



Towards satellite tests combining general relativity and quantum mechanics through quantum optical interferometry: progress on the deep space quantum link

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Abstract

The Deep Space Quantum Link (DSQL) is a space-mission concept that aims to explore the interplay between general relativity and quantum mechanics using quantum optical interferometry. This mission concept was formally presented to the United States National Academy of Science Decadal Survey as a research campaign for Fundamental Physics in 2022. Since then, advances have been made in the space-based quantum optical technologies required to conduct a DSQL-type mission. In addition, other research efforts have defined alternative measurement concepts to explore the same scientific questions motivating the DSQL mission. This paper serves as an update to the community on the status of the DSQL mission concept and related research and technology development efforts.

Keywords: Quantum Optics; Quantum Networking; Fundamental Physics; Quantum Interferometry

1 Introduction

1.1 Quantum mechanics and general relativity

One of the grand challenges of contemporary physics is to reconcile general relativity (GR) with quantum mechanics (QM) [1]. These two theories precisely describe nature across a wide spectrum of laboratory and observational measurements. Quantum field theory in curved spacetime (QFTCST) is the best theoretical framework that explains observations made to date while maintaining consistency with other phenomena [2–6]. QFTCST may be inductively advanced through a narrow regime of astrophysical and analog-model observations [7–9].

These observational experiments would be complemented by controlled experiments that directly explore the physical effects of QFTCST in the weak-field regime [10, 11]

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available to us in our solar system. Quantum optical interferometry experiments involving satellites could explore the regime in which both relativistic and quantum physical processes are predicted to simultaneously influence the measurement outcome. In this article, we describe the nature of these experiments. While these experiments would certainly help us to better understand the interplays of GR and QM, we point out that these are not experimental tests of “quantum gravity” ($Q \otimes G$), where gravity is non-perturbatively quantized [12]. They are better thought of as tests of Quantum $\oplus$ Gravity, when two titans coexist and their possible contradictions are magnified, especially in the light of quantum information issues [13, 14]. These experiments belong to the realm of gravitational quantum physics [15], where many experiments have been proposed for the exploration of gravitational effects in atomic-molecular-optical and condensed matter systems.

There is a further subtlety that many experiments that combine QM and gravity can be explained using quantum mechanics and *Newtonian* gravity [16–18]. This subtlety creates a gap in our ability to design an experiment that unambiguously combines QM and *general relativity*, GR. For example, ongoing laboratory experiments and pioneering demonstrations that explore gravitational effects using quantum-mechanical sensors, such as atomic interferometers and quantum bouncers [19], are adequately explained with a Newtonian model for gravity [20, 21]. The earliest demonstration of such a process was the evolution of neutron phase under free-fall (the Collella-Overhouser-Werner or COW experiment) [22, 23]. The COW experiment is also an example of a quantum process coupled to the dynamics of Newtonian gravity.

While the focus of this article is on purely photonic techniques to explore the interplay between GR and QM, there are other approaches. One proposed direct experimental approach to observe relativistic effects in quantum systems is the realization of quantum-clock interferometry experiments [17, 24], where various components of a delocalized quantum superposition experience different gravitational time dilation [25, 26].

Additionally, proposed experiments that aim to teleport the quantum states of large molecules [27] offer an important window into alternative theories to GR and QM using massive particles, with photonic quantum states used as an intermediary. One such approach is to create matter superposition states governed by weak-field gravity [28]. Experiments with molecules of up to $25kDa$ have been carried out [29], and further experiments have been proposed [30, 31]. These and other high-mass interference experiments could yield insights into the interplay between GR and QM [32], as well as alternative theories.

The Deep Space Quantum Link (DSQL) [33] is a proposed space mission to conduct direct tests of the coupling between GR and QM. Unlike existing or proposed experiments using massive particles, the DSQL experiment will use various quantum photonic states in a long-baseline quantum optical interferometer. The quantum interferometers, which are described later in this article, are spread out between Earth and space, or between two or more satellites occupying different orbital heights and therefore different gravitational potentials. The arms of the interferometer are necessarily connected with free-space optical (FSO) channels. Photons propagate along the FSO interferometer arms following null geodesic trajectories. The underlying spacetime curvature determines the overall phase accumulated along that path. The resultant quantum interferogram for the DSQL is predicted to exhibit fringes driven by general relativistic processes. The leading GR effect contributing to the interference is the gravitational redshift. In COW experiments, for comparison, the proper time along the two arms of the COW interferometer is the same

[33], resulting in observable interference fringes that cannot be related to redshift alone. Furthermore, with increased sensitivity, other general relativistic effects may be evident in long-range quantum interferometry [34].

1.2 DSQL history and related research efforts

The DSQL concept was first proposed in 2018 [35]. Later that year, at the NASA Fundamental Physics Workshop, DSQL was one of the topics highlighted in a session dedicated to fundamental science enabled by entanglement. In 2019, NASA formed a science definition team (SDT) to define a DSQL mission concept. Over the course of two years, the SDT formulated over 30 separate experiments that a future DSQL mission could support. The findings of the SDT were published in the open literature [33]. The highest priority experiment recommended by the SDT was the long-baseline quantum interference driven by gravity. A DSQL satellite mission concept was submitted to the United States National Academy of Science Decadal Survey for Fundamental Physics in 2021.

The DSQL SDT recognized a technology gap that needed to be addressed before any space-based DSQL experiment could be credibly proposed, and accordingly, created a technology development roadmap required for the DSQL mission. Some technology development priorities identified by the SDT include precision time transfer protocols compatible with quantum communications, enhanced robust satellite entanglement sources and single-photon detector systems, quantum memories, and developed stabilization systems for quantum optical interferometry. An ensuing DSQL technology development program helped advance critical technologies to the point where today, the key building blocks for a DSQL mission have been demonstrated in a laboratory environment (TRL3+).

The quantum optical time synchronization required for a DSQL-type mission has been achieved through DSQL program [36] and through other research endeavors. A robust time synchronization system suitable for tracking the extreme Doppler shifts associated with a LEO-to-LEO flyby was emulated in the laboratory [36]. In parallel, and unrelated to the DSQL project, other high performance time synchronization systems for quantum communications protocols were demonstrated [37–40] by other groups not affiliated with DSQL.

To address the needs for a highly robust, space-qualified entangled photon pair source and detector system, the SEAQUE mission was started as an outgrowth of the DSQL project, supplemented with funding from JPL's Space Technology Office, and later, Boeing [41]. The SEAQUE mission, launched in November 2024, deployed an integrated optical entangled photon pair source and Bell test apparatus on an external payload of the International Space Station. SEAQUE's single-photon detector array is conditioned through periodic thermal and laser annealing to counteract radiation-induced dark counts.

Independent international initiatives outside of NASA's DSQL effort also aim to study the intersection of QM and GR using space-based quantum optics experiments. A broad survey of these types of goals was published by Rideout in 2012. ESA's proposed "SPACE-QUEST" mission [42, 43] is a proposal to implement space-based quantum optics experiments. The Micius mission [44] from the QUESSE research campaign conducted a test of the "event operator formalism" [45]. The event operator formalism is a proposed non-linear extension of quantum field theory that predicts a measurable effect on quantum optical propagation. A joint JPL-Caltech team evaluated high-performance low-jitter superconducting nanowire single-photon detector (SNSPD) based receiver systems for lunar-to-Earth range quantum communication with a laboratory emulator of effects predicted

by the event operator formalism theory [46]. Another study conducted a lunar-to-Earth emulated quantum link [47].

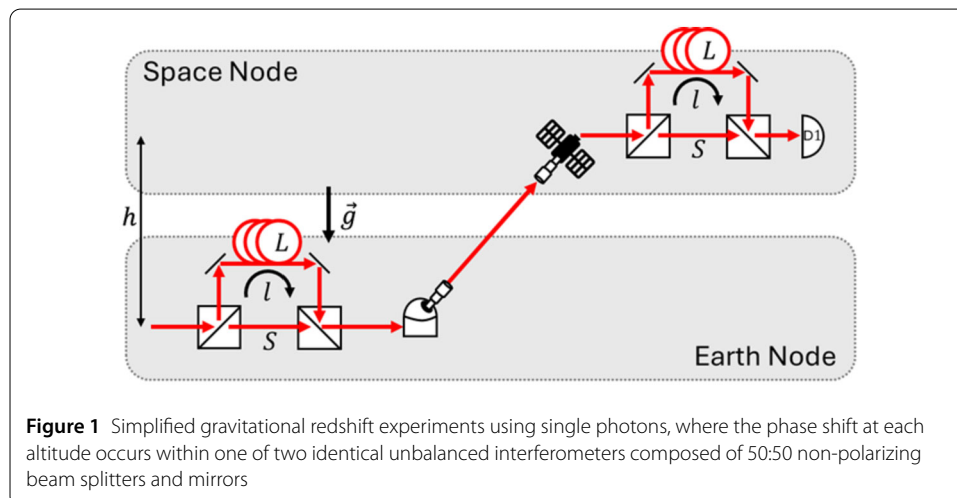
Recently, multiple advances in quantum interferometric techniques that are at the heart of long-range quantum interferometry experiments have been made. These achievements are referenced and described below.

In summary, the DSQL concept was developed and matured through the participation of an international team of quantum technologists and researchers. A coordinated technology development campaign followed, and resulted in measurable advances against technology maturation requirements for the future mission. A quantum optics space mission launched in November 2024, SEAQUE, originated from the DSQL program as part of the technology development effort. Outside of the DSQL initiative, other independent efforts to conduct similar experiments are ongoing. In the sections that follow, we summarize the general mathematical framework for DSQL-like measurements outlining the concept of the DSQL space mission. We also provide a brief review of the non-DSQL efforts to conduct experiments with synergistic goals, concluding with an outlook for the future.

2 Experimental framework

A simple scheme for measuring the effects of the gravitational redshift on single photons, and the one proposed for use in the DSQL, is shown in Fig. 1. The probe photon travels first through a terrestrial unbalanced Mach-Zehnder interferometer (MZI), and is emitted in a time-bin superposition based on whether the photon traveled the long path L or the short path S , with total delay $l = L - S$. This superposition state is then transmitted vertically through free space to a satellite node containing a second interferometer of similar construction. If the two paths are recombined on a final 50:50 beamsplitter, interference is observed between the two processes in which the probe photon took exactly one of the long paths in the terrestrial interferometer or the satellite interferometer.

The input photonic quantum state can, in principle, be arbitrarily polarized. Careful selection of an appropriate polarization state would facilitate measurement. For example, by preparing the probe photon to be diagonally polarized and utilizing polarization-maintaining optics and fibers in each interferometer, one may guarantee that if the photon took the short (long) path in the initial interferometer, it would take the long (short) path in the space-based interferometer.



Since the two interferometers are held at different gravitational potentials, the photon, with the time spent in each optical delay line acting as a clock variable, will acquire a relative phase shift due to the gravitational redshift [48] (see Appendix B of [49] for full derivation):

$$\Phi_{GR} = \frac{2\pi l}{\lambda} \frac{U(h_2) - U(h_1)}{c^2} + O\left(\frac{v^3}{c^3}\right) \quad (1)$$

The corresponding altitude difference of measurement in Fig. 1 is $h = h_2 - h_1$, the interferometer length mismatch l is defined above, and λ is the wavelength of the light. Rewriting the gravitational potential using the altitudes of the two interferometers h_1 and h_2 , gravitational constant G , mass of Earth M_e , and radius of Earth R_e yields

$$\Phi_{GR} = \frac{2\pi l}{\lambda c^2} G M_e \left(\frac{1}{R_e + h_1} - \frac{1}{R_e + h_2} \right) + O\left(\frac{v^3}{c^3}\right) \quad (2)$$

The parameterized post-Newtonian GR effects are in the third order in v .

This result is obtained by calculating the propagation of the photonic wave packets along the delay line in each interferometer arm as well as the long baseline between the ground station and the spacecraft, using, for example, the methods employed in [50], and determining the small time differences between the two interfering wave packets at each exit port. If a single-photon detector is placed at one of the output ports of the final beam splitter, the accrued phase shift will be observed as a change in relative detected-photon flux according to

$$P = \frac{P_0}{2} (1 + \cos(\Phi_{GR} + \Delta\Phi)) \quad (3)$$

with P_0 the total number of photons incident at the beamsplitter, and $\Delta\Phi$ the phase error associated with uncorrected noise in the system and uncompensated special relativistic effects.

A key feature of the proposed architecture is the independence of the interferometer system on a specific photon source. This allows the system to simultaneously measure the effects of GR on classical and quantum states of light, providing a direct comparison. Further, it opens the possibility to use the interferometers to study the interplay between gravity and more exotic states of light, including entangled photon pairs. For example, frequency-entangled photons can be employed; that is, pairs of the form

$$|\Psi\rangle = \frac{1}{\sqrt{2}} (|\omega_1\rangle|\omega_2\rangle + |\omega_2\rangle|\omega_1\rangle) \quad (4)$$

with ω_1, ω_2 the frequencies of the two photons. This frequency entanglement leads to a sinusoidal two-photon-interference fringe [51] within the Hong-Ou-Mandel dip [52]:

$$P_c = \frac{1}{2} (1 + \cos((\omega_1 - \omega_2)\Delta\tau) e^{-2\sigma^2 \Delta\tau^2}) \quad (5)$$

where σ is the bandwidth of the photons, and $\Delta\tau$ is the temporal delay between the two photons as they arrive at the final 50:50 beamsplitter. This measurement relies on two-photon interference, a uniquely quantum phenomenon, while the factor driving the vis-

ibility derives from GR. Note that the photon interference is robust against unbalanced loss and background noise.

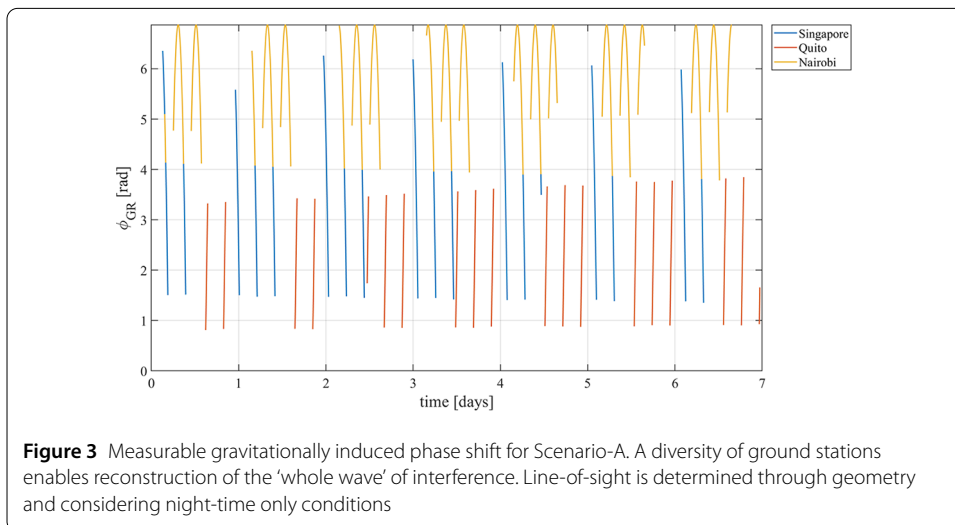
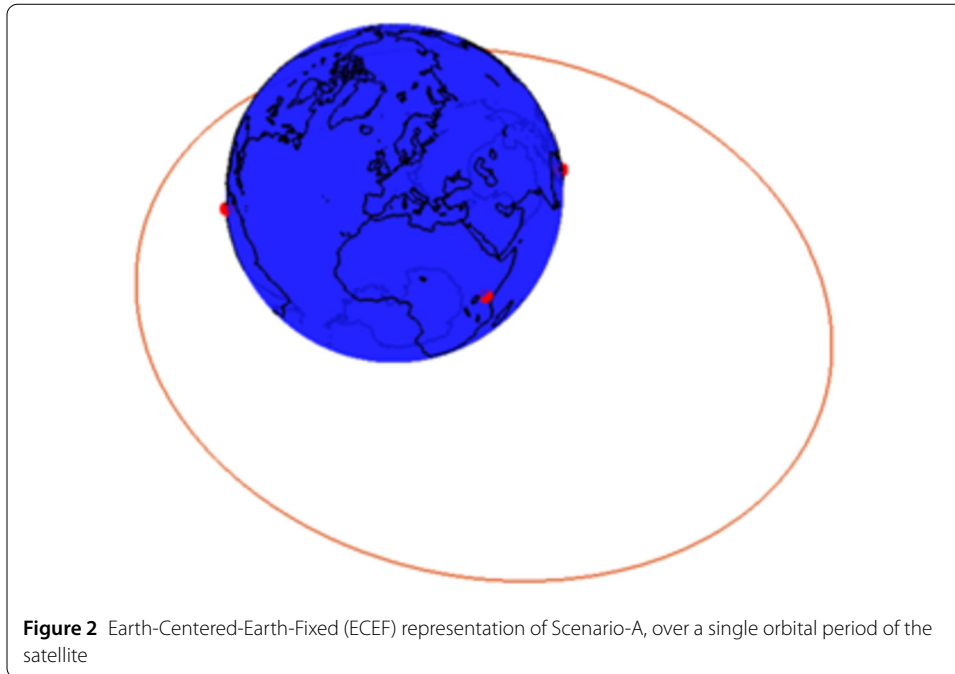
The main goal of DSQL is to conduct the quantum interferometry experiments described above. A secondary goal of DSQL, as determined by the SDT, is to evaluate QM in the regime of special relativity. In this class of experiments, the relative motion between nodes in a quantum communication network is large enough to be measured. Left uncorrected, such effects would corrupt the underlying quantum communication protocol. Some experimental configurations, developed during the DSQL concept study, show seemingly paradoxical causal relationships driven by relative motion between nodes in a quantum communication network [53, 54]. Ultimately, the special relativistic effects on QM underscore the need for precise synchronization in terms of a global time coordinate such as UTC (rather than the local times associated with specific observers) to be utilized in the implementation of space-based quantum networks.

3 Mission concept

Measuring the GR-induced phase shift is difficult for two fundamental reasons. First, at some fixed height difference $h = h_2 - h_1$, the GR-induced phase is static and therefore essentially impossible to distinguish from the usual path-length imbalance phase $2\pi \Delta h/\lambda$. To address this difficulty, the mission concept put forth by the DSQL SDT calls for quantum interference between a ground station and an orbiting satellite. The satellite would ideally be placed in an elliptical orbit [55], and there would be multiple ground stations arrayed about the Earth. In this configuration, the height difference varies along the orbit. The varying height difference is predicted to cause the GR-induced phase shift to vary with time. This facilitates measurement, thanks to the orbital modulation of the interferometric signal. Other factors that also vary across the orbit include solar heating and atmospheric drag.

For a fixed height difference between the two arms of the interferometer, the gravitationally induced phase shift will be a single value. The measurement precision required to measure this may be achieved through the mitigation of other phase-shift contributions. A first generation test would interleave classical pulses with quantum photonic states. In this set of experiments, the measured phase shift on the classical signal will be compared to the measured phase shift of the quantum signal. The prediction is that these two shifts would be identical.

A valuable experimental implementation would be to observe the gravitationally induced phase shift over a range of 2π (or more). Scenario-A (see Fig. 2) achieves this observation using an Earth-to-satellite link, with the satellite in an equatorial orbit of ellipticity of 0.5 and semi-latus rectum of 11,000 km. To observe the range of phase shifts requires multiple ground stations arrayed about the equator. In this example, we chose nearly equatorial ground stations at Singapore; Nairobi, Kenya; and Quito, Ecuador. The links between the satellite and ground stations are constrained by geometric line of sight and operations during night-time only. We note that as the line-of-sight conditions change to favor one ground station versus the others, there is a slight discontinuity in the predicted phase shift (see Fig. 3). This discontinuity is driven by the assumed geoid (in our simplified case, the WGS84 geoid), and the fact that the ground stations are at different altitudes. A further constraint on performance is dictated by the local cloud cover and other weather patterns of the ground stations. However, this detail is not indicated in the scenario, as it can be overcome by running the experiment repeatedly over the course of many months.



Scenario-B (see Fig. 4) perhaps better represents a different array of ground stations supporting a DSQL-type mission. Here, the satellite is inserted into an inclined elliptical orbit, and the ground stations are arrayed among the home cities of the co-authors of this paper.

The other reason measuring the GR induced phase shift is difficult is that it is small relative to other phase-shift contributions. Note that the experimental configuration shown in Fig. 1 mitigates how some of these error terms propagate into a phase or timing error. In the case of a DSQL-type experiment using single-photon superposition states, only processes that change the time-superposition result in measurable error. The three leading sources of error are the differential Doppler shift across time-superposition, the change in the atmospheric propagation time caused by turbulence, and the overall quality of mea-

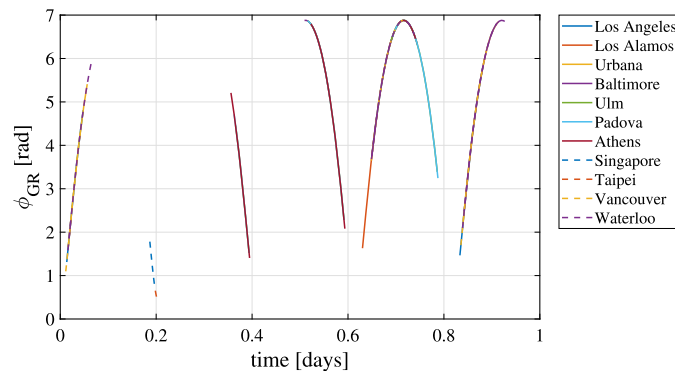


Figure 4 Measurable gravitationally induced phase shift for Scenario-B, representing a more realistic DSQL-type mission

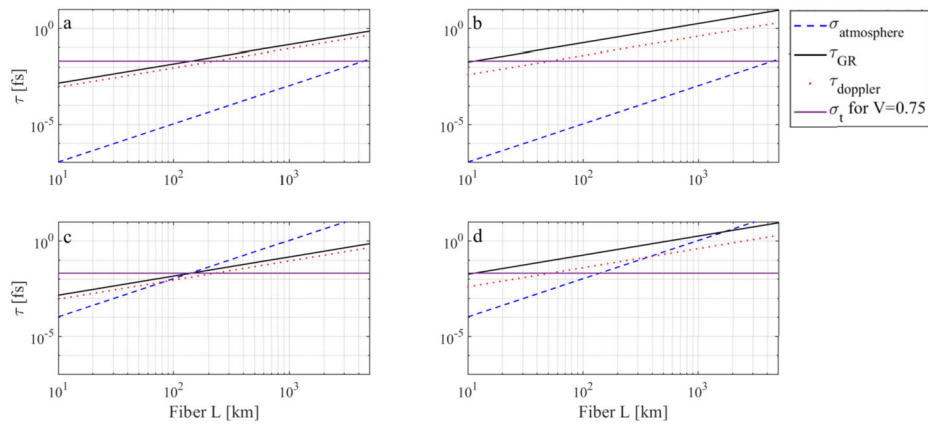


Figure 5 Error model for different measurement scenarios. In all figures, solid black-curve is the gravitationally induced phase shift $\Phi_{GR} = \omega_0 \tau_{GR}$, described in the text; the solid purple line is the equivalent timing error associated with a maximum interferometer visibility of 0.75 (independent of the other error terms in the plot); the dashed blue curve is the effect of atmospheric turbulence; and the dotted red curve shows the effect of the residual first-order Doppler shift. The y-axis on all four plots is time in units of femtoseconds, and the x-axis of all four plots represents the unbalanced Mach-Zehnder interferometer mismatch length L . In (a), the orbital altitude is 400 km, the atmospheric Greenwood frequency is 100 Hz, with peak power spectral density of $\frac{20ps}{\sqrt{Hz}}$, consistent with [56]. In (b), orbital altitude is 5000km with the same atmosphere as (a). In (c), the orbital altitude is 400 km, the atmospheric Greenwood frequency is 1000 Hz, with peak power spectral density of $\frac{200ps}{\sqrt{Hz}}$. In (d), the orbital altitude is 5000 km with the same atmospheric conditions as (c)

surement (characterized by an interferometric visibility in [33]) is a function of collected signal photons and background noise events. This framework is applicable to DSQL-type experiments that use entangled photon pairs as well: error sources must drive different effects on the two photon paths. The purely special-relativistic effect resulting in a time dilation roughly scales as the square of the first-order Doppler effect, and is well below the other error mechanisms described above. Other sources of error are described in reference [33].

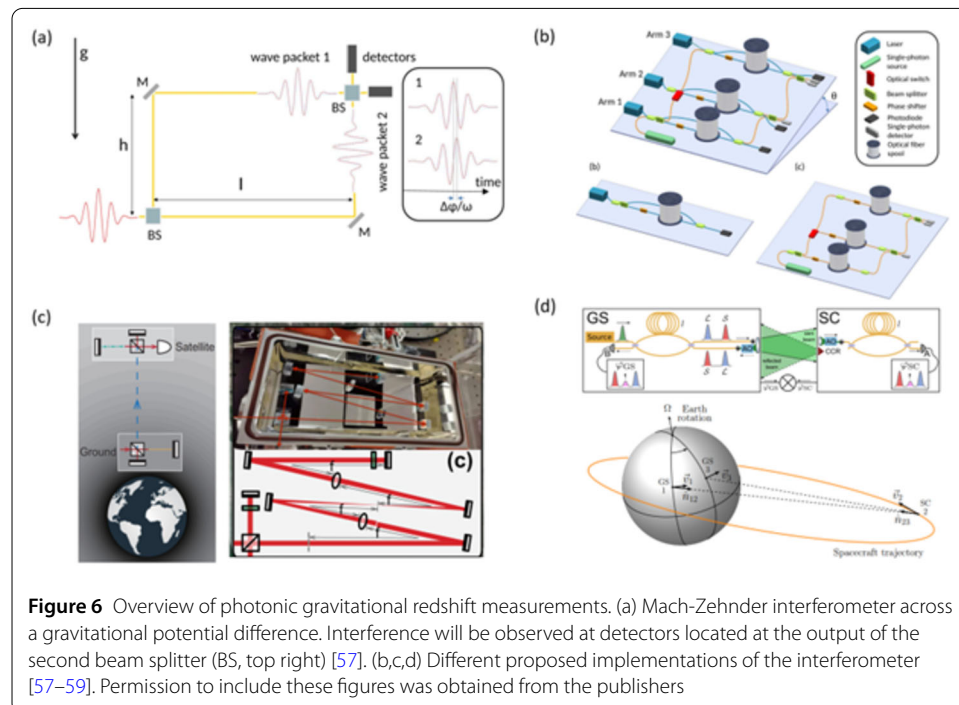
The error model illustrated in Fig. 5 may succeed for fiber lengths in excess of 200 m; the model in Fig. 5b for most fiber lengths; Fig. 5c would never yield single-shot visibility of the gravitationally induced phase shift; while Fig. 5d shows plausible measurement when fiber

lengths are less than 2 km. In these scenarios, a baseline interferometer visibility of 0.75 is assumed. This baseline would correspond to the visibility of fringes when coupled to an entirely local source of single photons that is not affected by any of the physical mechanisms contributing to the other error sources. Combined with an oversampling approach described in detail in our earlier work, (Appendices A and C of [33]), our analysis suggests single-shot measurement of the gravitationally induced phase shift is possible with appropriate selection of MZI length L , relative to orbital altitude, in a realistically calm atmosphere. Fluctuations of the length L would also contribute to a measurement error. This effect could be counteracted with a real-time length control servo, where the length mismatch is measured in situ using a classical laser.

4 Related work

Several experiments have been proposed to directly measure the gravitational redshift on quantum states of light using large area MZIs, as shown in 6. Terrestrially, the group of Hilweg et al. (see Fig. 6(a) and (b)), describe a system to measure the effect within a tabletop experiment [57]. The interferometer is to be built on a rotating table, allowing the altitude difference h to be adjusted incrementally from 0 m to 3 m. Each of the 100 km fiber arms includes its own unbalanced MZI, to be used for path-length stabilization of the individual coils as the table is rotated. The length of these interferometer coils makes such stabilization challenging, as the requirements for ancillary system components (such as the stabilization laser) become more stringent with increased interferometer length.

A recent experiment by Wu et al. (see Fig. 6(c)) explores a terrestrial technical demonstration of interferometer free-space optical link technologies for use in a potential future satellite-based mission [58]. In their demonstration, two unbalanced interferometers were employed, each with a free-space path imbalance of 1.2 m. The two interferometers were connected via an 8.4 km horizontal free-space link. Using this system, they quantified



the noise contributions accrued from each experimental subsystem, including photonic wavelength drift, atmospheric turbulence, and temperature and pressure fluctuations in the interferometer. This experiment provides an important stepping stone to future missions, but cannot in and of itself measure the phase shift caused by curved spacetime. This is due to the horizontal nature of the link, with no appreciable gravitational potential difference between the two interferometer stations. Instead, Wu et al. proposes a satellite experiment with geosynchronous orbits ($\sim 36,000$ km) and interferometer lengths of 50 m.

The direct measure in the Earth-satellite link is studied in Terno et al. (see Fig. 6(d)), which proposed a satellite-based experiment in which the first-order Doppler term is assessed with the simultaneous one-way and two-way interference of a time-bin state [59]. The effect due to GR was then derived analytically and simulated for different types of satellite orbits. The highly-elliptical Molniya case (altitude from 1600 to 38,000 km) emerged as the most interesting case, for the large modulation of the phase.

Advances in quantum memory devices based on atomic systems [60] or reconfigurable free-space optical delay lines [61] could potentially be used in the DSQL or other configurations to measure gravitationally induced quantum interference. In this application, the quantum memory (whether it is based on an atomic transition or a passive delay line) takes the place of the fiber-optic coils depicted in 1. The two key performance factors that determine overall sensitivity to ϕ_{GR} are the coherence time of the quantum memory, and its end-to-end coupling efficiency. From this standpoint, a quantum-memory would provide greater sensitivity to measurements of ϕ_{GR} if the coherence time is greater than a fiber-optic coil, and if the end-to-end coupling efficiency is greater than the fiber-optic coil throughput efficiency. There is a potential system-level advantage in using atomic quantum memories in place of passive delay lines or fiber optic coils. Active stabilization of the coherence length would not be required, which could simplify implementation. However, the classical control pulses (e.g. microwave or optical) used to switch the photon in and out of the memory must then be phase stabilized to each other.

5 Outlook

The baseline DSQL mission concept remains an intriguing approach to measure the interplay of GR and QM. The elliptical orbit measurement configuration would best be implemented using multiple ground stations arrayed around the world. The DSQL mission concept implicitly requires international cooperation, since the more ground stations available, the greater the measurement precision. In fact, the technology required to execute the DSQL mission exists today.

The publication of multiple experimental efforts to advancing similar experiments to the DSQL demonstrate the worldwide interest in conducting tests combining quantum optics and gravity. Some of these concepts are on the cusp of a proof-of-concept measurement across terrestrial links. These experimental concepts and DSQL will complement ongoing tests of gravity that use classical sensors, atomic systems, and other types of quantum matter.

Since the DSQL initial proposal in 2018, advances made in space-based quantum optical technologies, timing synchronization, and management of free-space optical channels all improve the projected performance of a long-baseline quantum optical interferometer. The single-photon superposition state DSQL tests may be feasibly executed today

across extremely long baselines. The entangled-photon or hyper-entangled DSQL protocols [33] are plausible across relatively shorter baselines, because they require transmitting two photons per experiment. Advances in high-repetition-rate entangled-photon sources and low-jitter detection systems would support longer-baseline testing. Advances in fiber-optical loop stabilization would further improve future mission performance. A coordinated effort to conduct ongoing technology development for critical subsystems, terrestrial field testing of end-to-end protocols, and refinement of the theoretical side of the experimental protocols would further improve the space mission design. All of these technological improvements directly benefit future space-based quantum networks.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Consent for publication

In 6, authors have granted permission for reuse of figures from [57, 58], and [59].

Competing interests

The authors declare no competing interests.

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