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Event: SPIE Optical Engineering + Applications, 2021, San Diego, California, United States

Invited Paper

Goals and feasibility of the Deep Space Quantum Link

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ABSTRACT

In this article, we review the proposed experiments for the Deep Space Quantum Link (DSQL) mission concept aiming to probe gravitational effects on quantum optical systems. Quantum theory and general relativity are the two most successful frameworks we have to describe the universe. These theories have been validated through experimental confirmations in their domains of application— the macroscopic domain for relativity, and the microscopic domain for quantum theory. To date, laboratory experiments conducted in a regime where both theories manifest measurable effects on photons are limited. Satellite platforms enable the transmission of quantum states of light between different inertial frames and over distances impossible to emulate in the laboratory. The DSQL concept proposes simultaneous tests of quantum mechanics and general relativity enabled by quantum optical links to one or more spacecrafts.

Keywords: Quantum Optics, Foundational Quantum Theory, General Relativity.

1. INTRODUCTION

Recently, satellite-based quantum experiments and applications have witnessed unprecedented growth spanning from fundamental physics to experimental demonstrations and technological development, including the launch and operation of the first quantum satellite, Micius,[1] by the Chinese Academy of Science. These groundbreaking

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Quantum Communications and Quantum Imaging XIX, edited by Keith S. Deacon, Ronald E. Meyers,
Proc. of SPIE Vol. 11835, 118350J · © 2021 SPIE · CCC code: 0277-786X/21/$21 · doi: 10.1117/12.2593986

results have spurred an international space race[2] involving university consortia, national agencies, and private companies, including QEYSSat (Canada),[3] UK–Singapore Bilateral (RAL Space—CQT),[4] and IOD-6/ROKS (UK).[5] A comprehensive review on the latest status of the field can be found in ref.[6]

The maximum range over which QM was directly tested was an experiment carried out using the Micius spacecraft, which resulted in quantum optical teleportation and Bell tests across a 1200 km baseline.[1,7] This distance is insufficient to observe significant general relativistic effects[*] under the Earth gravity conditions. Much larger distances, as well as stronger variation of the gravity potentials, are required to get insight on the unification of quantum mechanics and general relativity. The experimental configuration was not designed to observe predicted relativistic impacts on quantum measurements. The most successful framework to describe these phenomena is given by Quantum Field Theory in Curved Space-time (QFTCST).[8,9] Current observations are compatible with QFTCST (e.g., the scale-invariant spectrum of CMBR predicted by inflation model, the Casimir effect, and the circular Unruh effect) but they do not constitute a direct test. DSQL could provide the first direct test of QFTCST.

The Micius spacecraft was also used to probe an alternative theory to QFTCST,[10] predicting coupling new between quantum states and curved spacetime (the "Event operator formalism").[11] However, the experiment was not able to observe this newly proposed effect. This has led to a re-parametrization of the event-operator formalism, which now predicts a much smaller effect. This and other alternative theories to QFTCST (see for example ref.[12–14]), if true, would profoundly modify physics but have only been tested partially. Precise measurements of their predictions would be valuable even to provide upper bounds, or disprove, the proposed coupling mechanisms.

DSQL[15–18] study efforts are focused on exploring QFTCST in the weak-field regime, using quantum optics in space. The regime where both quantum optics and general relativity manifest non-trivially is defined by the sensitivities of available instrumentation. Satellites allow access to long transmission baselines, large relative velocities, and large difference of gravitational potentials not achievable using laboratory experiments. Practically, given today's state-of-the-art quantum optical light sources and detection systems, these effects should be measurable directly across spacecraft-to-earth links.

DSQL experiments are built on three pillars: Test of the Einstein equivalence principle, long-baseline Bell test, and long-baseline teleportation. These experiments require the distribution of quantum states and their uniquely quantum correlations i.e., entanglement, over extremely long distances. This is a set of challenging technical tasks, which need to be overcome to develop a global quantum network. Therefore, the technological developments required to perform these fundamental physics experiments will also pave the way for the implementation of the future quantum internet.[19]

In the rest of this proceeding, we review the proposed set of the experiments, highlighting possible critical requirements and the future technology development to achieve them. More details on the DSQL mission architecture and road-map can be found in ref.[17]

2. PROPOSED EXPERIMENTS

2.1 GR Effects on Light and Tests of the Equivalence Principle

The Einstein equivalence principle is at the heart of every metric theory of gravity, such as general relativity.[20] It involves several different aspects. One of them is the *Weak Equivalence Principle* (WEP), according to which all test masses fall with the same acceleration in a gravitational field. A second one is the *Local Position Invariance* (LPI), states that "the outcome of any local non-gravitational experiment is independent of where and when in the universe it is performed".

The LPI can be tested by using identical frequency standards subject to different values of the gravitational potential, where the LPI implies the *redshift* and the frequency variation are linked to the gravitational potential variation via the formula:

$$\frac{\omega_2 - \omega_1}{\omega_1} = (1+\alpha)\frac{U_2 - U_1}{c^2}, \tag{1}$$

[*]Beside of course GPS corrections.

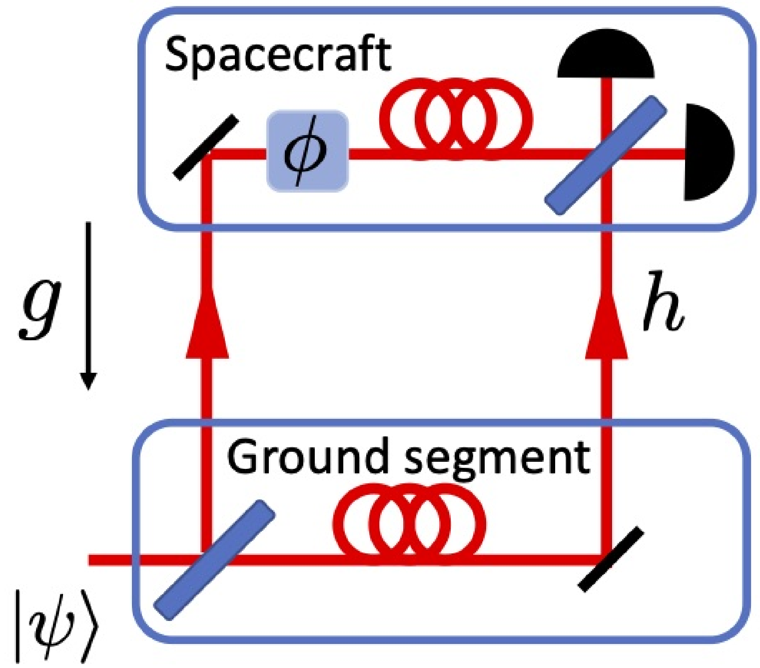

Figure 1. Schematics of the optical Colella, Overhauser and, Werner experiment. An input state $|\psi\rangle$- a coherent state, a single photons state, or half of an entangled state- is fed into a Mach-Zhender interferometer. The horizontal arms of the interferometer can be replaced by fiber coils so they can be located in both the space and the ground segments.

where $\omega_{1(2)}$ and $U_{1(2)}$ are the frequency and and gravitational potential at location 1 (2). The parameter α is equal to zero for general relativity. The goal of this experiment is to measure possible deviation of α from such a value and therefore possible violations of general relativity.

To do so, one can envisage an experiment as shown in Fig. 1. Here, a quantum particle is injected into an interferometer whose upper and lower arms are subject to different gravitational potentials. As a consequence of the LPI there is a gravitationally induced relative phase shift ϕ between the two paths that will be imprinted on the quantum state of the particle:

$$\phi \sim (1+\alpha)\frac{2\pi}{\lambda}\frac{ghl}{c^2}. \tag{2}$$

Here, λ is the vacuum wavelength of the source (measured at $h=0$), l is the optical delay line (including any index of reflection), g is the acceleration of gravity at altitude h, and c is the speed of light.

Such a phase shift can be measured using the counts statistics at the two detectors. The first quantum interferometry measurement sensitive to the gravitational field was performed by Colella, Overhauser and, Werner[21] employing neutrons. However, that experiment and more recent ones based on light-pulse atom interferometry[22,23] test the WEP, but not LPI, which can be probed instead with recently proposed interferometry schemes involving atomic clock states.[24]

Recently, a test similar to that depicted in Fig. 1 has been proposed using photons.[25] Assuming a low Earth orbit platform and 1 km of fiber, the magnitude of the effect is a few radians. Furthermore, the magnitude of the relative phase increases with the altitude, though so do the losses, leading to an optimization of the orbital parameters, to achieve the best sensitivity given the available classical and quantum optical capabilities. Note that a unique capability of a satellite-based experiment is the opportunity to measure over sufficient altitude variations that the variation of the gravitational acceleration g is no longer negligible.

There are numerous challenges associated with these experiments for example, the compensation of the first-order Doppler effect due to the relative motion of the satellite and the ground station. A technique to correct for this was recently proposed in ref.[25,26] Furthermore, this experiment poses strict requirements on the stabilization of fiber coils: any mismatch in their length should be minimized in order to not compromise the phase measurement.

It is important to stress that the original Colella, Overhauser and, Werner experiment was conducted on massive particles in a regime where it can be described using Newtonian gravity. The use of photons requires the use of general relativity to describe the effects on the state of the quantum system, so this new experiment would be a genuinely simultaneous test of quantum theory and general relativity.[27]

2.2 Long-Baseline Bell Test

Entanglement is a uniquely quantum correlation by virtue of which joint quantum systems can be fully described only using a non-separable joint quantum state. Entangled states are at the heart of the violation of the Bell inequality implying that quantum mechanics is incompatible with hidden-variable theories.[28] Quantum mechanics and its most credited extension to the relativistic domain i.e., QFTCST, predict that entanglement essentially persists at any length scale, provided the quantum system at hand is protected from its environment. Photons are excellent candidates for long-baseline tests because of their limited interaction with the environment compared to other particles.

The empirical violation of Bell inequality is one of the biggest successes of quantum science and has been performed with increasing precision and scope, for example, by closing first the locality loophole,[29] then the detection loophole,[30] and finally both of these simultaneously.[31–33] Currently, the longest-range violation of the Bell inequality is over a distance of 1200 km, obtained by the quantum satellite Micius.[30] It is fundamentally important to test the persistence of entanglement and therefore the validity of quantum mechanics and QFTCST over longer and longer baselines. Disentanglement due to some interaction with the space-time structure could in principle produce detectable traces in a Bell test. The aim of DSQL is to conduct Bell tests over increasing distances in a series of experiments, culminating with one at the Earth-Moon distance. Besides the expected confirmation of the predictions of quantum mechanics and QFTCST, this will also allow us to assess a number of more exotic theories predicting detectable influences on entangled quantum states by the space-time features.[11–14]

Efficient entanglement distribution will also be required to operate global quantum networks, enabling, for example, quantum communications with un-trusted nodes at a global distance. DSQL will thus build up technical capabilities that will enable the development of the future quantum internet.

Finally, approaching the baseline length of the order of the Earth-Moon distance results in a propagation time long enough to allow for human involvement in the Bell test, a similar test has been proposed in[34] . Such distances will allow for a latency of the order of a second, allowing for the basis decision from each experimenter to be made outside of the light-cone of the created entangled photon and the other experimenter, and thereby addressing the freedom of choice loophole.[35,36] To achieve this, one could place the entangled state source in some convenient mid-point between the Earth and the Moon, as shown in Fig. 2. The experimenters located near the Earth and on the Moon, possibly in the Lunar Gateway, would have sufficient time to perform the basis choice in the Bell test.

An Earth-Moon link is a good estimation of what state-of-art technology can currently achieve. This link will be subject to extreme link losses (as high as 90 dB for a one-way link). To compensate for this, an exceptionally bright, high-fidelity entangled photon source with a pair production rate of the order of 10^8 pairs per second[17] this experiment could also benefit from further development in photonic quantum memories, as one photon could be stored locally and the other sent away.[24] In order to improve the signal-to-noise ratio and achieve a statistically significant Bells' inequality violation, exceptional time tagging capabilities will be required.

2.3 Long-Baseline Teleportation

The third class of the proposed experiments are long-baseline teleportation[37] and entanglement swapping.[38] Teleportation is a quantum protocol that does not have any classical analog, where an unknown quantum state is transmitted between two users using a maximally entangled state and a classical communication channel as resource, as shown in Fig. 3. Entanglement swapping is a modification of quantum teleportation that can be used to distribute entanglement between distant parties; the particle to be teleported is itself already entangled

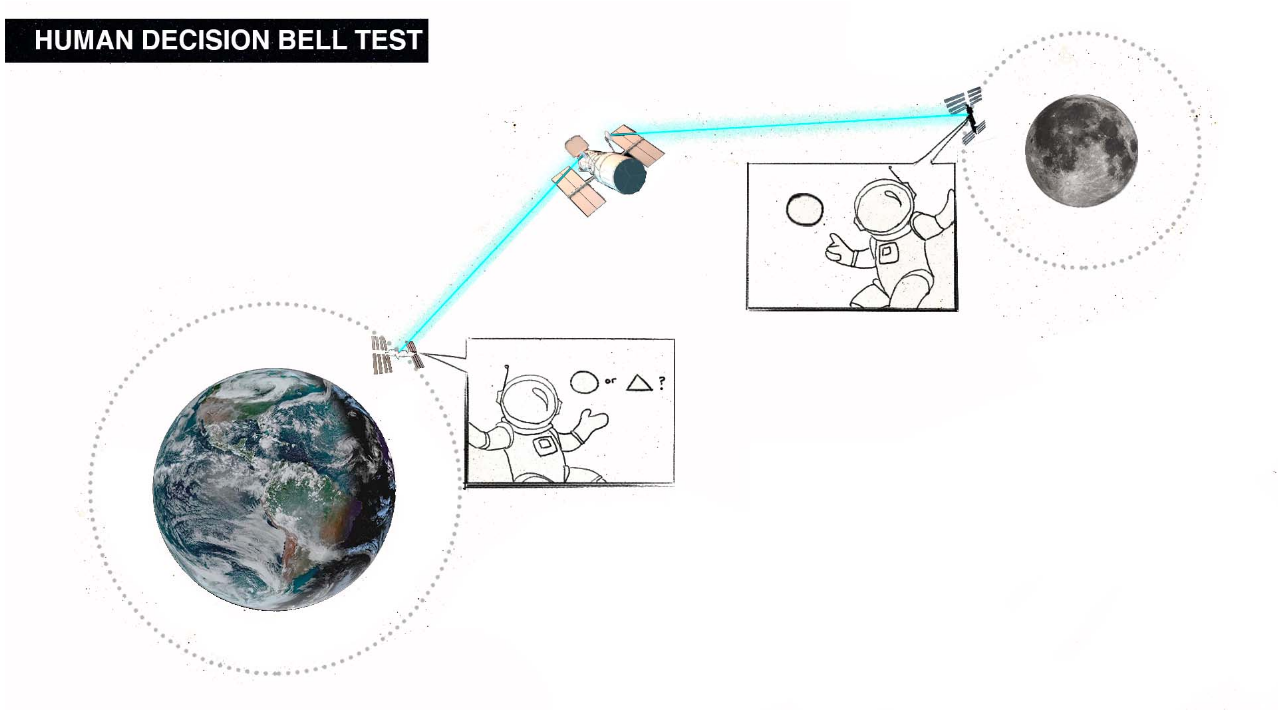

Figure 2. Schematic of a possible implementation of a Bell test with human involvement. The source is located midpoint between the Earth and the Moon e.g., in a Lagrangian point, and the two measurements are performed in the proximity of the Earth and the Moon.

with another particle. Also in this case, standard quantum theory does not predict any limitation in the range of validity of these protocols.

Teleportation was initially demonstrated about two decades ago first in the laboratory[39] and soon after over long ranges outside the laboratory.[40] Since then, experiments have been refined and the ranges have been pushed up to 1200 km using Micius,[7] although this implementation was "passive" as the last operation of the protocol was performed post-selecting the data; also, the source to be teleported and the entanglement source were in fact collocated, so there is no actual benefit to communication application with this configuration.

Testing these protocols at increasing distances and in the presence of general relativistic effects, like the gravitational redshift, will improve our understanding of the interplay between gravity and quantum mechanics. Besides this relevance for fundamental physics, the development of long-distance teleportation and entanglement swapping capabilities will serve as pathfinder for the deployment of a global space-based quantum network harnessing the promised power of quantum communication, sensing, and computing. For example, entanglement swapping could also be used as a resource to enable multi-party quantum communication and to improve the sensitivity of networks of clocks.[41]

It is important to note that efficient entanglement distribution over planetary scale cannot be achieved only by ground-based infrastructures. In fact, the unavoidable losses of fiber networks prevent the distribution of entanglement at a non-negligible rate at distances above a thousand kilometers and this is likely to remain true even if one leverage on realistic future development of quantum repeaters operations. A first remarkable milestone would thus be to achieve teleportation over a range of the order of the Earth's diameter, followed by teleportation over a distance of the order of a geostationary orbit (because of its role in the classical telecommunication infrastructure). Finally, a teleportation experiment between the Earth and the Moon would allow a test of the scenario where the experiment events are space-like separated i.e., their order depends on their reference frame.[42] This experiment would be extremely difficult, not only due to the extreme losses, but also because of the requirement of quantum memory with a storage time of the order of the light propagation time between the Earth and the Moon ($\sim$ 30 s), in order to complete the protocol without post-selection. Memories with such

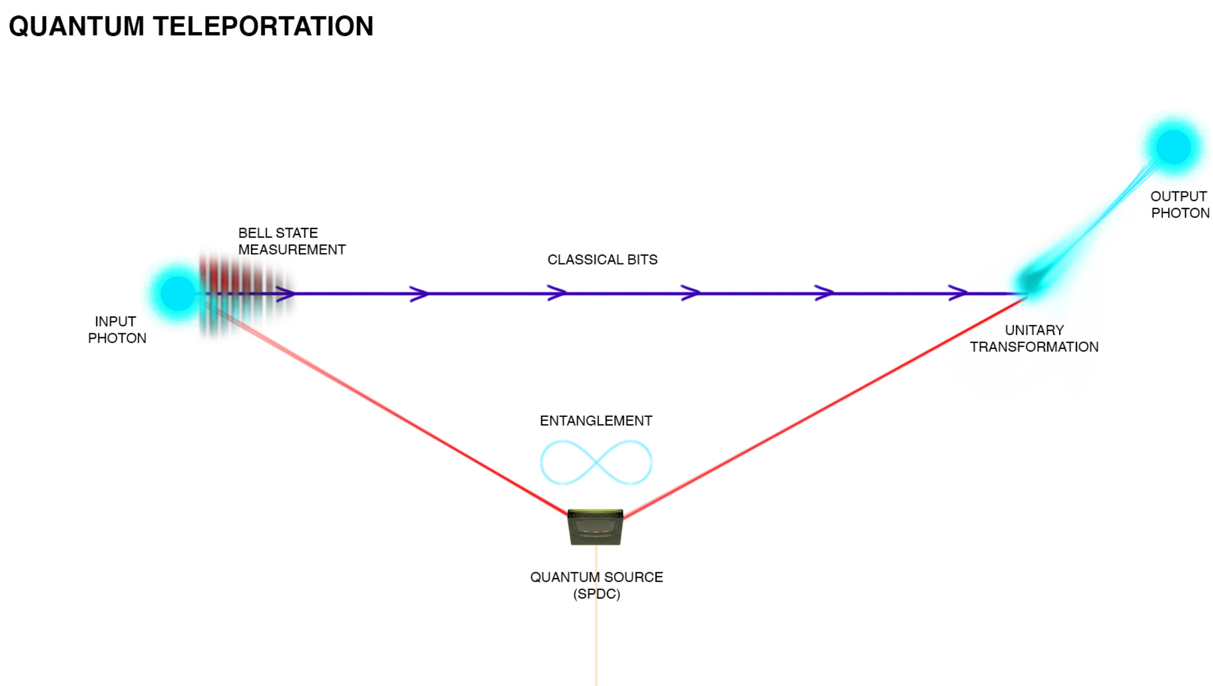

Figure 3. Illustration of the quantum teleportation protocol. An entangled pair is produced, part of the entangled state is sent to Alice and the other to Bob. Alice coherently mixes her part with the unknown state to be teleported and performs a Bell state measurement on the joint state. Alice communicates the result of the Bell measurement via the classical channel to Bob, who can recover the unknown input state performing a unitary transformation based on Alice's outcome.

storage time are still in their infancy. However, shorter-lived memories could be used as a temporary storage to improve the entanglement distribution rate over a global quantum network.[43]

3. CONCLUSIONS AND FUTURE DIRECTIONS

The Deep Space Quantum Link concept proposes to perform a number of quantum optics experiments at the interface of quantum mechanics and general relativity. These experiments have the potential to shed new light on the interplay between these two well-established theories in the framework of QFTCST, and to address alternative frameworks. These experiments include the optical COW experiments, Bell tests, and teleportation and entanglement swapping. The long-baseline regime that is considered cannot be addressed by ground-based experiments and will require the deployment of space-based platforms ranging from low Earth orbit to a Moon orbiter such as the Lunar Gateway.

Beside the relevance for fundamental physics, these activities will spearhead the development of the first global quantum networking capabilities. In fact, the realization of these space-based experiments presents a number of technology challenges requiring top performance in terms of entangled photon production rate, pointing and time synchronization capabilities, and detection efficiency. As mentioned, the use of future photonic quantum memories could enhance the performance in the ground and space segment. Furthermore, the development of ground infrastructure such as large telescope apertures—of the order of one meter and above—will be required. More details on the DSQL mission architecture and road-map can be found in.[17]

4. ACKNOWLEDGMENTS

The research was performed at the Jet Propulsion Laboratory, California Institute of Technology under a contract with the National Aeronautics and Space Administration's Biological and Physical Science Division (0NM0018D0004).

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