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A quantum science space station

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Abstract

In the coming years we expect to see a diverse array of quantum instruments being developed and flown in space, including quantum gas experiments, optical clocks, atom interferometry experiments, and quantum information/quantum optics experiments. The International Space Station has proven itself as an exceptional platform for such missions, providing long-term microgravity in a pressurized and temperature controlled environment, with ample power, thermal and data resources. However the station is currently planned to operate only through 2030, well before many proposed quantum sciences missions could be ready for launch, and we undertake here to explore what an ideal follow-on platform might look like. In particular, we believe that a much smaller and less expensive low Earth orbiting facility, optimized and dedicated to quantum science, could be an exceptionally powerful platform for exploring the quantum world and harnessing quantum technology. Such a platform would allow multiple quantum instruments to share resources and explore related phenomena in concert.

1. Introduction

The success of the Cold Atom Laboratory aboard the International Space Station has opened a new era for the exploration of quantum phenomena in space [1, 2]. In coming years we expect to see a diverse array of quantum instruments being developed and flown, including follow-on quantum gas experiments, optical clocks, atom interferometry experiments, and quantum information/quantum optics experiments. The International Space Station has proven itself as an excellent place for such missions, providing long-term microgravity in a 'shirtsleeve' environment (pressurized and temperature controlled). Having astronauts to unpack, install, maintain, and upgrade instruments significantly improves the ability to deploy state of the art experiments at a reasonable cost (admittedly neglecting the vast costs of the station itself), and operate them for long periods.

The ISS is only planned to operate through 2030, and we undertake here to explore what an ideal follow-on platform might look like. In particular, we believe that a much smaller and less expensive facility, optimized and dedicated to quantum science, could be an exceptionally powerful platform for exploring the quantum world and harnessing quantum technology. Such a platform would allow multiple quantum instruments to explore related phenomena in concert. At the same time the use of shared hardware and common interfaces would enable NASA and its partners to most efficiently leverage investments in this area.

2. Overview of the quantum space station

We envision a station roughly half the size of the current destiny module (roughly 4 m long and 4 m diameter) providing 6 EXPRESS Rack (or similar) accommodations for science payloads, along with at least 2 external facilities. In addition there would be space for instruments that are common to several

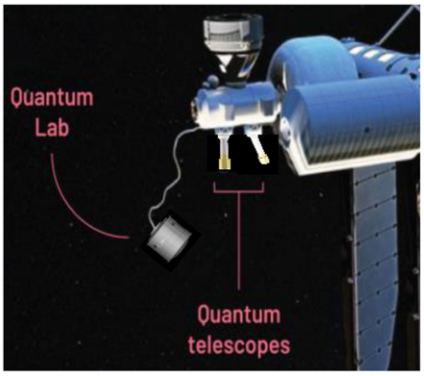

Figure 1. An artist's conception of one possible quantum space station, in this case a facility tethered to a commercial space station. Power, data and optical connections are included in the tether.

Figure 2. Artist's conception of astronauts working in a quantum facility.

investigations, including at least 2 small telescopes, and an internal metrology suite (each of these will be described below). The ability to control the orientation of the station and even make minor changes to the orbit are crucial for certain experiments; so the preferred configuration would be a self-contained free-flying satellite that could be periodically visited by crewed vehicles or berthed to a larger space station for astronaut operations. Alternatively a laboratory that is tethered to an existing vehicle or station could be an attractive option, especially if orientation control was allowed. Here there could be a considerable reduction in complexity by removing the need for separate power generation and data links. In both of these cases, we take advantage of having astronauts for installation and maintenance, allowing for significantly more complex payloads to be considered and extending the lifetime of both payloads and the station itself. At the same time, not having a permanent astronaut presence on the vehicle improves performance and reduces costs (figures 1 and 2).

3. Synergies

The advantages of putting all of our quantum eggs in one basket are three-fold. First having common interfaces for mechanical connections, power, thermal and data, facilitates sharing of designs for standard hardware between payloads. Second different facilities can share resources between themselves, including laser systems, frequency combs and communication telescopes. Astronauts with a background in experimental physics can be used to install and upgrade instruments and monitor their performance. Finally, many experiments in this area are synergistic with one another. For example different types of clocks may be compared to each other, facilitating both technical comparisons and allowing tests of fundamental physics, including searches for variations in fundamental constants. Studies of gravity may benefit from having both atom interferometric probes, along with high precision clocks which have also demonstrated a high sensitivity to gravitational fields [3].

4. Features of a quantum space station

4.1. Telescopes

Optical telescopes on the space station will support laser communications, optical time transfer, and quantum optical science. The quantum experiments considered for deployment on the space station all use data-intensive instrumentation, such as high-resolution cameras. Adding optical communication capability will ensure the data downlink capacity of the space station matches the needs of its hosted experiments [4]. Using precision clocks to test fundamental physics is another key goal of the space station. An optical telescope could be used to establish an optical time transfer channel between the clocks on the space station and other clocks, potentially on Earth or in orbit [5]. The telescope infrastructure supports quantum optical experiments such as performing long-baseline tests of Bell's inequality, demonstrating long-baseline quantum teleportation and other quantum communication protocols between different inertial frames, and testing Einstein's equivalence principle in the photonic regime [6].

The telescope system would consist of two independent apertures, coupled to an array of optical modems. A classical laser communication modem will support data communications, and a time-transfer modem will support one-way and two-way optical time transfer protocols. The quantum optical modem capability will need to be supported by the individual quantum optical experiments hosted on the space station. An integrated-optical switch bank will form the back-end of the telescope system, and control which functionality is engaged at a particular time. The optical switch bank will extend to the core of the space station, and could be applied to establish optical linkages between various experiments hosted on board. Notional spectral allocation would be 1550 nm for data communications and time-transfer, 780–810 nm for quantum optical channels, 980 nm and 1064 nm for uplink and downlink beacon channels. Auxiliary quantum channels corresponding to strontium and potassium lines will also be supported, primarily as a linkage between other quantum instruments aboard the space station.

4.2. Metrology suite

A metrology suite would provide common hardware that could be shared between payloads. It could contain ultra-stabilized lasers, frequency combs along with sophisticated rf and microwave spectrum analysers and sources. A goal would be to develop a lab that provides shared resources that are far in advance of those available in a typical university research lab.

4.3. Inter-payload links

Critical to the concept of a dedicated quantum space station is the need for very high quality optical and electrical links between payloads, including links to external payloads. This should include single-mode polarizing preserving fibre connections at several wavelengths, as well as high quality rf and microwave connections. Common trigger signals should be provided to synchronize measurements between payloads.

4.4. Wake shield facility

A wake shield is essentially a metal plate that pushes residual gases out of the path of a rapidly moving spacecraft. As long as the velocity of the shield is substantially higher than the average velocity of thermospheric molecules, an ultra-high vacuum can be created in its wake. The Wake Shield Facility was utilized on three Space Shuttle missions (STS-60, STS-69 and STS-80) and achieved vacuums of 10^{-10} Torr behind a 3.7 m diameter stainless steel shield. Such a vacuum is barely adequate for an ultra-cold atom experiment. However, this vacuum was likely limited by outgassing from the shield itself, and a properly vacuum-processed shield could potentially achieve pressures as low as 10^{-14} Torr, sufficient for most applications [7].

Such a wake shield will be of great interest to researchers who wish to access the vacuum of space in lieu of self-contained vacuum systems. This has the potential for achieving larger and colder atomic samples than can be achieved on Earth [8].

4.5. Orientation control

The ability to rotate the facility 180° will allow a number of precision measurements to accurately assess systematic effects related to spacecraft mass distribution and Earth's gravity gradient. Setting up a rotating frame of reference also open up a number of possibilities for experiments that are not possible on the ground.

4.6. Orbit control

Significant changes to the orbit will be challenging for a station that needs to be maintained by astronauts, and would almost certainly be impossible for a tethered facility. None the less we mention that a number of tests of general relativity are greatly enhanced by moving to a highly elliptic orbit, with a significant change in gravity.

4.7. Microgravity environment

The ISS is a very large platform that is subject to vibrations from crew activity, pumps, exercise equipment, visiting vehicles, etc. Thermal flexing of the structure itself can also introduce vibrations, while the long lever arm of the station can amplify disturbances. A significantly more compact, free-flying or tethered facility, that is not occupied by astronauts would be expected to have a dramatically improved microgravity environment in comparison to the ISS.

5. Science

A number of ideas for the utilization of space for investigations of quantum matter and optical clocks are presented elsewhere in this issue and in other publications. In this section we focus on those investigations that could be enabled or enhanced by their inclusion on this facility.

The capability of rotating the platform would allow for a number of quantum matter experiments that are not possible on Earth. A possible example would be studies of the fractional quantum Hall effect (subject of the 1998 Nobel prize), which remains poorly understood at the microscopic level.

As we mentioned previously, by having multiple atomic clocks onboard we facilitate intercomparisons which is useful for technical development as well as for the testing of fundamental physics. In addition having such devices share a platform with a source of squeezed light could facilitate comparisons of classical and quantum time transfer protocols [9].

6. Practical benefits

Beyond their intrinsic scientific interest and their usefulness for addressing issues in fundamental physics, quantum technologies are expected to have broad impact as sensors, enabling inertial navigation, aiding the monitoring of Earth's environment, and perhaps someday finding utilization in searching for resources on planetary bodies [10, 11]. A quantum memory is a device that stores the quantum state of an incoming light pulse and releases it on-demand at a later time. Such a device placed in space could function as a hub of a world-wide quantum network, linking quantum computers on different continents [12]. A state of the art clock on a space based platform such as we describe here could function as a world-wide master clock, synchronizing clocks around the world. Many other applications of cold atoms in space are discussed elsewhere in this issue and also in [13].

7. Costs

Developments in the commercialization of space over the last decade lead us to believe that the cost of a station similar to what is envisioned could be a small fraction of the cost of an ISS segment. Clearly there would remain significant upfront costs of building a facility that could be maintained by astronauts, compared to the costs of a free-flying spacecraft. However, we expect a the costs of building and deploying the Quantum Space Station to be significantly below the total costs of the instruments flown on it (including their launch and operations costs). If this station is capable of flying at least ten instruments similar to the Cold Atom Lab, we would expect to be flying about 1 billion dollars' worth of instruments every 4 years, or 5 billion dollars' worth over an anticipated 20 years lifetime.

The ISS is world-class, yet still an expeditionary research facility, with ground-breaking experiments also acting as pathfinders for reducing complexity and costs for future experiments. Providing reusable, reliable, routine transportation to a future quantum station is an important component of reducing costs for quantum experiments, as it allows for the delivery of components that support upgrades and changes in experiment parameters. For example, the ISS's Cold Atom Laboratory was delayed three times in 2017 until it finally launched to ISS in 2018. Delays such as these impact costs ranging from hardware delivery to science implementation. Another potential cost-saver would be the ability for investigators to iterate on their experiments using the same hardware within a sustained quantum research program on orbit in many of the same ways they would in their laboratories on Earth. This would enable the most efficient operational approaches through implementation of a carefully planned research program saving astronaut time, consumable costs, and even launch needs. Designing experiments to be used in the same hardware system that has many common capabilities would save costs over having to design and build unique, experiment-specific components with each round of implementation. Human-centered design to make access to the facilities as easy and efficient as possible for astronauts, and even advanced automation as much as possible, are all additional important cost reduction considerations.

A goal would be to bring the marginal cost of adding PI specific hardware associated with a particular investigation well below the costs of developing a similar experiment from scratch in a terrestrial laboratory. This will be aided by the development of shared designs for common hardware, allowing payload developers to focus on the unique hardware needed for their investigations. We believe that this will allow payloads to be developed by university researchers with little or no spaceflight experience, with a minimum of collaboration from space agencies or commercial space vendors.

This cost information is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of Blue Origin, DLR, JPL and/or Caltech.

8. Conclusions

We have outlined what we believe would be an ideal platform for the continuation of quantum physics experiments in space after ISS decommissioning. We expect that other disciplines within the microgravity science community, such as biology, or soft matter, to undertake similar exercises. An array of 'bespoke' space stations, each optimized for a particular research field, might be one vision for microgravity research in the coming century. On the other hand, we may well find certain research disciplines to be compatible or even synergistic with one another, which potentially could lead to significant cost savings.

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Data availability statement

No new data were created or analysed in this study.

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