DEEP SPACE QUANTUM LINK. M. Mohageg, D. Strekalov, S. Dolinar, M. Shaw, and N. Yu, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 298-102, Pasadena, CA, 91109. Makan.Mohageg@jpl.nasa.gov (818) 354-0843.

Introduction: The Deep Space Quantum Link (DSQL) will perform pioneering experiments on gravitational effects on quantum systems, test the basic assumptions of quantum optics theory, and demonstration of quantum key distribution (QKD) at deep space distances.

Background: Quantum optical communications is an emerging space-based technology that could potentially increase the information capacity of communications networks by 100% [1], and provide fundamentally secure communication links between trusted nodes within the network with QKD [2]. Demonstrations of LEO-earth and GEO-earth quantum channels published by European and Chinese agencies have proved the maturity of the underlying technology [3, 4]. The proposed orbits of the Deep Space Gateway (DSG) spacecraft provide a unique avenue to test the effects of both extreme range and gravity on the quantum channel. The tests enabled by DSQL by virtue of the orbit of DSG, are important from the perspective of both fundamental physics and deploying a future quantum communication infrastructure.

Objectives: The scientific objective of DSQL is to test the coupling of General Relativity, the physics most often associated with cosmology, with Quantum Field Theory, the physics of wave-particle duality. The DSQL will perform three experiments. The results of these three tests will represent the first direct probe of how general relativity affects quantum particles. These scientific results, in addition to answering a fundamental question of modern physics, will facilitate the design of future quantum communications missions.

*Experiment A—Quantum Teleportation***.** Entangled photons are a set of photons that are governed by a single wavefunction. Pairs of entangled photons are generated by DSQL, then transmitted to distant receivers designed to recover the quantum state. The transmitter and the receiver will be at different inertial reference frames, at different gravitational potential. The untested theory that describes the proportion of entangled particles between inertial frames predicts that the single particles will undergo changes due to both the mutual acceleration, and the curved spacetime between the transmitter and receiver [5, 6, 7]. Gravity is expected to modulate the fidelity of the particle entanglement. Because of its proximity to the Lagrage point, DSG provides an access to a unique set of inertial reference frames with strongly varying gravitational potential. Because of that, a measurable change in the fidelity of teleported quantum states is expected. The DRO, ELO, NRHO, and HALO orbits available to DSG will result in sensitivity to gravitational effects higher than that of an earth-orbiting spacecraft. The theory predicts that the LLO orbit will have reduced sensitivity.

Experiment B—Bell Test. Experiment B will test for violations of Bell's Inequality by using quantum teleportation. Successful teleportation will prove that quantum wavefunctions are non-local: that a single wavefunction can be used to describe two particles nominally separated by the earth-moon distance. The longest distance Bell's Inequality test to date was conducted over 1600 km between Delingha, China, and the low earth orbiting satellite Micius [4]. The DSG enabled experiment will be the first ever test of Bell's Inequality where the local curvature of the spacetime between transmitter and receiver is predicted to impart a measurable signature upon the teleported state. Conducting the 'Bell Test' experiment along different points of the DSG Distant Retrograde Orbit will allow increased sensitivity to the gravitational effects. Other proposed orbits of DSG will result in an improved Bell Test compared to what is possible with an earth-orbiting satellite (Fig. 1.) By virtue of the distances travelled, this Bell Test will eliminate the freedom-of-choice loophole inherent in ground based tests. A human-operated Bell's Test conducted by astronauts onboard the DSG would test the foundational concept of Local Realism in quantum measurement [8].

Experiment C—Quantum Communication. Experiment C will establish a primitive quantum communication link between DSQL and a ground station. Monitoring the net quantum bit error rate will test the integrity of a free space quantum communication channel that traverses a curved spacetime.

Quantum communication systems surpass classical communication systems performance by adding quantum resources. The ultimate information capacity of an efficient quantum channel is double that of an equivalent classical channel. QKD protocols can provide a fundamentally secure information channel that is immune to eavesdropping. Ground-to-ground fiber-optical quantum links that are longer than a few hundred kilometers apart are ineffective due to fiber losses; a free space link through an orbiting satellite is required for long-range ground interconnects [2]. For these reasons, future quantum communication systems will be space-based. The effects of gravity on the quantum channel must be experimentally measured.

It is predicted that the ultimate quantum bit-error-rate (QBER) of a quantum information channel depends on the spacetime curvature and mutual acceleration between transmitter and receiver. Theory predicts that transmission from any of the proposed DSG orbits will result in twice the sensitivity to QBER modulation compared to earth orbiting satellites (Fig. 2). This prediction will be tested in Experiment C.

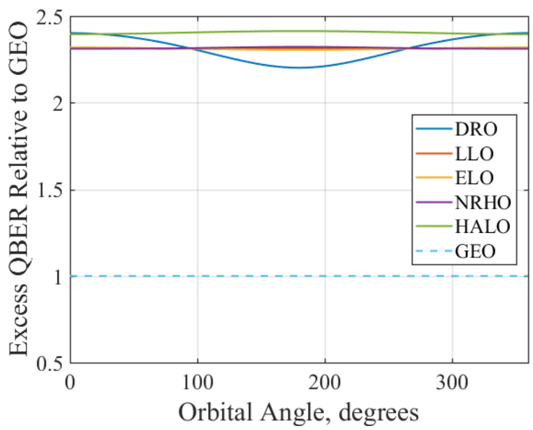

Figure 1

Variations on the experimental setups can be applied to directly probe causal-relationships between quantum detection events. Interestingly, the Copenhagen Interpretation predicts a result for measurably different than the Many Worlds Theory of quantum mechanics. This difference is only reconciled by validating causality in quantum measurement [9] for space-like and time-like separated detectors. This test will be a subset of Experiments A, B, and C.

Instrument Concept: *Size, Weight, and Power:* The DSQL will consist of a source of entangled photons and a source of single photons that also produces squeezed light. It will also have an array of single photon detectors and associated optical conditioning circuits and read-out electronics. Transmission will be accomplished through use of an external gimballed telescope and up to six classical optical links (lasers) used for pointing, tracking, and acquisition. Successful execution of the tests listed above requires an earth-based ground station or an auxiliary satellite to serve as a receiver. The size, weight, and power consumption of the DSQL is estimated based on comparison to similar technology under development at JPL, namely subsystems designed for the Deep Space Atomic Clock and the Cold Atomic Laboratory. The current estimate is 1-cubic meter volume, 190-220kg total mass, with 300W-400W power draw while operating. The DSQL system can be located either inside or outside of the DSG spacecraft—though the gimballed telescope is required to be on the outside.

Photon Source: Successful execution of the experiments requires a narrow bandwidth, high repetition rate source of entangled photons. JPL has pioneered the development of such sources [10]. Broadband sources, which would be required for LEO probes of gravity-quantum coupling [9] have orders of magnitude lower production rate.

Preferred Orbits: All orbits allow execution of the three proposed experiments. The orbits are ranked as follows: (1) DRO, (2) NRHO, (3) HALO, (4) ELO, and (5) LLO. Orbits (1)-(4) are preferred for DSQL. Orbit (5) reduces sensitivity in Experiments A and B. Line of sight time to the receiver will limit all experiments.

Astronaut Involvement: Astronauts onboard the DSG could participate in science experiments of the Bell Test by picking random numbers to define instrument settings during operation per [8] to overcome the pseudo-random number loophole inherent of earlier long range Bell Tests [4] and resolve potential human factors in quantum measurements.

Cost Estimate: The DSQL is based on technology that has been proven to work in space missions. Still, it would represent one of the most complicated optical systems ever flown. The cost for the instrument and ground station is estimated by comparison to similar subsystems developed at JPL: Deep Space Optical Communications, Cold Atomic Laboratory, and Deep Space Atomic Clock. A rough cost estimate is $100M for program planning purpose.

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