Accommodation of a quantum communication transceiver in an optical terminal

J.M. Perdigues Armengol[1], C.J. de Matos[1]
W. R. Leeb[2], M. Pfennigbauer[2]
G. Neckamm[3], F. Tiefenbacher[3], M. Aspelmeyer[3], T. Jennewein[4], A. Zeilinger[3,4]
G. Baister[5], K. Kudielka[5], T. Dreischer[5]
H. Weinfurter[6]

Abstract: the implementation of quantum communication schemes using free space links between a spacecraft and optical ground stations enables novel telecom applications (with worldwide coverage) such as quantum key distribution. It is also a crucial technology for new fundamental tests of quantum physics. The ESA's General Study ACCOM investigates the adaptation and the accommodation of a quantum communication transceiver in a classical optical terminal. Furthermore, preliminary analysis shows the feasibility of accommodating the complete quantum communications terminal (QCT) on the ISS, in view of a potential future space-to-ground demonstration.

1. Introduction

Quantum Information Theory opens new frontiers to our understanding of information processing and communications. The properties of "superposition of states" and "quantum entanglement" lead to completely new methods of information processing and computation more powerful than their classical counterparts, as well as to a variety of fundamental experiments for the test of Quantum Physics that rely on the unique properties of the space environment.

These new communications schemes might offer substantial advantages in terms of capacity, efficiency, absolute security and computational capabilities, as identified in the two (parallel) fast-track studies with leading scientists in Europe, [1] and [2], under the ESA's General Studies Programme.

Communication schemes based on quantum physical principles will allow, for example:

- Quantum key distribution (QKD) using single and entangled photons: the quantum cryptographic protocol relies on the transmission and detection of single photons. Its security is based on the impossibility to copy the quantum state of a single photon in any arbitrary state.
- Quantum state teleportation: the transfer of a quantum state from one site to another without the use of a physical carrier. Its primary resource is shared quantum entanglement between transmitter and receiver.
- Quantum dense coding (QDC): it utilizes quantum entanglement as a resource for communication with higher-than-classical channel capacity.
- Quantum communication complexity (QCC): it profits from entanglement to decrease the amount of information exchange that is necessary to accomplish computational tasks between distant parties.

Conceivable experiments for the demonstration of more fundamental principles of quantum physics that makes use of the space infrastructure include long distance Bell experiments, the test of the collapse of the wave function, experiments concerning special relativistic and general relativistic effects on quantum entanglement, etc.

[1] European Space Agency, Noordwijk, The Netherlands. Email: Josep.Maria.Perdigues.Armengol@esa.int
[2] Institute of Communications and Radio-Frequency Engineering, Vienna University of Technology, Gusshausstrasse 25/389, A-1040 Vienna, Austria

[3] Institut fuer Experimentalphysik, Universitaet Wien, Wien, Austria

[4] Institut fuer Quantenoptik und Quantenkommunikation, Wien, Austria

[5] Contraves Space AG, Zuerich, Switzerland

[6] Ludwig-Maximilians-Universitaet Muenchen, Germany

A huge step forward would be attained if such experiments were performed in space. Indeed, space environment offers substantial advantages over ground based experimental facilities. On the one hand, vacuum allows diffraction-limited long distance experiments (no influence of atmospheric turbulence or fibre birefringence/absorption effects). On the other hand, the achievable distances exceed the possibilities of earth based experiments by far thus allowing some novel fundamental quantum tests. All in all, space environment provides a unique environment for long-range quantum communications and fundamental tests of Quantum Physics[4]-[7].

With all the above items into consideration, ESA initiated another study in the field of Quantum Communications for space applications, "Accommodation of a quantum communication transceiver in an optical terminal" (ACCOM, contract n°17766/03/NL/PM, [3]), awarded to a consortium led by Vienna University of Technology, in collaboration with Vienna University, Contraves Space AG and Ludwig Maximilians University.

This paper will present the main results and conclusions from this accommodation study of a quantum communication transceiver in a classical optical terminal. The main objectives of this study are:

- to identify the subsystems of a classical optical terminal that can be re-utilized, removed, optimised or modified to best accommodate a quantum communication transceiver,
- to design a complete space-based quantum communication optical terminal (QCT, including both transmitter and receiver) capable of performing both downlink and uplink quantum experiments.

2. Scenarios trade-off and critical requirements

2.1. Scenarios trade-off

A spacecraft can be positioned at different orbital locations. The most common orbits are LEO (low Earth orbit), MEO (medium Earth orbit) and GEO (geostationary Earth orbit).

Spacecrafts in LEO orbit can offer the advantage of re-visiting the same ground location several times per day. One satellite is sufficient to provide non-real time global coverage (in spite of the small instantaneous coverage). The spacecraft could establish separate quantum channels and distribute a different quantum key with each ground station by downloading a key from the satellite to the first ground station, and a few minutes later downloading a different key to the second ground station (i.e. two different single downlinks). Since the space terminal has access to both keys, it can transmit a logical combination of the keys, which can then be used by either ground station or both ground stations such that they obtain the same key. This logical combination can easily be chosen such that it cannot reveal any information about the key. In principle, a quantum key exchange can be performed between arbitrarily located ground stations.

GEO orbit is widely used for telecom satellites. The main reason is the continuous accessibility to the same coverage area (about 1/3 of the Earth area), much larger than the instantaneous coverage provided from LEO orbit, at the expenses of attenuation increase. The simultaneous distribution of entangled states to two separate ground stations would allow instantaneous key exchange between these two communicating earth-bound parties, relaxing the security requirement for the transmitter module with respect to the case of sequential single downlinks. Only the use of entangled states sent to two separate ground stations allows instantaneous key exchange.

MEO orbit constitutes a compromise between LEO and GEO orbit and covers medium-size ground areas with relatively long access time but at the expenses of increased re-visit time period and attenuation with respect to LEO orbit.

In order to make a trade-off between different orbit types a figure of merit has been defined in terms of the total amount of qubits per day to generate a quantum key. This figure of merit takes into account typical acquisition time to establish an optical space-to-ground link, the average number of accesses per day and the average link attenuation. This trade-off shows that although requiring a new acquisition for each pass, LEO orbit still can offer approximately 4 times and 8 times larger keys than GEO and MEO orbits respectively, considering a minimum elevation angle requirement between 15-30 degrees and single downlinks. Therefore a spacecraft in LEO orbit was chosen for further analysis, in particular the external pallet of the Columbus module in the International Space Station (ISS).

As far as the ground stations are concerned, the following ground stations have been considered as potential candidates of locations for a ground-based quantum communications terminal:

- ESA's optical ground station OGS (Tenerife, Spain).
- one of the telescopes of Calar Alto astronomical observatory (Spain).
- the laser ranging observatory MLRO (Matera, Italy).

2.2. Assessment of critical requirements

The quantum communications optical terminal (QCT) is compatible with the following top-level mission experiments:

- Distribution of faint pulses or single photons to one ground station (QKD based on faint laser pulses or on single photon source respectively) and to two (or more) ground stations with only one link at a time (quantum key exchange between ground stations).
- Simultaneous distribution of entangled photons pairs (QKD based on entanglement and fundamental tests of Quantum Physics, i.e. testing of Bell's inequalities).
- Reception of single photons (QKD in up-link configuration).

The minimum duration required for performing a quantum communication link experiment is some 200 seconds when taking into account present-time technology. Both the location of the space terminal on the ISS and the geographic position of the ground station should allow at least one link with such a duration per day.

Table 1 and Table 2 show average durations and maximum attenuation factors for single downlink and simultaneous accesses from the ISS to one or two ground stations respectively, at different minimum elevation angles. Access opportunities are sometimes interrupted by gaps of several days or even longer.

ground station elevation	average access duration (minutes)	maximum access gap duration (hours)	average access gap duration (hours)	link range (km)	Atmospheric attenuation @ 808 nm (dB)
> 5°	5.5	< 15	< 1.8	< 1800	9.6
> 15°	3.5	< 17	< 9.0	< 1200	3.6
> 30°	2.0	< 40	< 25	< 700	2.2

Table 1. Key parameters for single optical downlink from the ISS at different minimum ground elevation angles. The results are similar for all considered optical ground stations (OGS, Calar Alto and Matera)

ground station elevation	average access duration (minutes)	maximum access gap duration (hours)	average access gap duration (hours)	link range (km)	Atmospheric attenuation @ 808 nm (dB)
> 5°	3.0	< 17	< 1.8	< 1800	9.6
> 10°	1.5	< 22	< 5.0	< 1200	3.6
> 15°	0.3	< 70	< 8.0	< 700	2.2

Table 2. Key parameters for simultaneous optical downlinks from the ISS at different minimum ground elevation angles to two separated ground stations (OGS/Calar Alto and Matera/Calar Alto)

For the space terminal, the quantum communications link shall be maintained for azimuth angles between –180° and +180° and elevation angles between –20° and +70°.The azimuth and elevation slew rate achievable by the space terminal when not tracking shall be at least 10°/s. Tracking of the link shall be possible for any rate of change of the terminal azimuth and elevation angle that does not exceed 1°/s. The required azimuth rate for the ground terminal is in the range of 0.2−1.0°/s, the elevation rate needed is 0.01−0.2°/s. Tracking shall be achieved for the link with a burst error probability of ≤ 10-6.

The reference laser, needed for classical optical communication, for tracking and pointing, and as a reference for the plane of polarization, must not operate at the same wavelength as the signal. It must be optically well isolated within the receiver terminal, i.e. straylight (even from the ISS surface) and backscattering into the signal receive path should be clearly below the level of background radiation. At λ=808 nm, we expect a background radiation of 10^3-10^4 photons per second per nm at the telescope entrance, mainly caused be sunlight reflected by the Earth.

The two driving requirements concerning the quantum channel are the attenuation which must not exceed 60 dB in order to achieve a SNR $\geq$ 6.8 dB and the time resolution below 1 ns to allow for pulse repetition rates in the range of 10^6/s. A SNR below the stated value would make impossible any quantum communication protocol, and lower pulse repetition rates would increase the duration of one useful experimental run beyond possible link duration of LEO-ground links. To provide the classical communication necessary to perform quantum communication experiments, a data rate of some 2.4 Mbit/s is sufficient. The classical communication link shall achieve a bit error probability of $\leq 10^{-6}$.

3. Overview of the classical optical communications terminal

Contraves Space AG has been developing a family of classical optical communications terminals since 1995 and today has designed a family of three terminals for telecommunication applications and one for deep space links (see Figure 4.1). The CSAG family of optical terminals are:

- OPTEL 02, the short range ISL terminal capable of transmitting data at Gbps rates over distances of typically 2,000 km.
- OPTEL 25, the medium range terminal capable of transmitting data at Gbps rates over dis-tances of typically 25,000 km.
- OPTEL 80, the long range terminal capable of transmitting data at Gbps rates over dis-tances of typically 80,000 km.
- OPTEL-DSL terminal, optical terminal for deep space links as required for planetary mis-sions such as those planned to Mercury and Mars, as well as to the L2 position.

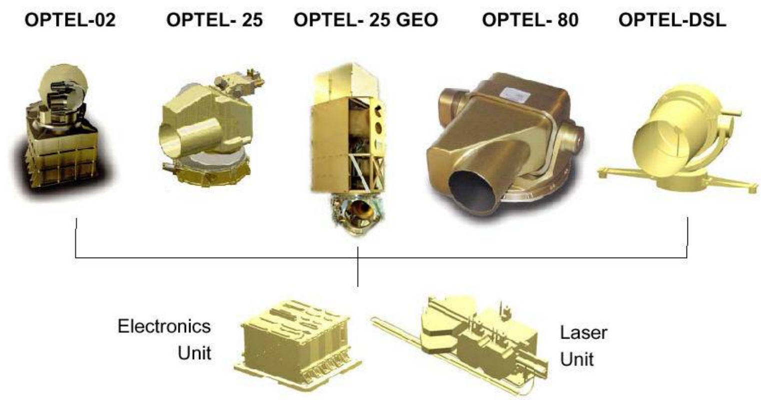

Figure 1. Contraves space family of optical communications terminals

The design of the three terminals follows a modular approach which begins with the splitting of the functions for the optical terminal between three main units. The three units are:

- Optical Head Unit (OHU) that is located outside the spacecraft (for example on the nadir panel of a telecommunications satellite) and which acts as the optical antenna.
- Laser Unit (LU) which can be located inside the spacecraft (for example within the communications module (CM)).
- Electronics Unit (EU) also located in the CM. For ease of accommodation the EU and LU are connected to one another via a harness making it possible to accommodate these units in different parts of the CM if required for spacecraft accommodation reasons.

The units are connected to each other by inter-unit harnesses which comprises both optical fiber and electrical cable for the routing of signals between the units.

4. Quantum communication transceiver concepts

In order that the quantum communication transceiver enables the range of envisioned experiments (mission requirements), it must be capable of performing the following tasks:

- generation of entangled photons (e.g. see Figure 2)
- generation of conditional single photons and faint-laser pulses,
- transfer of photons to transmission telescopes in single mode fibers,
- active and independent acquisition, tracking and pointing of two telescopes towards ground stations for transmitting or receiving quantum signals,
- performing onboard polarization analysis and detection of entangled photons (beam splitters with asymmetric splitting ratio are used to guide a small fraction of the outgoing photon beam to the polarization analyzer)
- performing onboard system tests and calibration,
- performing active polarization alignment of the quantum signals,
- storing onboard detection events as time tags,
- transmitting and receiving reference laser beam(s) for acquisition, for tracking, and for referencing the polarization plane,
- transmission of timing information and other data via classical optical links backing the quantum communication.

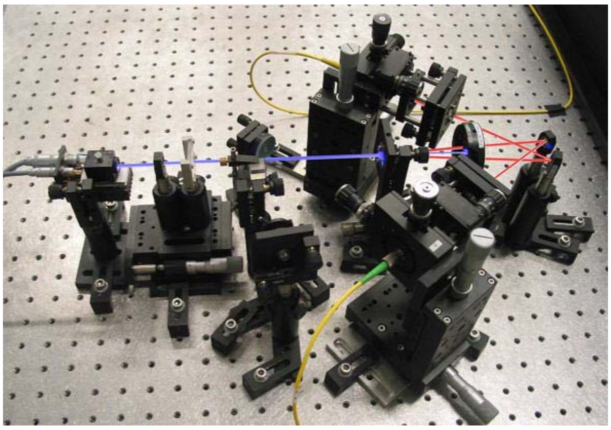

Figure 2. Breadboard demonstrator for generating entangled photons.

The quantum subunits required for realizing a quantum communication transceiver are the quantum communication source module, the polarization analyzer, the detector module, the polarization controller, and the data acquisition system. The estimated mass of the quantum modules is 8.4 kg (including 2.1 kg for mass memory) and the power consumption of the quantum communication transceiver is estimated to be 47 W. By supplementing a classical optical communication terminal with the quantum communication transceiver subunits allows to realize a quantum communication terminal suitable for performing experiments on quantum communications and fundamental physics experiments.

5. Design of a quantum communication optical terminal

5.1. Quantum communication terminal architectures

In order to determine the optimum architecture for the quantum communications terminal (QCT) a functional breakdown has been made to define the various functions that a QCT has to fulfil. This is summarized in Figure 3. This breakdown is based upon the existing Contraves Space AG functional decomposition for a classical optical terminal but with the addition of the quantum communications building blocks. Based upon this functional breakdown it has then been possible to accommodate the quantum subunit functions within one of the three units (OHU, LU or EU) depending upon the functional characteristic.

The main drivers for the derivation of candidate architectures for a quantum communications terminal are:

- The quantum channel operates at 0.81 µm. The stringent isolation requirement between this channel and the classical communications, tracking and acquisition channels has led us to technologies that operate at wavelengths that are spectrally separated from the quantum channel.
- The optical link for the classical communications channel is from space to ground. The link therefore has to contend with degradations induced by the atmosphere and therefore modulation and detection schemes that are robust to the degradations induced by the atmosphere are to be considered. Candidate systems for classical communication are therefore those based on direct detection, operating at, e.g., 1.0 µm and 1.55 µm.

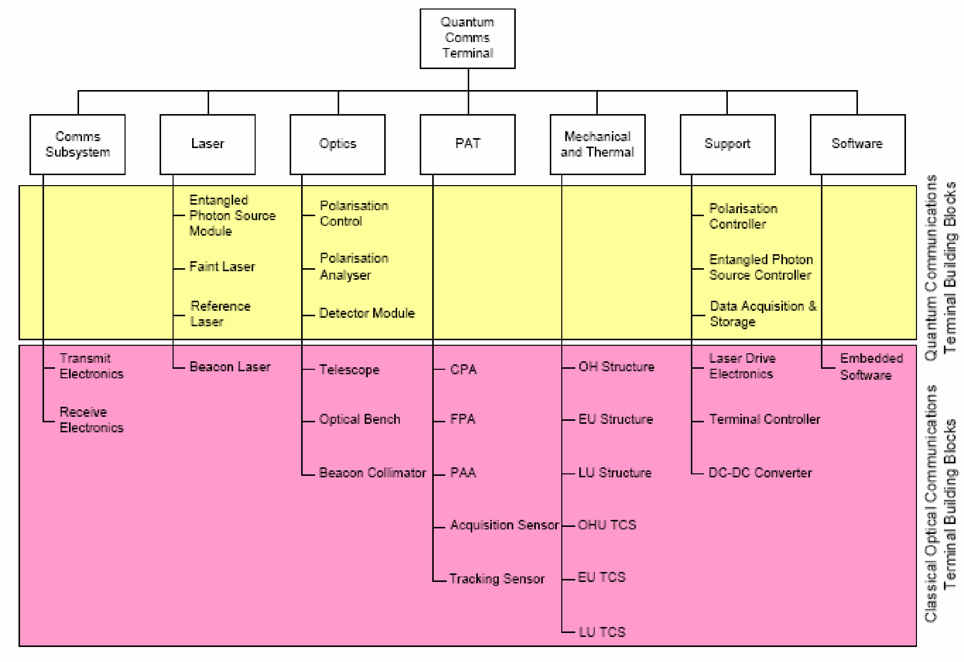

Figure 3. Functional breakdown of an optical communications terminal

For the identified quantum communications experiments as being scientifically of interest three fundamental architectures for the QCT were derived:

- Single photon source for a quantum key distribution experiment (with classical optical communications channel). This optical terminal is designated the single photon link quantum communications terminal (SPL-QCT).
- Entangled photon source for fundamental quantum physics experiment (with classical optical communications channel). This optical terminal is designated the entangled photon link quantum communications terminal (EPL-QCT).
- Entangled photon source for fundamental quantum physics experiment (without a classical optical communications channel). In this case it is assumed that a classical microwave communications link is available.

5.2. Architecture trade-off and selection

A trade-off of the three options for the quantum communications link has been performed for the candidate LEO mission –link from the ISS to ground. The criteria which have been taken into account for the trade-off are summarized below:

- Quantum communications terminal physical features – the mass, volume and power consumption.
- Terminal performance. Here the criteria has been chosen to determine if it
    - fulfils requirements for performing the range of quantum communications experiments,
    - achieves the envisaged scientific value for the quantum link experiments,
    - allows for quantum link experiments that have a potential for applications of scientific or commercial interest,
    - provides a classical communications link to ground.
- Risk assessment. A consideration on the risk of the different options has been considered:

    - Complexity – this criterion is intended to assess the risk associated with the complexity of the derived quantum communications terminal configuration.
    - Implementation risk – this criterion is intended to assess (in addition to the complexity) the risk associated with the implementation of the derived QCT configuration. Of importance for this criterion are issues such as the dependence of the QCT option on a specific technology that may have some risk associated with it.
    - Flight heritage – this criterion is to include an assessment for technologies that do have some space heritage from other applications.
    - Qualification status – this criterion is to include an assessment for technologies that would require a component qualification programme to support the flight development activities.
- Programmatic issues. The issues that have been considered here are:
    - Development costs – criteria to include an assessment on the development activities to be performed before a flight programme can be kicked-off (i.e. before phase C/D).
    - QCT costs – criteria to include an assessment for the phase C/D/E costs.
    - European supplier base – criteria to include an assessment of the selection of technologies that are not available within Europe and which may in the future become covered by export restrictions (for example if used in military programmes).
    - Growth potential – criterion to account for growth of the system by being able to perform other scientific experiments, to demonstrate possible applications of the technology or increase in the link capacity.

The following conclusions are extracted from the trade-off exercise:

- the preferred option is a QCT comprising entangled photon source and a classical optical communications link,
- the EPL-QCT is larger and heavier than the SPL-QCT and also consumes more power. However, the range of experiments and their scientific impact is much higher using an EPL-QCT than using a SPL-QCT or EPL-QCT without optical classical communication. The different options do not differ significantly regarding the risk assessment and programmatic criteria,
- for the classical optical communications link, 1.0 µm technology has received a slightly higher score than the 1.55 µm option and is selected for the classical optical communications channel.

5.3. Preliminary design and accommodation of a quantum communication terminal on Columbus module

The selected QCT architecture is an entangled photon link with a classical optical communications channel (EPL-QCT). The main decisions that have been made in determining this configuration have been:

- Optical head configuration – in order to achieve adequate link availability and to satisfy the link budgets for the quantum and classical optical communications channels the OPTEL 25 optical head with hemispherical pointing capability has been selected. The selected configuration for the OPTEL 25 terminal is to gimbal the telescope and optical bench so as to achieve the required pointing ranges needed to have sufficient link duration for entangled photon link experiments. This configuration will place an additional demand on the polarization alignment of the quantum signals, because as the telescope is turning, the fibers connecting the entangled photon source with the telescope will be mechanically moved.
- Feasibility for the space-based quantum terminal to be able to perform a single photon uplink from the OGS has been included. The main modification which has had to be considered is the inclusion of the optical beam router within the optical bench.
- Modification of the transmit collimator interface within the optical bench so as to first collimate the quantum channel and the reference channel and then perform the beam combination function.
- A faint laser source has been included as part of the quantum communications source module.
- Selection of wavelength for the classical communications channel:
    - For the downlink a wavelength of 1060 nm has been chosen as well as a data rate of 100 Mbit/s.
    - For the uplink a wavelength of 980 nm has been chosen and a data rate of 1 Mbit/s.

The EPL-QCT optical communications terminal comprises two OHUs (to achieve the two simultaneous links to the optical ground stations) together with one LU and one EU (including the mass memory electronics). The LU and EU are both configured to be able to simultaneously operate and to interface to the two OHUs. Figure 4 shows the EPL-QCT accommodated on a base plate with the dimensions of 139 x 117 cm^2 as defined as the available area for the Columbus external pallet. The OHUs have been accommodated so as to have available the required swept volume to be able to achieve the necessary pointing angles for the link.
The mass estimate for the EPL-QCT optical terminal is <95 kg with a peak power consumption of <230 W.

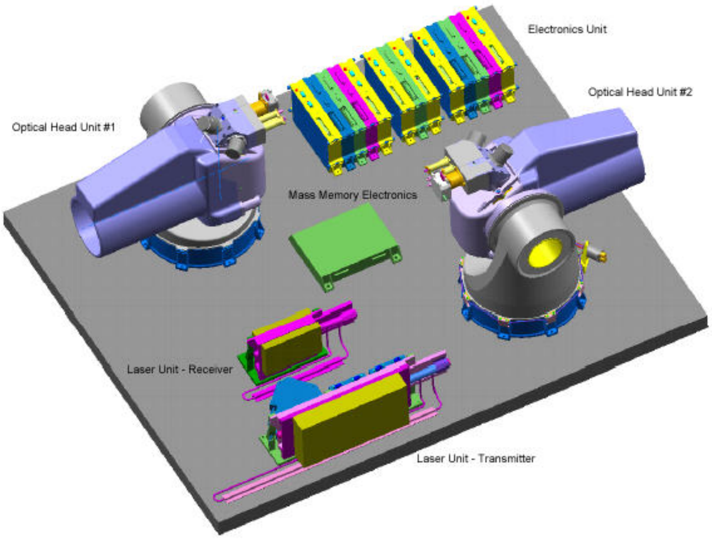

Figure 4. Entangled photon pair experimental payload

6. Conclusion

One vision of the science community is to establish a worldwide network for quantum communication – a task that can only be realized by bringing concepts and technologies of Quantum Physics to space (see Figure 5). Space environment provides ideal long free space diffraction-limited paths, a unique environment for long-range quantum communications and fundamental tests of Quantum Physics. Among different orbits, LEO orbit provides the best performance in terms of the total amount of qubits per day, about 4 times and 8 times larger than from GEO and MEO orbits respectively, considering typical acquisition time, average number of accesses per day and average link attenuation.
Most subsystems of a classical optical terminal can be reutilized to accommodate a quantum communication transceiver without major redesign. The preliminary design of a complete space-based quantum communication optical terminal (QCT including both transmitter and receiver) is capable of performing both downlink and uplink quantum experiments from the external pallet of the Columbus module in the International Space Station (ISS) to ground .

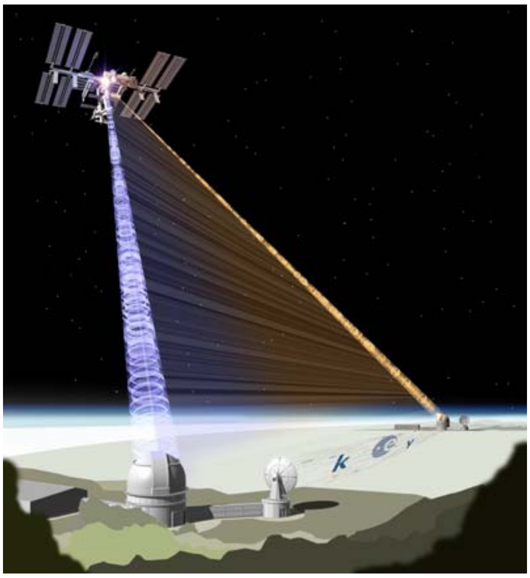

Figure 5. Distribution of pairs of entangled photons using the International Space Station . Entangled photon pairs are simultaneously distributed to two earth-bound locations thus enabling both fundamental quantum physics experiments and novel applications such as quantum key distribution.

References

[1] “Quantum Communications in Space: Executive Summary”, ESA contract 16358/02.

[2] “Quantum Communications in Space: Executive Summary”, ESA contract 16441/02.

[3] “Accommodation of a quantum communication transceiver in an optical terminal: Executive Summary”, ESA contract 17766/03.

[4] J.G.Rarity, P.R.Tasper, P.M.Gorman, and P.Knight, “Ground to satellite secure key exchange using quantum cryptography,” New Journal of Physics, no. 4, pp. 82.1–82.21, 2002.

[5] M. Aspelmeyer, T. Jennewein, M. Pfennigbauer, W. Leeb, A. Zeilinger, “Long-Distance Quantum Communication with Entangled Photons using Satellites”, IEEE Journal of Selected Topics in Quantum Electronics, special issue on "Quantum Internet Technologies", Vol. 9, 1541-1551 (2003); quant-ph/0305105

[6] R. Kaltenbaek, M. Aspelmeyer, T. Jennewein, C. Brukner, M. Pfennigbauer, W. Leeb and A. Zeilinger, “Proof-of-Concept Experiments for Quantum Physics in Space”, Proceedings of SPIE, Quantum Communications and Quantum Imaging, R. Meyers and Y. Shih (eds.), Vol. 5161, 252-268 (2003); quant-ph/0308174

[7] M. Pfennigbauer, W. Leeb, M. Aspelmeyer, T. Jennewein, A. Zeilinger, “Free-Space Optical Quantum Key Distribution Using Intersatellite Links”, Proceedings of the CNES - Intersatellite Link Workshop (2003)