the other for comparison.

→ Quantum 'entanglement' unravelled…

If two photons of light are allowed to properly interact with one another, they can become 'entangled'. Pairs of entangled photons can even be created directly using a non-linear process called 'Spontaneous Parametric Down Conversion' (SPDC).

These two entangled photons can then be separated but as soon as one of them interacts with a third particle, the other photon of the pair modifies its quantum state. This happens according to the random outcome of the interaction, even though this photon never actually interacted with the third particle.

Such behaviour has the potential to allow messages to be swapped with complete confidence. This is because, if an eavesdropper listens into the message, the act of detecting the photons changes the entangled partner. These changes would be obvious to the legitimate receiving station and the presence of the eavesdropper would be instantly detected.

On comparing the results from Tenerife with those from La Palma, it was obvious that the photons had remained entangled, proving that the effect of entanglement remained intact over a distance of 144 km. That means that an entangled signal will survive the journey from the surface of Earth into space, and vice versa, making an essential first step towards a future satellite-based quantum communications system.

The success of the experiment on the Canary Islands proved the technical feasibility of 'quantum key distribution' and fundamental tests of quantum physics over very long distances, and has paved the way to bring quantum communications into space.

Such a system in space may help the understanding of entanglement by testing it over much larger distances than possible on Earth. As next step, the idea is to use the International Space Station to distribute pairs of entangled photons through the atmosphere to widely separated ground stations to see if they remain entangled. If funding is available, experimental equipment might be ready by 2015.

ESA and quantum communications

ESA has supported R&D activities in the field of quantum communications for space since 2002, funded by its General Studies Technology Research and Advanced Research in Telecommunications Systems programmes.

The studies carried out under ESA's General Studies Programme, included:

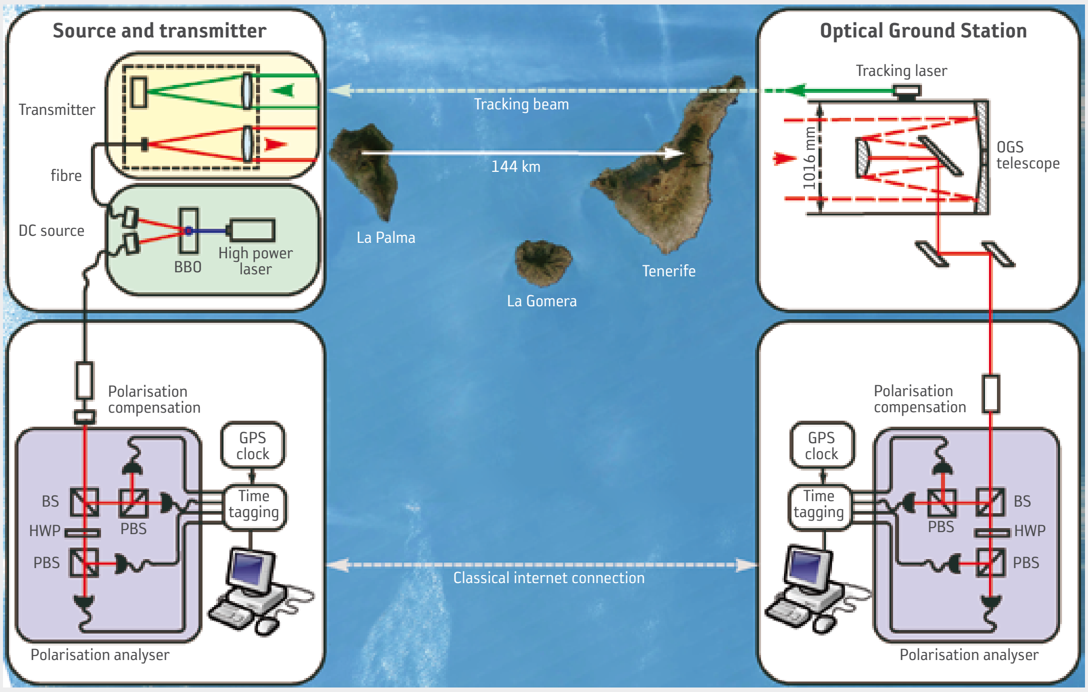
- 2002–3 Quantum communications in space ('QSpace', with Vienna University of Technology, Vienna University, QinetiQ and Ludwig Maximilian University)
- 2004 Accommodation of a quantum communication transceiver in an optical terminal ('ACCOM', with Vienna University of Technology, Vienna University, Contraves Space and Ludwig Maximilian University)
- 2005–7 Experimental evaluation of quantum communications ('QIPS', with Max Planck Institute, Austrian Academy of Sciences, University of Bristol, QinetiQ, University of Padova, Oerlikon Space Zurich, TESAT and Carlo Gavazzi Space)

First ESA quantum communications study (QSpace)

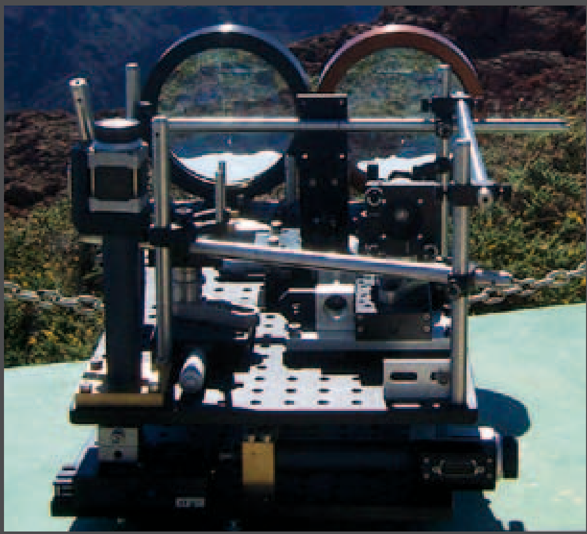
The objectives of QSpace were to identify and investigate novel concepts for space communication systems based on the foundations of quantum physics, and to conceive scientific experiments for the demonstration of fundamental principles of quantum physics, benefiting from the special environmental conditions in space. With regard to quantum communications, two promising areas were identified: quantum key distribution and quantum teleportation.

Quantum key distribution (QKD) guarantees the distribution of random sequences of bits with a level of confidentiality that cannot be achieved by any classical means. Its potential for security related applications is evident. QKD provides means for two (or more) separated parties to create a random secret key by transmitting photons over a quantum channel so interception by an eavesdropper can always be seen. After successful distribution, this symmetrical key can then be used for encrypting classical information for transmission over conventional, non-secure channels (e.g. phone line, radio link, fibre optic or optical free-space link).

Quantum teleportation (QT) allows the transfer of quantum information from one particle to another over, in



← Inter-island quantum communications experiment (Vienna Univ./MPQ)



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Transmitter telescope on La Palma looking towards the receiver on Tenerife. One of the large aperture lenses transmits single photons; the other receives the beacon laser from Tenerife for tracking purposes (Vienna Univ./MPQ)

principle, any distance. To perform QT it is necessary that transmitter and receiver share a pair of entangled photons. This connection via entanglement is usually referred to as a 'quantum channel', since there is no classical physical connection between transmitter and receiver (but only quantum correlations).

Note here though that matter and energy (and classical information) cannot be transferred from one place to another instantaneously, meaning that faster-than-light communications are not possible, since this would violate the rules of the theory of special relativity. Teleportation of quantum states is possible, but since QT requires classical communication, it is bounded by the speed of light.

Designing a quantum communications terminal (ACCOM)
To demonstrate quantum communications in space, this investigation envisaged establishing free-space optical links between a space-based transceiver and several transceivers at ground stations separated by long distances.

To a large extent, much of space optical communications hardware is already available in Europe, so the main objective of the ACCOM study was to investigate the hardware needed for carrying out quantum communications experiments. Specifically, what adaptations were needed in a laser communication terminal to allow the integration of a quantum communication transceiver, which subsystems could be reutilised or removed, and which subsystems needed to be modified.

The design of a complete space-based quantum communications terminal was carried out (including classical and quantum subsystems), which could perform downlink as well as uplink quantum experiments. Existing space-qualified and space-designed hardware (for example, telescopes, pointing/tracking mechanisms, acquisition sensors, etc.) was used.

The end result was a communications terminal, equipped with two telescopes, each with an independent pointing/acquisition/tracking subsystem capable of distributing entangled photon pairs from space towards two widely separated optical ground stations. The quantum communications transceiver included an entangled photon source, faint pulse laser sources, single photon detection modules and the associated optics for manipulating and analysing single photons.

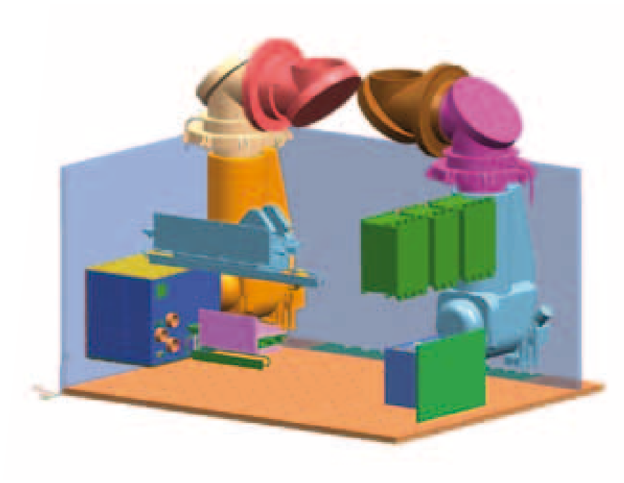
Inter-island quantum link demonstration (QIPS)
This study looked deeper into the designs of future mid-term and long-term experiments for demonstrating quantum communications applications, as well as fundamental principles of quantum physics in space. Both the scientific impact and the technical feasibility of the required space infrastructure were investigated.

To support these studies, basic ground-to-ground quantum communications experiments that represented the needs of space systems (i.e. very long distance links) were devised, in order to identify and evaluate the main critical areas of quantum communications. For example, how much is the quantum state or the entanglement of quantum particles affected when travelling through the atmosphere or in vacuum? Is there any distance limit for distributing entanglement between separated receivers?

This experiment would prove whether it was technically feasible to establish a single photon quantum channel (the transmission and detection of single photons) through long paths in the atmosphere, simulating a space-to-ground experiment in terms of total end-to-end link loss.

The Canary Islands (E) were chosen as location for the inter-island link to be established between a transmitter on the island of La Palma and a receiver on Tenerife. Both sites,

> **"Quantum communications can play a key role in future space systems, in telecommunications, navigations and science."**



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Design of a complete space-based quantum communication payload

operated by the Instituto Astrofisico de Canarias, are 144 km apart, and are higher than 2.3 km above sea level.

Before this experiment, the longest distance achieved by free-space faint pulse QKD was 23.4 km. Free-space entanglement based QKD had been demonstrated over 13 km. Using optical fibres instead of free space, faint pulse QKD had been tested at distances up to 150 km (although when considering potential eavesdropping risks, the maximum secure distance was only about 70 km). The inter-island quantum link experiment aimed at securely distributing quantum keys in free space at distances up to 144 km, which would become a world record.

The 144-km quantum channel established in this experiment represents a worst-case scenario for a space-to-ground link, due to atmospheric turbulence. The overall end-to-end transmission loss of this horizontal atmospheric link was 25–35 dB, which is comparable to the link loss between a satellite in low Earth orbit and a ground receiver. Therefore, faint pulses, single photons and entangled photons used for QKD could in principle be distributed from space either to other spacecraft or to ground stations. An important aspect is that link loss only affects the key rate, not the confidentiality of the key.

Quantum communications in space systems

Quantum communications can play a key role in future space systems, in telecommunications, navigation and science. Today, next-generation optical communication terminals (still based on classical optical communications) with reduced mass, size and power consumption, and increased data transmission rate are being considered by ESA for the implementation in the new European Data Relay System (EDRS).

The synergy between quantum communication transceivers and next-generation optical terminals would extend the range of applications beyond optical data relay. The capability of QKD is highly attractive for space applications where a very high level of security is necessary. Entanglement distribution might be of use in navigation, to improve the knowledge of satellite's orbit parameters (quantum positioning), for time reference distribution and clock synchronisation, or it could be exploited in the very long-term to efficiently communicate with deep-space probes. These applications are presently under investigation.

Besides, space offers the possibility of 'unlimited' long paths in vacuum (with no absorption loss due to the atmosphere or optical fibres), and therefore is an ideal medium to experimentally push the limits of entanglement (if there are any). Taking entanglement into space opens the possibility to address fundamental scientific questions, such as what are the limits of entanglement and quantum physics? What is the meaning of realism and locality in nature? Are there natural sources of entanglement in the Universe? Are there special relativistic and general relativistic effects on quantum entanglement?

Towards a quantum experiment in space

Moving into space enables photon entanglement to become a physical resource available for quantum experiments at a global scale. Many scientists want to test the theory of quantum physics over long distances and to establish a worldwide network for quantum communication, tasks that can only be realised by taking quantum physics into space.

In 2008, ESA initiated technology development activities to develop and increase the technology maturity level of the critical quantum subsystems, and also to explore additional quantum communications applications, in preparation for a future in-orbit demonstration.

A European research consortium led by Vienna University has submitted the Space-QUEST proposal to ESA, to develop a space-to-ground quantum communications experiment from the International Space Station. Alternative platforms are also being investigated.

The Space-QUEST experiment would be the first step towards the implementation of a World Wide Entanglement (WWE) service, and would accomplish the first-ever demonstration of QKD from space and fundamental tests on quantum physics, far beyond the possibilities of any ground-based experiment with current fibre optics and detector technologies.

Research groups in the United States and Asia are important players in the international race to bring quantum communications into space. However, with the success of the inter-island link experiment, European teams are a step ahead, and in cooperation with ESA, they are determined to keep this lead.