Towards quantum communication from global navigation satellite system

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Keywords: quantum communication, quantum key distribution, global navigation satellite system

Abstract
Satellite-based quantum communication (QC) is an invaluable resource for the realization of a quantum network at the global scale. In this regard, the use of satellites well beyond the low Earth orbit gives the advantage of long communication time with a ground station. However, high-orbit satellites pose a great technological challenge due to the high diffraction losses of the optical channel, and the experimental investigation of such quantum channels is still lacking. Here, we report on the first experimental exchange of single photons from a global navigation satellite system (GNSS) at a slant distance of 20 000 km, by exploiting the retroreflector array mounted on GLONASS satellites. We also observed the predicted temporal spread of the reflected pulses due to the geometrical shape of the array. Finally, we estimated the requirements needed for an active source on a GNSS satellite, aiming towards QC from GNSS with state-of-the-art technology.

1. Introduction
Satellite-based technologies are the enabling tools for a wide range of civil, military and scientific applications [1–4], like communications, navigation and timing, remote sensing, meteorology, reconnaissance, search and rescue, space exploration and astronomy. In particular, global navigation satellite systems (GNSS) were developed in the second half of XX century to provide autonomous geo-localization by exploiting a network of satellite exchanging position- and time-information with different locations on Earth [5]. The strategic importance of such infrastructure led different countries to deploy their own GNSS constellations, e.g. the American global positioning system, the Russian GLONASS, the European Galileo, the Chinese BeiDou, the Japanese QZSS and the Indian INRSS/NAVIC. The very core of these navigation systems is the capability of safely transmitting information and data from orbiting satellites to several ground stations on Earth by exploiting radio [2] or optical communications [6]. In fact, the protection of such infrastructure from a malicious adversary is of crucial importance for both civil and military operations, representing a critical issue that is continuously and extensively under development.

At the same time, space quantum communications (QCs) (see the reviews [7–9]) represent a promising resource to guarantee unconditional security for satellite-to-ground [10–12] and inter-satellite optical links [13, 14], by exploiting quantum information protocols as quantum key distribution (QKD) [15, 16]. Despite being a relative new research field born in the 2000s, satellite QCs developed rapidly from the first experimental studies of photon-exchange [17, 18] from Low-Earth-Orbit (LEO) satellites to the feasibility-test of different photon encodings such polarization [19, 20], time-bin [21], and continuous-variable [22]. Then, the strong efforts of the Chinese Academy of Sciences led to full in-orbit demonstrations of such technologies last year [23–26], culminated in the realization of an intercontinental quantum-secure communication between China and Austria [27].
Due to optical losses, most of the demonstrations of satellite QCs were limited, so far, to LEO satellites. However, the high orbital velocity of LEO satellites limits their visibility periods from the ground station, and subsequently the time available for QCs, to just few minutes per passage. Conversely, the use of satellites at higher orbits can greatly extend the communication time, reaching few hours in the case of GNSS. Furthermore, QCs could offer interesting solutions for GNSS security for both satellite-to-ground and inter-satellite links, which could provide novel and unconditionally secure protocols for the authentication, integrity and confidentiality of the exchanged signals. For example, a GNSS inter-satellite network for QC has already been proposed to strengthen the security of the Galileo architecture [28]. This would allow the generation of cryptographic keys and the construction of a secure satellite QKD-network, thus preventing the catastrophic consequences of malicious hijacking of GNSS satellites.

Here, we experimentally demonstrate the feasibility of QC between a GNSS terminal and a ground station, over a channel length of about 20 000 km by using current technology. We report on the first exchange of few photons per pulse between two different satellites of GLONASS constellation and the Space Geodesy Centre of the Italian Space Agency in Matera, Italy [29], by exploiting the passive retro-reflectors mounted on the satellites (see figure 1). By estimating the actual losses of such a channel, we can evaluate the characteristics of both a dedicated quantum payload and a receiving ground station, hence attesting the feasibility of QC from GNSS in terms of achievable signal-to-noise ratio (SNR) and detection rate. Our work extends the limit of long-distance free-space single-photon exchange, which was demonstrated so far with a channel length of about 7000 km by exploiting a Medium-Earth-Orbit (MEO) satellite [30].

2. Methods

The experiment presented here was performed at the Italian Space Agency’s Matera Laser Ranging Observatory by using the setup sketched in figure 1. The observatory is a satellite laser ranging (SLR) station equipped with a mode-locked Nd:YVO₄ laser oscillator (ML-laser), operating at 1064 nm with 100 MHz repetition rate and paced by an atomic clock. The SLR pulses (wavelength, 532 nm; energy, ≈100 mJ; repetition rate, 10 Hz) are obtained by selecting one seed pulse every 10² with a pulse-picker (PP), which is then amplified and up-converted via a second-harmonic-generation (SHG) stage. The SLR pulses are sent to the targeted satellites equipped with corner-cube retroreflectors (CCRs) [31, 32] by using the 1.5 m diffraction-limited Cassegrain telescope of the Matera Laser Ranging Observatory (MLRO) [33]. Then, after the reflection by the orbiting terminals, the pulses are collected by a fast analog micro-channel plate detector (Hamamatsu R5916U-50) placed after a polarizing beam-splitter used to separate the transmitted beam from the received one. A dedicated time-tagger with sub-picosecond accuracy recorded the start and stop signals generated by the PP and the detector respectively. The single-shot measurement of the satellite distance is then estimated from the time-difference of these two signals, i.e. the round-trip time, with an error below 20 ps.

A setup dedicated to study the pulse of QC from GNSS was implemented in parallel to the SLR system. The same ML-laser is used to produce an 100 MHz pulse-train with wavelength \( \lambda = 532 \text{ nm} \), ≈1 nJ of energy and 55 ps of pulse duration at full-width-half-maximum (FWHM) by exploiting a SHG stage given by a 50 mm long periodically poled lithium niobate nonlinear crystal from HC Photonics. This beam, synchronized with the SLR pulse-train, is combined with the outgoing SLR pulses by using a 50:50 beam splitter (BS) and the two light beams are sent to the targeted GNSS satellites.
The receiving apparatus of the 100 MHz beam is comprised of a 50:50 BS to separate the outgoing and ingoing beam, a 3 nm FWHM spectral filter (F) with transmission band centered at 532 nm, a focusing lens (L) and a silicon single photon avalanche detector (SPAD), provided by Micro-Photon-Devices, with \( \approx 50\% \) quantum efficiency, \( \approx 400 \) Hz dark count rate and 40 ps of jitter. The time of arrival of the returning photons (tag) is recorded with 1 ps resolution by the time-to-digital converter QuTAG from Qutools.

We implemented a communication protocol to separate the transmitting and receiving phases by using two mechanical shutters. Since the round trip time of photons reflected by GNSS satellites is around 130 ms, the total period of the communication protocol is 200 ms. In the first half, the transmitting (receiving) shutter is open (close) and the 100 MHz pulses are transmitted. Vice versa, in the second half the receiving (transmitting) shutter is open (close) and the 100 MHz pulses coming from the satellite can be detected. In particular, the communication protocol starts with the SLR start signal at \( t = 0 \) ms. The 100 MHz pulses are sent to the satellite from \( t = 0 \) ms to \( t = 100 \) ms, opening the shutter placed in the transmission path. At \( t = 100 \) ms a second SLR pulse is sent to the satellite and after 5 ms the receiving shutter opens the receiving path till \( t = 180 \) ms.

3. Results

3.1. Model of the channel losses

The feasibility of QC from GNSS orbits was experimentally investigated by exploiting two GLONASS terminals equipped with an array of CCRs, namely Glonass-134 and Glonass-131 (Space Vehicle Number: 802 and 747, respectively). We used the two-way scheme already tested with LEO [19] and MEO satellites [30], where a weak source is emulated at the satellite by sending a 100 MHz pulse train towards the orbiting terminals and detecting the returning photons on ground at the MLRO, as sketched in figure 1. Our scheme takes advantage of the SLR technique, in which bright laser pulses sent to CCRs are used to accurately measure the distance of such satellites for geo-dynamical purposes [31, 32]. The detailed description of the experimental setup can be found in the Methods section.

Due to optical diffraction, atmospheric absorption, and the finite sizes of the cross-section and active area of the CCR-array, the beam is attenuated by several orders of magnitude after being retro-reflected. As a result, the reflected pulses have a low mean number of photons \( \mu_{\text{sat}} \) at the satellite, thus emulating a weak source placed on a GNSS terminal orbiting 20,000 km away from MLRO. The mean photon number per pulse \( \mu_{\text{sat}} \) emitted by the simulated source is not known a priori, but it can be estimated a posteriori as \( \mu_{\text{sat}} = R_{\text{det}} / (\nu_{\text{tx}} t_{\text{down}} t_{\text{rx}}) \), by experimentally evaluating the detection rate \( R_{\text{det}} \), the transmittance of the receiving apparatus \( t_{\text{rx}} \), the repetition rate \( \nu_{\text{tx}} = 100 \) MHz of the source and by modeling the down-link transmittance \( t_{\text{down}} \). We will express the losses \( l \) in dB as \( l = -10 \log_{10} t \), where \( t \) is the transmittance. The receiver losses are promptly estimated taking into account the reflection and transmission losses through all the optical elements (8.8 dB) and the quantum efficiency of the detector (3 dB).

The down-link channel losses can be evaluated as the product of the atmospheric transmission \( t_\lambda \) and the geometrical transmission due to diffraction \( t_{\text{diff}} \). We follow two independent approaches for estimating the transmission due to diffraction and compare the results for the validation of the model. The targeted GNSS satellites are part of different generations, GLONASS-K1 for Glonass-134 and GLONASS-M for Glonass-131, both equipped with a planar array of CCRs, with circular and rectangular shape respectively [34]. Their CCRs are characterized by the absence of coating on the reflecting faces, such that the light is back reflected by total internal reflection (TIR). This implies a far field diffraction pattern (FFDP) which is quite different from the simple Airy disk given by a circular aperture [35]. The FFDP of a TIR corner cube has a central Airy-like disk, with 26.4% reduced central intensity peak from the circular aperture with equivalent area, surrounded by six lobes placed on the vertices of a hexagon. The lobes are displaced from the center of the FFDP by \( \theta_{\text{d}} \approx 1.4 \lambda / D_{\text{CCR}} \), with \( D_{\text{CCR}} = 26 \) mm the CCR diameter [36], corresponding to a displacement \( \theta_{\text{d}} \approx 29 \mu\text{rad} \). Since the velocity aberration of GNSS satellite is around 26 \( \mu\text{rad} \) [31], the MLRO telescope is receiving the lateral lobes of the FFDP. In particular, the lateral lobes have an intensity which is \( \approx 30\% \) of the central peak. Since the central intensity peak \( I_0 \) of a circular aperture of area \( A \) depends on the power \( P_0 \) incident on it via \( I_0 = P_0 A / (\lambda^2 R^2) \), with \( R \) the distance from the aperture, the transmission due to diffraction can be evaluated by

\[
t_{\text{diff}} = 0.264 \cdot 0.3 \frac{A_{\text{CCR}} A_{\text{tel}}}{\lambda^2 R^2},
\]

where \( A_{\text{CCR}} \) and \( A_{\text{tel}} \) are the areas of the CCR and the ground telescope, respectively [35].

An alternative approach is given in [30] in which the FFDP is approximated as a top-hat pattern with solid angle \( \Omega \), so that the diffraction transmittance is evaluated as \( A_{\text{tel}} / (\Omega R^2) \). Since the solid angle can be estimated by the array cross-section \( \Sigma \) [31, 37], we have that
3.2. Detection of single photons from GNSS terminals

We provide here a detailed analysis of the data obtained from Glonass-134. The case of Glonass-131, in which we used also a single-photon photomultiplier (PMT) in parallel to the SPAD to compare their performances, is described in the next subsection. In a single passage of Glonass-134, we had two distinct acquisitions separated by almost one hour corresponding to the maximum and minimum distance of the satellite from MLRO. In particular, the first acquisition lasted about 2 min, with mean slant distance of about 20 200 km, whereas the second one lasted about 5 min, with mean slant distance of 19 500 km.

In figure 2 we show the signal detection rate from Glonass-134 for the second acquisition (the results for the first acquisition are analog). The detection rate was estimated in the following way. We divided the whole acquisition in time intervals \( T_k \) of duration \( \tau = 5 \) s. For each interval we made the histogram (see figure 3) of the time difference between the tagged detection \( t_{mea} \) and the expected time of arrival of the photon \( t_{ref} \), estimated from the SLR acquisition performed in parallel [19, 30]. Then, we chose a time window \( w = 400 \) ps centered around \( t_{ref} \), much larger than the detector jitter (\( \approx 40 \) ps) since the retroreflected pulses are temporally spread by the CCR array, and estimated the number of photon detection \( N_{det} \) as the difference of the total and background counts within the window. The background was uniformly distributed within the 10 ns period between two sent pulses (see figure 3), therefore we estimated its rate counting the detections over a time window which is at least 1 ns away from \( t_{ref} \). Finally, the signal detection rate was obtained via \( R_{det} = \frac{N_{det}}{\tau} \) where \( \delta = 0.3 \) is the duty cycle of the communication protocol. Then, we discarded the time windows \( T_k \) with \( R_{det} < 30 \) Hz, to filter out acquisition with low SNR. Such selected time windows gave the integrated histogram shown in figure 3.

At the end of such analysis, we obtained a mean detection frequency \( R_{det} \approx 58 \) Hz, a SNR of 0.53 and mean number of photons at the satellite \( N_{sat} \approx 14.5 \) for the second acquisition of Glonass-134. In the same way we analyzed the first acquisition of the same passage, obtaining a mean detection frequency \( R_{det} \approx 59 \) Hz, a SNR of 0.41 and a mean number of photons at the satellite \( N_{sat} \approx 16.1 \). In this case we used a signal time window \( w \) of 600 ps due to the larger temporal spread. The results are summarized in table 1, along with the acquisition of Glonass-131.

It is worth noticing that we are able to resolve the temporal distribution of the returning pulse given by the particular design of the CCR array, hence revealing the ‘signature’ of Glonass-134 that is equipped with a holed circular CCR array [36], sketched in the left panel of figure 4. If the incident angle \( \theta_i \) with respect to the normal to the array is not zero (see the right panel of figure 4), the pulses reflected by the CCRs closer to the ground station have a smaller round trip time with respect to the further CCRs, resulting in a temporal spread with a

\[
t_{diff} = \frac{\sum \frac{A_{det}}{4\pi \rho A_{RRA} R^2}}{R},
\]

being \( \rho = 0.93 \) the reflectivity of the uncoated CCR and \( A_{RRA} \) the array effective area.

In clear sky conditions, the losses due to atmospheric transmission for the used \( \lambda \) is \( l_\lambda \approx 0.4 \) dB [31] and considering a satellite slant distance \( R \approx 20 000 \) km, the predicted down-link channel losses are \( l_{down} \approx 62 \) dB, from both models equations (1) and (2) to estimate the diffraction losses. This assessment of the channel losses allows us to experimentally estimate \( \mu_{sat} \) by measuring the detection rate, as presented in the following section.

Figure 2. Detection rate from Glonass-134 at 19 500 km slant distance. Each point is calculated integrating over an acquisition time window \( T_k \) of \( \tau = 5 \) s.
characteristic ‘dip’ of the pulse. We simulated the temporal shape of the pulse for incident angles $5^\circ$ and $9^\circ$, corresponding to the incident angles of the two acquisitions, and compared them with the actual data in figure 5. From the simulation, the corresponding temporal peak-to-peak distance is 250 ps and 430 ps for the two acquisitions respectively, in agreement with the experimental estimation. The simulation is performed supposing that the single CCR does not change the temporal shape of the pulse but introduces a temporal offset depending on its position in the array and on the incident angle of the beam. Using a pulse with 100 ps of FWHM and summing up the contributions of all CCRs we obtained the shapes depicted in the figure. It is worth noticing that the continuous lines shown in figure 5 are obtained by such a priori model (adding the measured background) and not by fitting the data.

| Satellite passage | Slant distance (km) | Detector | $R_{\text{det}}$ (Hz) | SNR | $P_{\text{sat}}$ | $l_{\text{down}}$ (dB) | $l_{\text{rec}}$ (dB) |
|-------------------|---------------------|----------|-----------------------|-----|--------------|----------------------|------------------|
| Glonass-134       | 19 500              | SPAD     | 58                    | 0.53| 15           | 62.1                 | 11.8             |
|                   | 20 200              | SPAD     | 59                    | 0.41| 16           | 62.5                 | 11.8             |
| Glonass-131       | 20 250              | SPAD     | 27                    | 0.43| 15           | 62.6                 | 14.8             |
|                   |                     | PMT      | 6                     | 0.21| 16           | 62.6                 | 21.8             |
As shown in the work by Otsubo et al[38], GLONASS flat CCRs array exhibits particular temporal distribution determining higher error in the laser ranging measurement, in which the mean number of photons at the receiver is usually much greater than one. The authors of [38] observed the ‘signature’ of the GLONASS satellites by integrating one year of data acquisition. On the contrary, our result shows that, using single photons detectors and a high repetition source, the temporal distribution of the pulse can be measured, even with a low mean number of photons at the satellite and with short data integration time. A more accurate measurement could be done using a mean number of photons of about one at the receiver, however this is beyond the scope of this work. We note that this measurement could even be used to determine the orientation of the array and hence the attitude of the satellite, which is of critical importance for the processing of GNSS data [32, 39, 40].

3.2.1. Analysis of photons coming from Glonass-131

In the passage of Glonass-131, we used a slightly different receiver setup with respect to the one in figure 1. Instead of using a single receiving detector, we placed a SPAD and a PMT detector (detection efficiency, 10%; active diameter, 22 mm; H7360-02, Hamamatsu Photonics), coupled both to the down-going link with an additional 50:50 BS. In this way we could compare the performances of the two detectors. Using the same analysis described above, we obtained the signal detection rate presented in figure 6. We noticed a good correlation between the signal detection rate of the two detectors, although the PMT shows a much lower rate, since its quantum efficiency is five times lower than the one of SPAD. We then discarded the time windows with low signal detection rate, obtaining two comparable values for the two detectors. The results are summarized in table 1. We noted that the SPAD has about five times the signal rate of the PMT, as expected for the higher quantum efficiency. Also the SNR of the SPAD is two times the SNR of the PMT, since the jitter on the time of arrival of the photons is lower.

3.3. Towards QC from GNSS

Based on these results, we can estimate the performance of a transmitter and receiver needed for the realization of QC from GNSS satellites. For practical QC we target a SNR larger then 100 and a detection rate larger than 10 kHz.

At the receiver, the background affecting the SNR can be significantly reduced with respect to present experiment in a dedicated QC application. In our work, the background was estimated by using the detections distribution on the 200 ms period, which is shown in figure 7 for the passage of Glonass-134 at 19 500 km. The blue bars correspond to the counts in which we expect the transmitted photons to arrive at the detector. This time window starts one RTT from the first transmitted qubit and ends when the receiving shutter is closed. A large part of these counts is due to noise. The intrinsic dark count rate of the detector amounts to $N_{\text{dark}} \approx 700$ Hz. They are estimated in the first 100 ms of the period, when the receiving shutter is closed. This noise could be almost halved, reaching the intrinsic dark count rate of the detector, by optimizing the optical isolation of the detector from the room light. Another source of noise is the fluorescence that occurs when the upgoing SLR pulse passes through the optical elements in common with our optical path. The intensity of the fluorescence light reduces...
exponentially in time with half-life that depends on the material. A remaining tail is included in the blue region and amounts to $N_{\text{fluo}} \approx 195$ Hz. This noise can be eliminated, since this pulse is useless for the protocol and can just be avoided. The remaining, and predominant, detections are due to satellite albedo and background of the field of view. This noise is uniformly distributed in time in the blue region and amounts at $N_{\text{alb}} \approx 1.9$ kHz. By using a bandpass filter of 0.3 nm instead of 3 nm, these background detections would be reduced by an order of magnitude. Moreover, a dedicated receiver would avoid signal losses due to BSs. Indeed the satellite tracking may be done using a different wavelength. With respect to our setup, this would enhance the signal by a factor of 4, although correspondingly augmenting $N_{\text{alb}}$. Adopting these solutions at the receiver we expect a SNR and a detection rate raised of a factor 10 and 4, respectively.

Regarding the transmitter, we consider an active source on the satellite with a mean photon number per pulse close to 1. Compared to the current result, this involves a signal reduction of about a factor 15. However, the down-link coupling efficiency can be greatly enhanced by using an appropriate telescope. We consider a down-going beam with 10 $\mu$rad of angular aperture, shrinking the beam spot on ground and using a point-ahead technique to compensate for velocity aberration as recently demonstrated in [25]. This would reduce the diffraction losses of 20 dB with respect to the channel losses estimated above. The temporal spread due to the reflector array would not be present, allowing for a narrower temporal filter $\tau$ that could be chosen considering
only the jitter of the detector (≈40 ps). Moreover, with 40 ps jitter, the repetition rate could be increased to more than 1 GHz, thus enhancing the detection rate. With these expedients, the expected SNR and detection rate are of the order of 100 and 10 kHz, respectively.

4. Discussion

This work demonstrates the first exchange of few photons per pulse ($\mu_{\text{sat}} \approx 10$) along a channel length of 20 000 km, from Glonass-134 and Glonass-131 to MLRO, reaching a SNR about 0.5 and a detection rate around 60 Hz. We evaluated the requirements needed for a transmitter mounted on a GNSS satellite and a ground receiver for the realization of QC between the two terminals. Our findings demonstrate that QC from GNSS satellite is feasible with current state-of-the-art technology.

Extending QC to GNSS is of primary importance for secure communications at the global scale, as discussed above, but it is also a resource for fundamental tests of physics in space [9]. Indeed, QC from satellite opens the possibility of testing the foundations of quantum mechanics in the space scenario, as envisaged in theoretical studies [41] and mission proposals [42–45], and already realized in actual implementations [23, 24, 46] at the LEO distance. A channel length of over 20 000 km could enable the design of new experiments that test the validity of quantum mechanics at higher orbits and permits the use of satellites following highly elliptical orbits. Such orbital characteristics might be of key importance to observe gravity-induced effects on quantum interference [47–49], that could shed light on the interplay between general relativity and quantum mechanics, thus validating physical theories and placing bounds on phenomenological models. Concluding, our results pave the way for new applications of quantum technologies and fundamental experiments of physics exploiting QC from high-orbit satellites, which may be implemented on next-generation GNSS constellations.

Acknowledgments

We would like to thank Francesco Schiavone, Giuseppe Nicoletti, and the MRLO technical operators for the collaboration and support. We acknowledge the International Laser Ranging Service (ILRS) for the satellite data. LC and FV acknowledge the Center of Studies and Activities for Space (CISAS) ‘Giuseppe Colombo’ for financial support. Our research was partially funded by the moonlight-2 project of INFN.

Competing interests

The authors declare that they have no competing financial interests.

Author contributions

GV, PV conceived and supervised the experiment. LC, CA, DD, FV, MS, AS designed and tested the optical setup. All authors took part in the data acquisition at MLRO. LC, CA, analyzed the data. All authors contributed in discussing the results and writing the manuscript.

Data availability

Data supporting the findings of this study are available from the corresponding author upon request.

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