

Satellite-based Quantum Information Networks: An assessment of Hong-Ou-Mandel interferences as a core effect for quantum teleportation and swapping

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ABSTRACT

With the deep understanding of single quantum objects and multi-partite entanglement, quantum devices such as sensors, computers and cryptographic encoder/decoders are now reaching the engineering level. Quantum Information Networks (QIN) will enable the interconnection of these devices and make their already promising applications even more powerful. The role of these networks will be to offer entanglement of remote quantum devices using Quantum Repeaters (QR) as relays, made-up of Entangled Photon Sources (EPS), Bell-state Measurement (BSM) devices and Quantum Memories (QM). In ground networks, the optical propagation losses encountered in optical fibres can be overcome by repeaters which relay entanglement through the swapping process. On long-distance links, satellite-based solutions possess a power-law advantage over ground fibered networks in terms of optical link budget and reach.

In this study, we considered a simplified QR link without QM, using a space segment with an EPS on board a satellite and a BSM in the Optical Ground Station (OGS). As two-photon BSM architectures rely on the Hong-Ou-Mandel (HOM) interference between a photon coming from a pair emitted by the satellite and a second photon emitted on ground, we focused on the study of this effect with a fibre optic demonstrator. To simplify the optical layout, we implemented only two Weak Coherent States (WCS) sources, representing respectively the photon transmitted from the satellite and that emitted on ground. The in-depth understanding of the HOM effect and its dependency on time, frequency and polarisation allowed us to assess the performance of satellite-to-ground quantum teleportation and entanglement swapping. Particular attention was paid to the synchronisation aspects, with the extensive study of two different synchronisation strategies: the optical distribution of a dedicated synchronisation signal directly from the satellite and a GNSS-based method. In practice, perfect optical distribution of a synchronisation signal was emulated by the distribution of an RF clock between the two sources, while the GNSS-based synchronisation approach used two GPS receivers connected to a common antenna.

The visibility of the HOM effect was studied experimentally in both configurations. We concluded that dedicated optical synchronisation can offer superior performance while GNSS synchronisation may suffer from limitations for nanosecond optical pulses. The paper will report on these achievements and findings in more detail, which we consider as an important step towards teleportation and quantum swapping, key functions of future global quantum information networks by satellite.

Keywords: Quantum Information Networks, Satellite, Bell-State Measurement, Hong-Ou-Mandel, Quantum Repeaters, Synchronisation.

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1. INTRODUCTION

1.1.SATELLITE-BASED QIN ARCHITECTURE

QIN architectures are a thriving topic in the quantum information community [1,2]. Generally speaking, QIN are made up of nodes (often called Quantum Repeater Nodes, QRN) combining Entangled Photon Sources (EPS), Bell-State Measurement (BSM) devices and Quantum Memories (QM) [3, 4]. Long-distance connections on ground are achieved using optical fibres in the telecombands, with typical losses of 0.2 dB/km .

On the other hand, the link budget of satellite Free-Space Optical (FSO) connections scales as

$$\frac{P_{R_x}}{P_{T_x}} \propto \left(\frac{\pi D_{R_x} D_{T_x}}{4\lambda L} \right)^2, \quad (1)$$

with the subscript T_x (R_x) corresponding to the emitter (receiver), P the optical power, D the telescope diameter, λ the optical wavelength and L the distance between the satellite and the Optical Ground Station (OGS) [5]. For end-users' distances typically above 100km, direct satellite connections thus provide higher transmission rates than optical fibres.

When designing the satellite segment of the QIN, two main constraints have to be taken into account.

The first one is linked to the limitations in Size, Weight and Power (SWaP) of the equipment a satellite payload can embark. This constraint rules out architectures where the BSM devices of the QIN are placed on-board the satellite. Indeed, these devices rely on Single Photon Detectors (SPD). Today, the most efficient type of SPD are Superconducting Nanowire SPD (SNSPD), which require cryogenic cooling in the 1K temperature range and are thus very challenging to embark. Moreover, efficient QM technologies are either based on cryostats for Rare-Earth doped ions, or on complex and high-SWaP apparatuses for cold atoms and trapped ions, ruling them out too for integration into the satellite payload [6].

The second constraint is due to the fact that uplink Free-Space Optical (FSO) connections are more prone to losses than downlinks, typically by a factor of 10 in the optical link power budget. The reason is that the turbulence induced by the atmosphere occurs in the first few tens of kilometres above the Earth surface, while the rest of the propagation channel is basically vacuum. In uplink, these turbulences induce a beam wandering, with a strong negative impact on the link budget. In downlink, the atmosphere disturbances only induce wave front deformations, which can be corrected by an Adaptive-Optics (AO) assembly.

Combining these two constraints leads to defining satellite-based QIN nodes with EPS on-board, and to placing BSM and QM on the ground segment. A simplified architecture of such a network is represented in Figure 1.

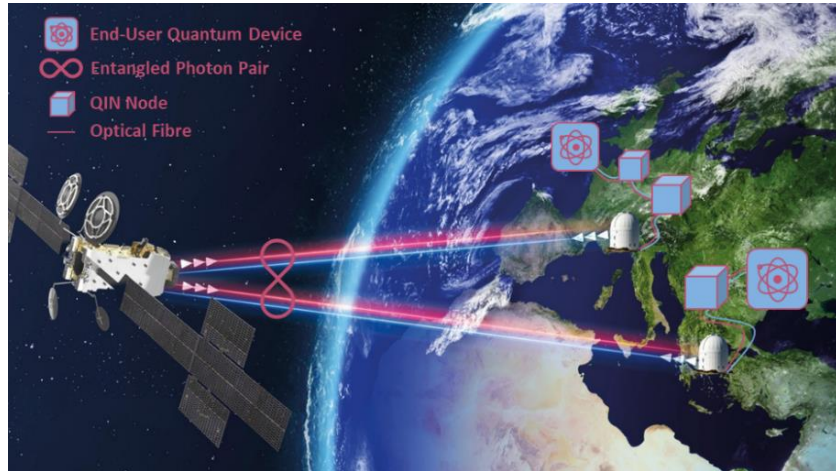


Figure 1. Simplified architecture of a QIN including space and ground segments. Entanglement generated by EPS is propagated through satellite FSO and ground optical fibre links. QIN nodes include EPS, BSM and QM. Red lines correspond to qubits, while blue ones include all the auxiliary channels such as synchronization signals, polarisation references, etc.

1.1. PROOF-OF-CONCEPT (POC)

As part of this work, we develop an embryonic QIN space segment demonstrator. To end up with a fully fibered optical testbed at telecom wavelength, we greatly simplify the above architecture by making several assumptions, considered valid for a Proof-Of-Concept (POC) demonstration of such a satellite system. First, we remove the QM, as their maturity is still quite low and their cost is too high to be included in a mid-term project. This simplification leads to the schematic of the POC sketched in Figure 2.

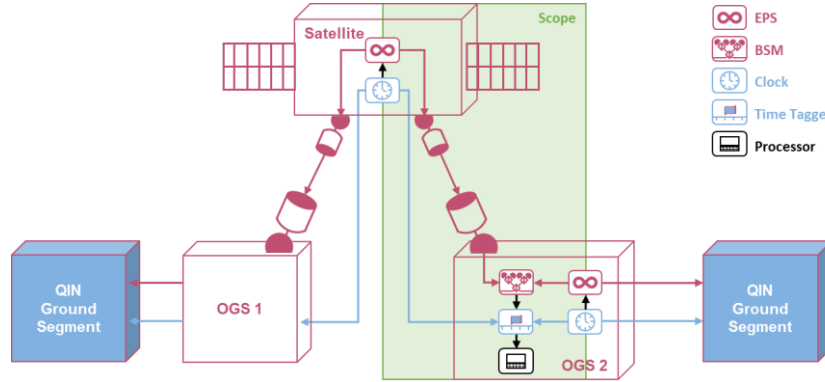


Figure 2. POC demonstrator without QM, including a satellite containing an EPS and a clock and two OGS with dedicated quantum receivers.

In this picture, the BSM device is assumed to be a passive 2-photon polarisation BSM apparatus. The simplest way of implementing this element is to use a combination of Beam-Splitters (BS) and Polarising Beam-Splitters (PBS). The physical principle behind the projection onto the Bell-State basis is based on the so-called Hong-Ou-Mandel effect [7]. If all the degrees of freedom of the two incoming photons are identical, they will bunch on the BS if they have similar polarisations. Post-selecting the right correlation events at the BS output then allows to project the incoming photons on one or two of the four Bell states [8, 9]. The second simplification thus consists in reducing the BSM device to a simple BS.

Finally, the third and final simplification consists in considering only the two photons interacting on the BS. In our experiment, we then forget about the two other photons in Figure 2, directed towards the OGS 1 and QIN ground segment. This last assumption allows us to work with attenuated laser sources instead of EPS to emulate the on-board and ground sources. The resulting HOM testbed is represented in Figure 3.

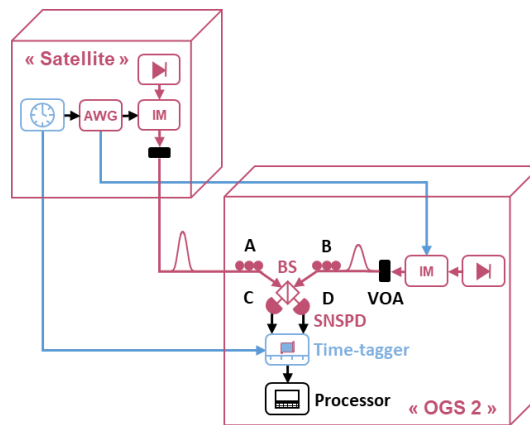


Figure 3. Optical layout of the HOM testbed.

AWG: Arbitrary Wave Generator, IM: Intensity Modulator, VOA: Variable Optical Attenuator.

2. HONG-OU-MANDEL EFFECT WITH PULSED COHERENT STATES

2.1. EXPERIMENTAL SETUP

First demonstrated in 1987 by the 3 physicists Chung Ki Hong, Zheyu Jeff Ou and Leonard Mandel, the HOM effect is a quantum interference between two photons impinging on each input port of a 4-way BS [7]. As the photons are bosons, if all their degrees-of-freedom are strictly identical, the two-photon wave function symmetrisation implies that they will go out in the same output port, even though this port is chosen randomly. Studying the correlation between the detections in the BS output ports with SPD thus reveals the existence of the effect, as depicted in Figure 3.

In a satellite-based QIN, the interference between downlink and ground photons can be affected by 4 types of impairments: timing jitters due to synchronisation imperfections, frequency mismatch due to laser drifts and Doppler effect, polarisation alignment issues and link budget variations. In this work, we have studied the dependency of the so-called HOM dip, *i.e.* the reduction of the coincidences between the output ports, as a function of the arrival time delay and frequency offset between two attenuated optical pulses, as well as their mean photon number ratio.

To generate the pulses, we use two telecom C band lasers at 1545nm: one temperature/current controlled Distributed Feedback Laser (DFB) and a tuneable external cavity laser. The frequency offset between the lasers is preliminary matched and then let free-running. This offset Δ can be tuned by changing the optical frequency of the external cavity laser. The intensity of each laser is then carved by a Mach-Zehnder interferometer modulated by one output of a common Arbitrary Wave Generator (AWG). This setup allows to control the arrival time delay δ between the two coherent states. Moreover, the internal clock of the AWG serves as a time reference for the time-tagger. Figure 4 shows the intensities of the optical signals obtained with this testbed for a repetition period of 30ns and a Full Width at Half Maximum (FWHM) of 2.5ns.

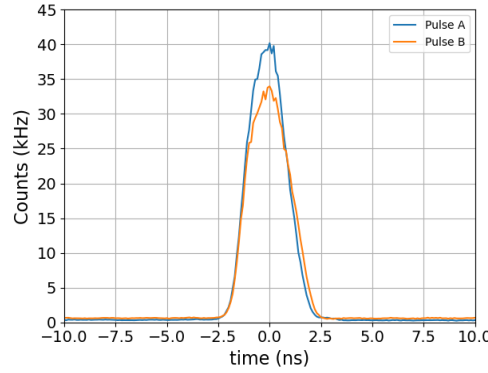


Figure 4. Optical intensities of the two pulses measured with SNSPDs.

Taking the normalised square root of the optical pulses shown in Figure 4 allows to define the wave function amplitudes $\epsilon_A(t)$ and $\epsilon_B(t)$ for the coherent states respectively incoming on ports A and B of the BS. The complete wave functions of these states are then expressed as

$$\xi_{A,B}(t) = \epsilon_{A,B}\left(t \mp \frac{\delta}{2}\right) e^{-i\left(\omega \mp \frac{\Delta}{2}\right)t}, \quad (2)$$

where ω stands for the central frequency of the lasers, δ for the time delay and Δ for the frequency offset between the two pulses [10]. The field operator corresponding to the annihilation of a photon in these ports writes

$$E_{A,B}^+(t) = \xi_{A,B}(t)a_{A,B}, \quad (3)$$

The BS transformation between the output C and D ports with respect to the input A and B ports gives

$$\begin{cases} E_C^+(t) = \frac{1}{\sqrt{2}} [-iE_A^+(t) + E_B^+(t)] \\ E_D^+(t) = \frac{1}{\sqrt{2}} [E_A^+(t) - iE_B^+(t)]. \end{cases} \quad (4)$$

In this experiment, we have worked with a low mean photon number $\mu_A = 0.02$. In this regime, only the events with a total of two photons, either incoming on the same input port or one for each port, are relevant for the coincidence calculation. The most important term for the HOM effect is the interference between a photon arriving at input port A and one at B, producing detections at the output port C at time τ_0 and D at $\tau_0 + \tau$. For an input state $|\psi_{in}\rangle = a_A^\dagger a_B^\dagger |00\rangle$, it is defined as

$$\begin{aligned} P_{CD}^{11}(\mu_A, \mu_B, \tau, \tau_0, \delta, \Delta) &= \langle \psi_{in} | E_C^-(\tau_0) E_D^-(\tau_0 + \tau) E_D^+(\tau_0 + \tau) E_C^+(\tau_0) | \psi_{in} \rangle \\ P_{CD}^{11}(\mu_A, \mu_B, \tau, \tau_0, \delta, \Delta) &= \langle \psi_{in} | E_C^-(\tau_0) E_D^-(\tau_0 + \tau) E_D^+(\tau_0 + \tau) E_C^+(\tau_0) | \psi_{in} \rangle. \\ P_{CD}^{11}(\mu_A, \mu_B, \tau, \tau_0, \delta, \Delta) &= \langle \psi_{in} | E_C^-(\tau_0) E_D^-(\tau_0 + \tau) E_D^+(\tau_0 + \tau) E_C^+(\tau_0) | \psi_{in} \rangle. \end{aligned} \quad (5)$$

The different contributions P_{CD}^{kl} with k photons in C and l in D are then weighted by the probabilities P_{AB}^{mn} that m photons arrive at port A and n photons at port B, given by

$$P_{AB}^{mn}(\mu_A, \mu_B) = \mu_A^m \cdot \mu_B^n \cdot \frac{e^{-(\mu_A + \mu_B)}}{m!n!}. \quad (6)$$

The coincidence probability, called P_c , results from the weighted probabilities of events containing 2 photons in total and integrated over τ_0 .

2.1. HOM DIP MEASUREMENT

The normalised coincidences on SNSPD¹ C and D as a function of the time delay between the optical pulses is represented in Figure 5.

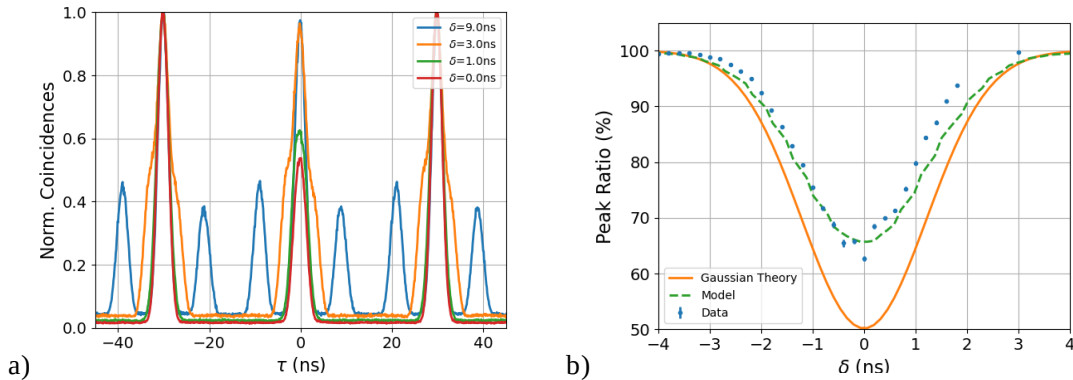


Figure 5. a) Normalised coincidences as a function of the tagger delay τ for different optical pulses delays δ , with a mean photon number ratio $\frac{\mu_A}{\mu_B} = 1.1$. b) HOM dip defined as the ratio of the central peak over the lateral ones. The orange curve represents an analytical Gaussian approximation, and the green dotted curve is a model based on the experimental wave functions.

The results of Figure 5.b show that our model, taking into account the actual wave functions and background noises of the experiment (limited by straight light in the laboratory), correctly reproduces the experimental results. The Gaussian

¹ Quantum efficiency $\geq 80\%$, dark count rate 10Hz, RMS jitter 30ps.

theory is computed without any noise on the detectors and shows a well-known maximum HOM dip visibility of 50%. The dip as a function of the frequency difference between the two lasers is represented in Figure 6.

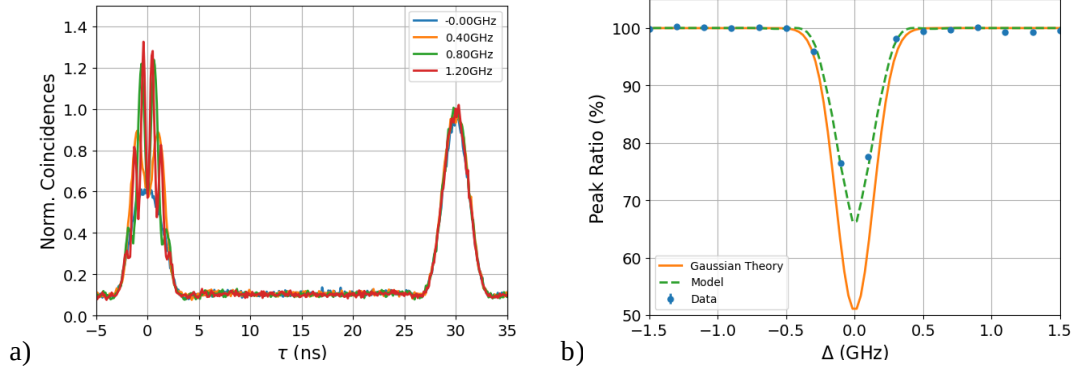


Figure 6. a) Normalised coincidences as a function of the tagger delay τ for different optical pulses frequency shifts Δ for a mean photon number ratio $\frac{\mu_A}{\mu_B} = 0.8$. b) HOM dip in frequency.

Interestingly, as the time-tagger resolution ($200ps$) is smaller than the pulses width, we observe a frequency beat note inside the central peak of Figure 6.a. The lateral peaks, produced by photons arriving 30 ns apart, do not interfere and only show the amplitude wave functions overlap. The resulting dip in Figure 6.b is obtained by integrating the central and lateral peaks and computing their ratio. It is only sensitive to the pulses frequency overlap, Fourier limited to 400 MHz FWHM. The beat note frequency stability between the two lasers was typically around 100MHz over 1 second.

Finally, we have performed a HOM dip visibility analysis as a function of the photon ratio $R = \frac{\mu_A}{\mu_B}$. In the final system, EPS will have a different statistics than the Poissonian photon number distribution of coherent states, but this study is still interesting for use cases such as teleportation between an EPS and a coherent state. The visibility, calculated with the correlation probabilities P_c , is defined as

$$V(\mu_A, \mu_B) = 1 - \frac{\int_{-\infty}^{+\infty} P_c(\mu_A, \mu_B, \tau, 0, 0) d\tau}{\int_{-\infty}^{+\infty} P_c(\mu_A, \mu_B, \tau, +\infty, +\infty) d\tau}. \quad (7)$$

The results for a set of experimental photon number ratios are shown in Figure 7.

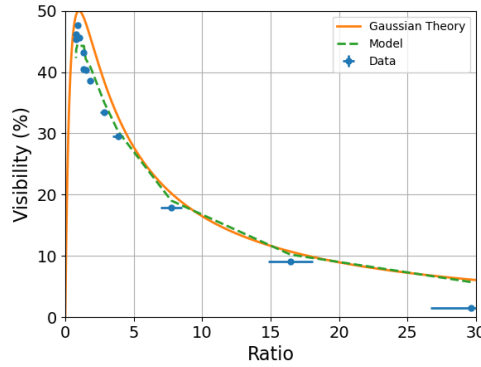


Figure 7. HOM dip visibility as a function of the mean photon ratio between the two coherent states for $\delta = 0 \pm 0.1ns$ and $\Delta = 0 \pm 100MHz$. Data points (blue dots), theoretical curve obtained with Gaussian pulses (orange line) and model (green dotted curve) taking into account the experimental wave functions and noises.

The theoretical visibility obtained with Gaussian coherent states (represented by the orange line in Figure 7), reaches the maximum of 50% as it is computed without any back-ground noise. The green dotted line, corresponding to our model,

is very close to the Gaussian curve shape as the actual pulses wave functions are almost Gaussian, but the visibility is reduced due to experimental noises. We still achieve a maximum of 47.5%. The slight discrepancy between the data points and the models are probably due to the fact that the photon number ratio estimation, based on the experimental wave functions integration, can be biased.

3. GNNS SYNCHRONIZATION EVALUATION

The final test to evaluate the effectiveness of synchronizing the two optical pulses consists in assessing the visibility of the HOM effect in real time over several minutes. Two operating modes are compared. The first is a direct synchronization of the two Synchro Tx modules via a wired connection between the 10 MHz output of one and the reference input of the other. This latter module then itself serves as the reference for the timer. The second synchronization mode uses the GPS system, with two GNSS receivers used as a reference for each Synchro Tx module. Once again, the output of the second Synchro Tx module also serves as a reference for the timer, as would be done in the ground station of the final system. The GNSS operating mode is illustrated in the diagrams of Figure 8.

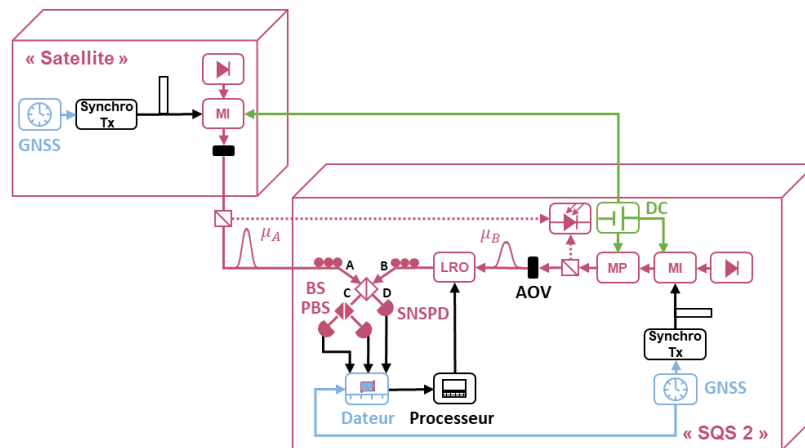


Figure 8. Optical layout of the HOM testbed in GNSS synchronization mode. The two GNSS receivers are independent but connected to the same antenna.

The direct synchronization mode serves as a reference for comparing with GNSS synchronization. In a satellite system, this direct mode would be implemented, for example, using a modulated or pulsed optical signal transmitted from the satellite to the ground. This configuration would thus introduce additional detection errors compared to the physical wired connection possible tested in the laboratory. However, such a system has the advantage of directly measuring and compensating for propagation time delays without additional calculations, whether these delays are atmospheric or due to components in the chain. In the GNSS synchronization mode, a compensation for the photon propagation time is necessary. This compensation can be calculated using the precise ephemerids of the satellite. Regarding the performances, short-term stability ($<1\text{s}$) depends on the reference clocks of each receiver, while long-term stability is corrected by the navigation system at a rate of 1Hz .

The visibility of the HOM effect for different pulse widths in GPS synchronization mode is represented in Figure 9.a, while the direct mode is represented in Figure 9.b. A comparison of these two modes is given in Figure 9.c.

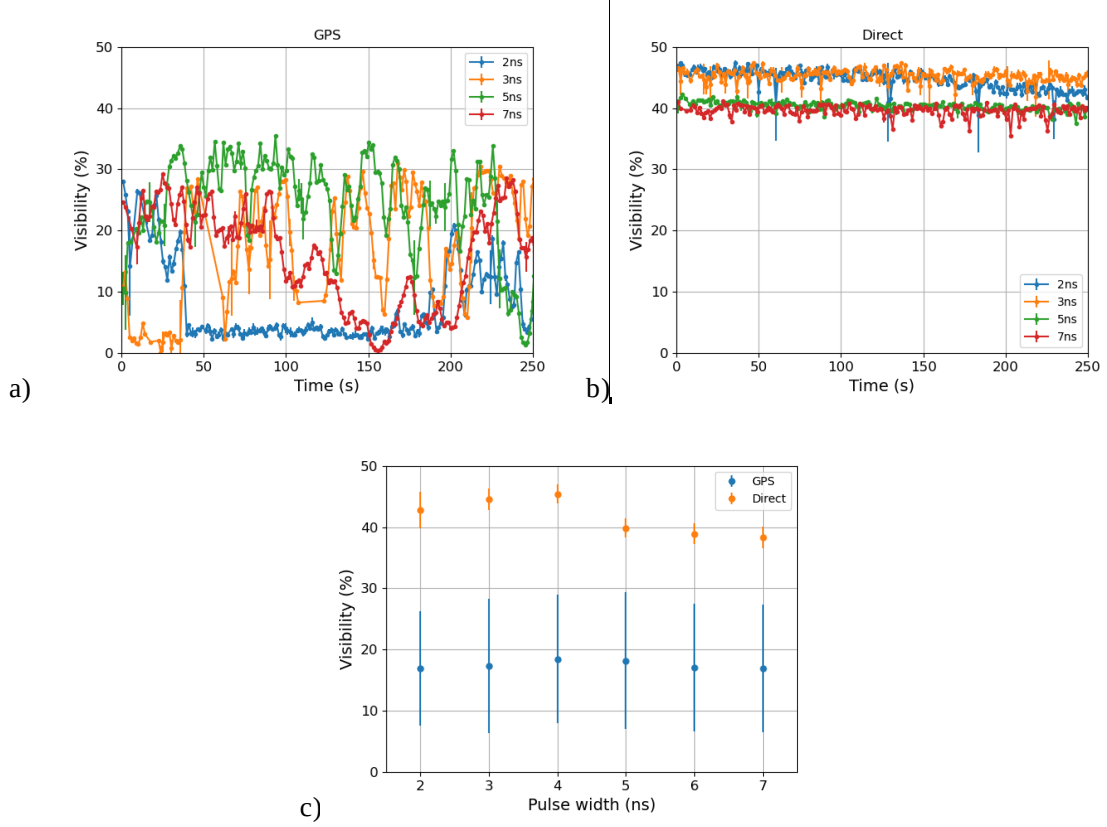


Figure 9. Real-time visibility of the HOM dip in a) GPS and b) direct synchronization mode for four different square pulses widths. c) Mean values in GPS (blue) and direct (orange) modes. The error-bars represent standard-deviations of 250s.

The long-term results in Figure 9.b demonstrate a maximum visibility of $45.4 \pm 1.5\%$, with a slow long-term drift probably due to laser frequency shifts. On the other hand, the visibilities with GPS synchronization represented in Figure 9.a fluctuate between 0 and 35%. These results show that GPS synchronization, combined with the internal clocks performances of the GNSS receivers used in this experiment, is not sufficient to ensure the synchronization of pulses narrower than 10 ns.

4. CONCLUSION

We have reported on a set of preliminary POC experiments that allowed us to assess a simplified architecture for a future satellite-based QIN system. The results on the HOM effect between the equivalent of a satellite payload-emitted photon and a ground source photon reveal the dependency on the arrival time, the frequency offset and the mean photon number ratio of the two pulses. In the final system, we expect a higher visibility when considering entangled photon pairs instead of WCS, as the statistics will be different.

Moreover, two modes of time synchronization between the optical pulses were assessed. In a direct synchronization mode, used as a benchmark, the two sources were synchronized through a 10MHz reference signal fed from one emitter to the other by a coaxial cable. We obtained a high and stable HOM visibility of $45.4 \pm 1.5\%$, compared to the 50% theoretical maximum for WCS sources. In a second synchronization mode using two independent GPS receivers connected to a common satellite antenna, we showed that the long-term stability is not sufficient to synchronize square optical pulses narrower than 10ns. This work paves the way to a QIN demonstration by satellite in the next decade.

ACKNOWLEDGEMENTS

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