The Quantum Leap
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The Quantum Space Race

Some have described the rapidly accelerating global push in Quantum Computing as a **figurative** "space race" given the potential reach of its computational power and its applications in drug development, logistics, material science, and its potential ability to overpower existing encryption techniques. However, this post is focused on the **literal** quantum space race – the increasing number of quantum devices in orbit and their profound applications. While the fragility of quantum states has been a core challenge in advancing Quantum Computers, that same challenge is a powerful asset for creating ultra-sensitive measuring instruments, and these quantum sensors are now making their way into orbit.

Quantum sensing and quantum communications are making important advances in space in the following areas:

1) Earth Sensing and Observation
2) Quantum Key Distribution (QKD) and Secure Communication Networks
3) Time and Frequency Transfer
4) Fundamental Physics and Space Exploration

Today there are 77 countries with space agencies,16 of these countries have launch capabilities, and more than 4,500 satellites are currently in earth orbit. Satellites containing quantum devices are increasingly being placed into orbit, and quantum devices have been used in, and deployed from, the International Space Station. As Arthur Herman noted in a recent *Forbes* article: "Quantum communication satellites will become hubs of not only a future quantum internet, but hubs for hack-proof networks for transfer of classified data and communications – **not to mention a command-and-control architecture that will be an integral part of space domain dominance**" [emphasis added].

The following chart is a partial sampling of existing and planned quantum space launches:

Lead Country	Program	Highlights	Timing
China	Micius Satellite	First space-based demonstration of QKD	2016
China	Space Lab Tiangong-2 Quantum Terminal	Has transmitted quantum-encrypted keys to four ground stations	2016
US	Satellite Gravimetry	NASA and AOSense demonstrated space-based quantum gravity sensor	2018
US/Canada	CAPSat (Cool Annealing Payload Satellite)	U of Illinois Urbana-Champaign/U of Waterloo project aboard ISS; photon detector for QKD	2021

China	Jinan 1 Satellite	Improved QKD	2022
UK	QKDSat-1 and QKDSat-2	Joint program of Arqit, Virgin Orbit and ESA; Plans to transmit QKD	2023
Australia	Nanosatellite mounted quantum sensors	Q-CTRL, Fleet Space Technologies/Seven Sisters Consortium; to detect water/mineral deposits on moon and other planets; quantum-enhanced space navigation and timing	2023
Europe	Eagle-1 Satellite	Joint program of SES and the European Space Agency (ESA); Plans to transmit QKD	2024
Canada	QEYSSat	QKD distribution; collaboration among the Canadian Space Agency and IQC, Univ. of Waterloo, Honeywell, Loft Orbital and Blue Canyon Technologies	2024
Singapore/France/ UK/Netherlands	Speqtre and SpeQtral-1	QKD projects from RAL Space (UK); Thales Alena (France); ISISPACE (Netherlands) and SpeQtral (Singapore)	2024/ 2025
Germany	QYRO Satellite	Quantum gyroscope for satellite positioning to be launched by Q.ANT, Bosch,TRUMPF Card and German Aerospace Center	2027

Note: Above chart not intended to be all-inclusive, and some programs have contributions from additional countries.

We are already increasingly dependent on satellites for global communications and GPS service, among other applications, and space-based experiments are advancing basic science and human knowledge. Adding the powerful capabilities of quantum technologies will accelerate and expand upon these space-based advances. The following summarizes some important space-based quantum initiatives:

1. Earth Sensing and Observation

A key attribute of quantum mechanics, which is one of the main rate delimiters in advancing Quantum Computing, is the fragility of the tiny particles placed into a quantum state. Specifically, attempting to control individual atoms, electrons or photons has been very difficult due to the sensitivities of such particles to external forces including gravity, electromagnetic radiation, temperature fluctuations, and vibrations. However, it is this sensitivity to such forces that make “qubits” such powerful sensors enabling them to study and assay the earth in detail never before available.

Space (satellite) based quantum sensors can provide reliable detection, imaging, and mapping of underground earth environments from transit tunnels, sewers and water pipes to ancient ruins, mines, and subterranean habitats. There are important civil engineering benefits that more precise sensing can achieve, particularly around large projects (e.g., nuclear power plants, highspeed rail, etc.) where existing subsurface surveys are extremely expensive, time-consuming, and often not as precise as necessary. Such space-based sensors can also be used to track minute gravitational changes and tectonic shifts that can forewarn of avalanches, earthquakes, volcanic eruptions, or tsunamis. The strength of Earth's gravitational field varies from place to place, often due to underlying causes of climate change. Variations in gravity are caused by factors such as relative positions of mountains and ocean trenches and variations in the density of the Earth's interior, but also by small fluctuations in underground water reservoirs or changes in ice mass, so gravimetry is an important new tool to help monitor global warming.

2. Quantum Key Distribution (QKD) and Secure Communication Networks

QKD is a secure communication method that uses quantum properties of photons to encrypt secret keys that can be share by two parties to encode their communications. The technique is considered un-hackable since any attempt to eavesdrop destroys the keys. Current forms of encryption, such as the widely used public-key cryptosystem developed by RSA, rely on the difficulty of solving mathematical problems whereas QKD instead relies on physical processes. In quantum physics, there is a "no-cloning" theorem which states that it is impossible to create identical copies of an unknown quantum state. This prevents hackers from simply copying the quantum encoded information. Another quantum property known as "observer effect" causes quantum states to change upon observation and therefore, if anyone were to try and read the QKD it would change it and that change would be instantly known by the parties involved. (If interested in learning more about QKD please see here.)

QKD has already been successfully implemented via fiber optic cables, but only over short distances. Beyond 100 kilometers (about 60 miles) the signal degrades and beyond 300 kilometers the information transmission becomes prohibitively slow (i.e., only about one bit per second). In fact, the signal degradation increases exponentially as the distance increases. By using satellites in low-earth orbit (LEO) to send and receive transmissions via line-of-sight, this distance challenge can be largely overcome. LEO orbits can provide line-of-sight transmission between earth-based ground stations that are up to about 700 kilometers (about 430 miles) apart, although this limitation can be exceeded if the key can be stored in the satellite while it orbits or, preferably, by relaying the signal among connected satellites.

Naturally, un-hackable communications is a key objective of many governments as well as certain industrial firms, hence the broad number of countries currently working on space-based QKD.

3. Time and Frequency Transfer

An overwhelming array of modern conveniences are reliant upon highly accurate clocks. [In fact, this is such a prevalent and important observation that my next post will be dedicated to need for more precise time measurement]. Many electric power grids use clocks to fine-tune current flow. Telecom networks rely on GPS clocks to keep cell towers synchronized so calls can be passed between them. The finance sector uses clocks to timestamp ATM, credit card and high-frequency trades. Doppler radar, seismic monitoring and even multi-camera sequencing for film production all use highly precise clocks. Today's earth-based atomic clocks are extremely accurate, and you can readily synchronize your computer to the atomic clock of your choice. However, relying on existing atomic clocks for timestamping, such as currently done for GPS satellites, is becoming increasingly challenging. GPS navigation is currently accurate to about three meters (about 10 feet), so it presents challenges to using it for autonomous driving, as one example.

In order to improve on existing timekeeping and related applications, we need both a more accurate clock as well as more precise dissemination and sharing of time. Quantum technologies can improve time accuracy by orders of magnitude and placing them in space can enhance dissemination. Increased time accuracy will improve current communications and geolocation services as well as enable new applications and a space-based quantum clock can enable long-range transfer timing.

4. Fundamental Physics and Space Exploration

NASA's Cold Atom Lab aboard the International Space Station (ISS) has used atom interferometry to create a new generation of exquisitely precise quantum sensors that scientists are using to explore the universe. Applications of these spaceborne quantum sensors include tests of general relativity, searches for dark energy and gravitational waves, spacecraft navigation and drag referencing, and gravity science, including planetary geodesy—the study of a planet's shape, orientation, and gravity field.

In 2019, the image of a supermassive black hole was created using earth-based synthetic aperture telescopes. By precisely measuring the arrival time of radio waves at two different locations, an image of their source was created. Because visible light wavelengths are much shorter than radio waves (nanometers vs meters), more sensitive detectors and clocks are required to use this methodology for visible light, such as those now being placed in orbit. The resolution of such an image would match the resolution of a conventional telescope with an aperture equal to the distance between the two satellites. Such telescopes would be extremely sensitive, potentially enabling astronomers to study planets around other stars in vast detail.

Space-based quantum sensors will also be crucial for space exploration. As spacecraft venture further away from Earth, the ability to provide navigational instructions diminishes. Naturally "GPS" would be unavailable in deep space, and Earth-based control signals have increased time lag times as spacecrafts travel further away. Additionally, if such Earth-based navigational commands are not precise enough, the target craft may miss its destination completely. Sensors that can measure a vehicle's acceleration and rotation can enable navigation without requiring external commands. In addition, space-based quantum sensors are planned to help search for water and other resources on the moon and Mars.

Conclusions

The pace of advances in quantum science is rapid and paradigm shifting. While Quantum Computing gets most of the headlines, important advances in quantum sensing and communication is also advancing rapidly including via deployment in space. By placing powerful quantum devices into space, significant advances in earth observation, space exploration and secure communications are being achieved. Given the intense competitive nature of terrestrial quantum advances, extending this to a "space race" is inevitable and, in fact, is already underway. Readers should anticipate more and more headlines on this topic, and I look forward to providing periodic updates.

***Disclosure**: The author does not have any business relationship with any company mentioned in this post. The views expressed herein are solely the views of the author and are not necessarily the views of Corporate Fuel Partners or any of its affiliates. Views are not intended to provide, and should not be relied upon for, investment advice.*

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