Topical: Quantum technologies in space

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In 2017, we received news that the Micius satellite, built and placed in orbit by the Chinese science community, had produced entangled photon pairs and beamed them to Earth. These photons were received at stations separated by more than 1200 km, enabling quantum key distribution between distant entities on the ground. This achievement represented a new "Sputnik moment." Just as, generations ago, Sputnik had spooked the United States science and technology community by its persistent radio signal, so too does Micius' persistent flash of photonic spooky-action Bell states signal a fierce international competition in the deployment of quantum technologies.

The United States National Quantum Initiative (NQI) of 2018 responded to this quantum Sputnik moment by establishing a network of quantum science and technology centers selected and funded by the NSF and the DOE. These centers have focused on ground-based quantum technologies for quantum computation, communication, sensing and simulation. Our Challenge Institute for Quantum Computation is one of these NSF centers. Our mission is to address fundamental challenges to the development of the quantum computer.

Yet, even though a response as strong as the NQI was prompted by news of a quantum-enabled satellite, it does not yet appear that the United States, and specifically NASA, has developed a coherent plan for the development of quantum technologies in space. Nor has the United States scientific community been mobilized for such development, as it was for ground-based quantum technologies following the NQI Act.

We argue for a coherent and ambitious plan by the United States physical sciences and space sciences communities to explore potential uses of quantum technologies in space, to develop quantum technologies to a sufficient technical readiness, and then to deploy and operate quantum technologies in space. The authors of this white paper, scientists from the Challenge Institute for Quantum Computation, identify the lack of such a plan as a fundamental challenge to the development of the quantum computer, and, more generally, to the development of quantum science and technology both on Earth and beyond.

1 Uses for quantum technologies in space

The call to develop quantum technologies in space has been decreed previously by others. We refer the reader to a thoughtful argument posted by members of the European science community [1]. They propose several compelling scientific applications of space-based quantum instruments for probing fundamental physics, enabling new forms of gravity-wave detection and other astronomy, long-distance quantum communication networks interconnected via satellite, remote sensing of the Earth, and navigation. Here, we amplify the arguments of the aforementioned paper in three particular application areas.

1.1 Space-based quantum networks

As demonstrated at a basic level by the Micius satellite, routing photonic quantum bits through space allows one to construct a quantum communication network over long distances. This network would be empowered by space-borne instruments for generating many-photon entangled states, transmitting and receiving single photons, and storing, transducing and processing quantum information. This quantum network has many important scientific and technological applications.

The Micius satellite already allowed for quantum key distribution (QKD) over long distances. Beyond this, quantum networks allow for a stronger notion of security for QKD, based on a concept called **device independence** [2]. In the device independent framework, secure cryptography can be done with completely untrusted devices, and their security solely relies on the validity of quantum theory [3] or more generally no-signalling principle [2].

Further, at the very long distances afforded in space, it will be possible to realize novel **relativistic cryptography** protocols, including *relativistic bit commitment* [4] that allows distant parties that do not trust one another to exchange and lock information securely, *spacetime-constrained oblivious transfer* [5] that allows two parties to exchange information securely while neither can be fully knowledgeable about the information transferred, and *position-based quantum cryptography* [6] in which the geographical location of a party is its credential.

Space based networks allow not only the exchange of classical information, but also for the transmission of quantum states. Such transmission allows for quantum information processing on quantum databases that are remote or distributed.

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1.2 Quantum sensors

The Global Positioning System (GPS) represents one of the most profound demonstrations of the power of quantum sensing in both terrestrial and space applications. The GPS satellites, each of which contains relatively primitive atomic clocks, allow users to triangulate their position with accuracy below the meter level. Just this year a group based at NASA's Jet Propulsion Laboratory demonstrated a more sophisticated version of these clocks using similar amounts of power but achieving more than an order of magnitude better stability [7]. These clocks would enable coordinated timing over the long distances one encounters with space exploration.

Optical atomic clocks are developing rapidly in laboratories around the world. Clock accuracy is sufficient to count the age of the Universe with an error far below one second, and clock precision is sufficient to detect the gravitational red-shift on Earth over vertical distances below a millimeter.

It is imperative to try to close the present yawning gap between what can be done on Earth and what can be done in space. One very fundamental reason to do so is that the time shared by people on Earth cannot be based on clock standards that are positioned on the Earth, because the now-extreme gravitational shift of clock standards on Earth from changes in the surrounding mass distribution and changes in elevation would render them useless.

Optical atomic clocks will also serve as indispensable sensors. These could be applied, for example, for remote gravitational sensing of mass distributions on Earth, for gravity wave detection, or for precision tests of general relativity.

Ultracold atomic gases also offer advantages for quantum sensing. Atom interferometers are already used to measure rotation, acceleration, gravity, and other forces. In space, such interferometers can acquire even greater sensitivity owing to the long interrogation times that can be achieved in a freely falling instrument and the radically longer propagation distances that can be achieved, for example, in the open vacuum of space.

Quantum sensors have myriad other applications. For example, optomechanical sensors can provide extreme sensitivity to forces and displacement. Scanning probe quantum sensors can be used to characterize materials precisely. Quantum sensors are being developed for biomedical application, a capability that may be important for providing low weight/power medical diagnostics for space explorers.

1.3 Fundamental quantum science

Quantum theory is a non-local causal theory and predicts 'action-at-a-distance' phenomenon, and has been sharply debated on its interpretation and validity to describe Nature [8, 9].

Testing non-locality is one way to test the validity of quantum theory. This requires two or more spatially separated laboratories, across large distances, that share quantum entanglement. While bipartite nonlocality is well understood and tested, multipartite nonlocality is still not well understood and needs to be more robustly tested. Most recent experimental efforts led by TU Delft in 2015 demonstrated a robust test of Bell nonlocality and closed the major loopholes in experimental verification of bipartite nonlocality [10], and thereby almost settling a century old debate about nonlocality in quantum theory.

Space communications will enable similar tests and going beyond bipartite systems, and for **loophole-free tests for multipartite nonlocality**, such as testing Svetlichny type inequalities [11], that generalize Bell setup. These would test genuine multipartite nonlocality. Setting up such an experiment would necessarily need long distance multi-agent quantum networks.

The availability of quantum networks through space communication would also necessarily have a positive impact on designing quantum gravity experiments such as those described in [12, 13, 14, 15], that examine aspects of information scrambling.

2 Technological requirements

Clearly, there are widespread uses for quantum instruments in space. It is then important to delineate what are the technologies underpinning these instruments. The list is long.

Quantum communication relies on the generation and sharing of multi-photon quantum states. These tasks require advanced laser-optical systems and both linear and nonlinear optical components. Optical communication systems on Earth often operate on dedicated telecommunication bands, dictated by properties of optical fiber. However, communication through space or to ground through the Earth's atmosphere (or through other planetary atmospheres) has different constraints.

Quantum networking also required quantum information storage, repeaters, and some amount of quantum information processing. Thus, technologies are required for space-based transduction of quantum information, for example between photons and internal states of atoms or ions, or involving states of superconducting qubits, microwave resonators, mechanical resonators, or between photons of different energy. Research and development of such transduction, all the way from ground-based efforts to proving technologies suitable for space applications, is warranted.

Quantum sensors utilize a wide range of sensing media: ultracold atomic gases, trapped ions, solid-state color centers, and others. With each of these media there comes a range of technology required for their use, including long-term stable, narrow and reliable laser systems; ultrahigh vacuum systems; optical or magnetic traps; methods for producing cold atomic beams; laser-based interrogation and high resolution imaging; single photon detectors; and so on.

Similar to quantum sensors, quantum computers require physical media that retain quantum coherence for long times. However, the task of quantum computation goes further in requiring quantum coherence and entanglement within large-scale quantum systems. The goal of realizing quantum computation in space, e.g. for use in a remote space station, on a planetary explorer, or on board a free-flying instrument, seems quite remote: We don't yet have large-scale quantum computers operating on Earth, so it's hard to predict when one will be operating in space. Yet, there is sufficient technological synergy between quantum sensing and quantum computing, and also between ground-based and space-based technologies for the control of quantum systems, that we can already call for a research and development effort that could, down the line, enable quantum information processors in space.

In all these areas, a robust research program is required with several goals: (1) developing novel approaches that are suitable to space applications, (2) developing technologies that meet the SWAT (and other) requirements of space, (3) testing technologies in ground-based testbeds, (4) progressing technologies through a steady pace of technological readiness, and (5) deployment, demonstration, and use in space.

3 Path forward

It is imperative to develop a coordinated, long-term, inter-agency plan to move forward. We are aware that several pieces of such a plan area already under consideration at NASA. For example, the Space Communication and Navigation Directorate has formulated plans for the development of a limited-scale optical quantum network. The Fundamental Physics program within the Physical Sciences Directorate is actively developing cold-atom experiments that operate within the shirt-sleeve environment of the ISS. Other additional efforts are distributed elsewhere among NASA's activities.

However, there is clearly a need for synthesizing these myriad pieces and developing a coherent, and much more comprehensive, plan of action. We are agnostic about whether such a plan should be developed from within one of NASA's existing programs, or at a higher level of coordination between NASA directorates, or even at an inter-agency level involving

NASA as well as other Federal research agencies.

One favorable approach we can recommend is to engage the quantum science and engineering communities already energized to develop ground-based quantum technologies. There should be a way to form partnerships with the strong existing NQI quantum centers (including ours) and also with the growing quantum industry, and to direct their attention upwards toward space.

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