Australian Government
Office of the Chief Scientist

Quantum Meets Space Workshop Summary

A workshop led by Australia's Chief Scientist
in partnership with the CSIRO and the Australian Space Agency

CSIRO

Australian Space Agency

Acknowledgement of Country

The Office of the Chief Scientist acknowledges the traditional owners of the country throughout Australia and their continuing connection to land, sea and community. We pay our respect to them and their cultures and to their elders past and present.

Artwork: Connection to Country, 2021 by Shaenice Allan

Meeting Place icon by DISR employee Amy Huggins

Disclaimer

The purpose of this publication is to summarise the events and outcomes of the Quantum Meets Space event which occurred in Adelaide on 1 May 2024.

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Microsoft Co-Pilot was used in developing this summary.

Workshop Overview

Quantum Meets Space was presented by Australia's Chief Scientist in partnership with the CSIRO and the Australian Space Agency. The workshop was held at Lot Fourteen, Adelaide, on 1 May 2024. Approximately 80 people attended, including representatives from the Australian space and quantum industries, academia and government.

Space refers to environments beyond a 100 km altitude. The space sector is a critical enabler of essential services that underpin modern society, including transport, communication, agriculture and finance. Space and quantum technologies can work together to make these services better and create more value for society.

Quantum Meets Space was an opportunity for the space sector to learn about quantum technologies and the potential these have for space sector applications. It also provided an opportunity for the quantum industry to find new markets, explore funding and business opportunities, and learn about technical issues in the space sector where quantum may provide solutions. The space sector has changed over time with more companies now present in Australia. Thanks to the increasing numbers of commercial launch providers and lower costs, space is now more accessible, presenting opportunities for the roll-out of quantum technologies.

Scene setting

Australia's Chief Scientist, Dr Cathy Foley, described the workshop as an opportunity to identify potential applications of quantum technologies in the space sector. She welcomed the event as part of broader efforts to realise the ambition embodied in Australia's National Quantum Strategy.[1]

Enrico Palermo, Head of the Australian Space Agency (the Agency), highlighted recent investments for developing quantum technologies in Australia under Agency programs, and acknowledged the increasingly prominent role that quantum will play in the future. With space as an enabler of critical technologies across multiple sectors, Mr Palermo emphasised the opportunities for quantum to enhance existing capability as people rely more on space-based technology and services.

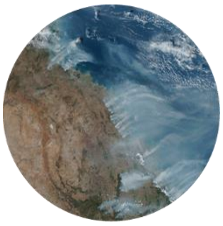
Enrico Palermo, Head of the Australian Space Agency: "*Leveraging the space environment to develop quantum technologies will help drive the next generation of secure quantum communication, Earth observation and remote sensing, to improve various industries and challenges we face on Earth."*

[1] https://www.industry.gov.au/publications/national-quantum-strategy

Areas of industry impact

Low Earth orbit to deep space communications

We need faster, stronger, safer and more reliable ways to communicate between low Earth orbit and deep space. This technology supports telecommunications, crewed spacecraft missions, advanced telemedicine and complex image delivery. Lasers, quantum entanglement, and secure methods such as quantum key distribution and cryptography will help develop these communication technologies.



Positioning, navigation and timing (PNT)

Quantum technologies make existing space-based PNT services more reliable by using atomic clocks and quantum-enhanced navigation systems. Mapping the Earth's gravitational and magnetic fields can improve and localise quantum positioning systems.

Monitoring the Earth

Quantum sensors can provide better images from space, which can help with many services including agriculture, disaster relief and climate change modelling. Precise gravity measurements of the Earth can also help by mapping small changes in sea levels.

Monitoring space objects

Quantum technologies can be better than traditional systems at tracking fast-moving objects with low reflectivity. This can be useful for monitoring space debris, space assets and overall awareness of what is in space.

Program schedule

Setting the scene

- Dr Cathy Foley, Australia's Chief Scientist
- Enrico Palermo, Head of Australian Space Agency

Keynote 1 – Critical challenges for the space sector

- Dr Geraldine Baca Triveno, Director of Space Systems at Deloitte Space
- Imelda Alexopoulos, Director of Exploration Strategy at Fleet Space

Keynote 2 – Meeting the challenge with quantum technologies

- Dr Jie Zhou, Researcher in the Department of Quantum Science and Technology at ANU
- Dr Jim Rabeau, President of Infleqtion Australia

Panel 1 – Quantum sensing for understanding Earth & space

Chair: Professor Allison Kealy, Director of the Innovative Planet Research Institute at Swinburne University of Technology

- Professor Andrew Greentree, Professor of Quantum Physics at RMIT
- Dr Jie Zhou, Researcher in the Department of Quantum Science and Technology at ANU
- Professor Andre Luiten, co-founder and Managing Director of QuantX, Chair of Experimental Physics at the University of Adelaide
- Dr Stephen Gensemer, Senior Research Scientist at CSIRO

Panel 2 – Quantum technologies for enabling space based PNT and communications

Chair: Professor Andrew White, Director of the Quantum Technology Lab and of the Australian Research Council Centre for Engineered Quantum Systems, Professor of Physics at the University of Queensland

- Dr Alex Arriola Martiarena, Photonics Team Leader at Advanced Navigation
- Nick Miller, Senior Director, Optus Satellite and Space at Optus
- Dr Michael Hush, Chief Scientific Officer at Q-CTRL
- Professor Ed Kruzins, Professor of Space Communications and Tracking at UNSW and Adjunct Professor at University of Adelaide.

Panel 3 –Quantum technologies for a sustainable space environment

Chair: Dr Marcel Bick, Business Development Manager at CSIRO

- Tori Tasker, Director Human Spacelight Strategy and Projects at RayTracer
- Nick Carter, Space Research Group Lead at CSIRO
- Peter Kerr, Principal at KerrNected Space at SmartSat CRC
- Dr Rebecca Coates, Research Scientist in Responsible Innovation at CSIRO

Panel 4 – Utilising the space environment to test & develop quantum technologies

Chair: Professor Andre Luiten, co-founder and Managing Director of QuantX,
Chair of Experimental Physics at the University of Adelaide

- Dr Pina Dall'Armi Stoks, Research Leader Undersea Systems at Defence Science and Technology Group (DSTG)
- Dr Hai Tan Tran, Researcher at DTSG
- Dr Howard D'Costa, Assistant Director Space Communications Lead at Australian Space Agency
- Dr Jim Rabeau, President of Infleqtion Australia

Breakout sessions

Five breakout sessions focused on space sector issues where there could be applications of quantum technology.

Overview of government funding opportunities

Nicola Powell, Manager in the Quantum Branch, Department of Industry, Science and Resources

Next steps and closing statement

Dr Cathy Foley, Australia's Chief Scientist

Keynotes

Critical challenges for the space sector

Dr Geraldine Baca Triveno, Director of Space Systems at Deloitte Space, referred to the economic opportunity of space, which could be worth US$1.8 trillion by 2035.[2] She said quantum technologies played a role in both upstream and downstream capacities, with an emphasis on communications, satellite design and manufacture, as well as solving community challenges for the benefit of society. Working with international satellite constellation companies, she noted digital twins were used to simulate orbital configurations and coverage, with future roadmaps seeking to incorporate quantum algorithms for detailed analysis. She then discussed the Deloitte gravity challenge which saw students from the Imperial College, London, investigate integrating satellite communications with internet enabled devices to track and monitor the health of Northern Territory nurses operating in remote communities.

Imelda Alexopoulos, Director of Exploration Strategy at Fleet Space, explained Fleet's mission to connect the Earth, Moon and Mars through commercial space exploration. She described Fleet Space as a leader in using ambient noise tomography for finding minerals with its technology, ExoSphere. It had also started using this technique for exploring the Moon with SPIDER (Seismic Payload for Interplanetary Discovery, Exploration, and Research). Alexopoulos noted customers were always seeking high-quality, higher resolution data. Quantum technologies such as magnetometers, gravimeters and muon tomography could provide solutions.

Meeting the challenge with quantum

Dr Jie Zhou, a researcher in the quantum optics group at the Australian National University, described space as a great place to test and combine the theories of quantum and general relativity. She spoke about quantum key distribution (QKD), which helps secure communications, and described a big achievement in 2017 by a team at the University of Science and Technology in China. This work showed the first secure quantum communication through the Micius satellite, with an encrypted virtual teleconference between Beijing and Vienna.

To overcome bottlenecks in ground communication, quantum repeaters were needed to communicate across transmission distances of more than 200 km. New protocols in QKD, distributed quantum sensing and better quantum memory were standouts of Australian quantum expertise.

Professor Jim Rabeau, then- President of Infleqtion Australia, welcomed the increasing maturity of the quantum sector. He noted that in the past, presentations focused on basic quantum physics, whereas now they focused on practical and near-term applications. While progress was being made, challenges

[2] https://www3.weforum.org/docs/WEF_Space_2024.pdf

remained. For example, qubits were sensitive to temperature, vibration and electromagnetic fields. However, the unique characteristics of the space environment made it an ideal place for quantum technologies, such as atomic clocks. He also highlighted the Cold Atom Lab experiments on the International Space Station, which aimed to deepen our understanding of quantum phenomena, and the GRACE missions, which used laser interferometry to measure small changes in Earth's gravity. This helped improve understanding of environmental processes affected by climate change, such as changing water levels.

Panel composition and discussions

Panel 1 – Quantum sensing for understanding Earth and space

Chair: Professor Allison Kealy, Director of the Innovative Planet Research Institute at Swinburne University of Technology

- Professor Andrew Greentree, Professor of Quantum Physics at RMIT
- Dr Jie Zhou, Researcher in the Department of Quantum Science and Technology at ANU
- Professor Andre Luiten, co-founder and Managing Director of QuantX, Chair of Experimental Physics at the University of Adelaide
- Dr Stephen Gensemer, Senior Research Scientist at CSIRO

This discussion focused on the opportunities and challenges of using quantum technologies for sensing. An important theme was improving climate models and getting better and higher resolution data to address environmental impacts. For example, one application includes using active optical sensing to measure trace gases like methane to monitor Earth's carbon emissions. To achieve this, specific laser and detection technologies need to be developed. Additionally, quantum cryptography could play a role in securing sensitive data collected through quantum-enhanced sensing.

Image 1. Panel 1 discussion.

Panel 2 – Quantum technologies for enabling space based PNT and communications

Chair: Professor Andrew White, Director of the Quantum Technology Lab and of the Australian Research Council Centre for Engineered Quantum Systems, Professor of Physics at the University of Queensland

- Dr Alex Arriola Martiarena, Photonics Team Leader at Advanced Navigation
- Nick Miller, Senior Director, Optus Satellite and Space at Optus
- Dr Michael Hush, Chief Scientific Officer at Q-CTRL
- Professor Ed Kruzins, Professor of Space Communications and Tracking at UNSW and Adjunct Professor at University of Adelaide.

Quantum technologies can improve space-based PNT and communications, including ground stations. Complete and precise gravity maps can provide the reference frame in which a quantum gravimeter could provide absolute location information independent of GPS connectivity – thereby providing reliability and resilience in applications where PNT are critical. Increasing the commercial use of large research and development efforts, and the role of quantum technologies in deep-space exploration, especially the idea of following the water, are essential. Searching for evidence of water is considered important for long-term missions and finding life elsewhere in the solar system.

Image 2. Panel 2 discussion.

Panel 3 – Quantum technologies for a sustainable space environment

Chair: Dr Marcel Bick, Business Development Manager at CSIRO

- Tori Tasker, Director Human Spacelight Strategy and Projects at RayTracer
- Nick Carter, Space Research Group Lead at CSIRO
- Peter Kerr, Principal at KerrNected Space at SmartSat CRC
- Dr Rebecca Coates, Research Scientist in Responsible Innovation at CSIRO

The discussion focused on the meaning of sustainability in space and quantum technologies, and the importance of innovating responsibly and understanding the risks of quantum technologies. Real-time health-monitoring data could support human spaceflights by enabling real-time decisions.

Another possible application suggested was the ability to support and sustain space activities, including trust in the availability of data and spectrum allocation, or managing space debris. Quantum technologies, with higher sensitivity than classical systems could offer improved performance for tracking fast-moving, low-reflectivity objects. Furthermore, a quantum telescope can see objects that classical telescopes cannot.

Image 3. Panel 3 discussion.

Panel 4 – Utilising the space environment to test and develop quantum technologies

Chair: Professor Andre Luiten, co-founder and Managing Director of QuantX,
Chair of Experimental Physics at the University of Adelaide

- Dr Pina Dall'Armi Stoks, Research Leader Undersea Systems at DSTG
- Dr Hai Tan Tran, Researcher at DTSG
- Dr Howard D'Costa, Assistant Director Space Communications Lead at Australian Space Agency
- Dr Jim Rabeau, President of Infleqtion Australia

The discussion highlighted the unique properties of space that could benefit quantum technology, such as the lack of interference from the environment. Certain parts of the electromagnetic spectrum are not weakened in space, which makes it possible to harness the magnetic and scattering properties of fields. Devevloping quantum technologies to a level suitable for space use is challenging, and international collaboration with partners such as the US and Singapore is crucial to overcome these challenges.

Such collaboration could also facilitate the creation of a dedicated test area for space-enabled quantum technologies. The discussion concluded with a call for 'quantum moonshot' ideas, such as using the shadowed regions of the Moon to control the temperature for a lunar-based quantum computer, applying quantum technologies to existing missions like GRACE to help predict water levels and manage fire risks, and establishing a cooperative research centre (CRC) for space-based quantum systems.

Image 4. Panel 4 discussion.

Breakout sessions

Image 5. Breakout sessions.

Attendees broke into smaller groups to discuss the following topics:

- quantum for deep space
- quantum solutions for tracking and mitigation
- quantum technologies for carbon and climate monitoring from space
- PNT (for Earth and space) and mapping
- space situational awareness for defence.

The breakout sessions aimed to define a series of problems based on the themes above and identify the quantum applications and the breakthroughs needed in order to propose a solution. Common problems across all themes included:

- securely transferring data
- combining traditional and quantum systems
- detecting and identifying objects in space
- making sensors more sensitive for observing Earth and creating maps.

Attendees noted that quantum technologies have the potential to bring real benefits to the space industry, such as:

- Better sensors for applications such as monitoring Earth's weather or finding minerals.

- Quantum-enabled communications and services for positioning, navigation, and timing (PNT), particularly in places where GPS does not work, such as underground or underwater.
- Engineering and fundamental physics experiments in space.

In realising these opportunities, attendees highlighted the importance of managing the thermal properties, size, weight and power (SWAP), sensor requirements and cyber needs of quantum technologies in space and finding a clear market demand and public benefit for these services.

Space and quantum sector representatives agreed that both sectors should work together to ensure smooth integration between classical and quantum technologies and an easy exchange of information between systems. Ideas generated included developing a quantum for space roadmap or decadal plan, setting up a relevant CRC and setting up a test bed for integration and testing of quantum systems in comparison to classical ones.

Attendees also discussed the importance for the quantum sector of understanding current space missions and existing capabilities to avoid missing opportunities where quantum technologies could be used. The GRACE missions (Gravity Recovery and Climate Experiment)[3] and Cold Atom Lab experiments[4] were highlighted as examples of space-based experiments that explore quantum phenomena.

The interest and discussions on these topics are the foundation of the case studies in the appendix. These case studies show the opportunities to understand and capture market value by leveraging existing national strengths, infrastructure and expertise.

[3] https://earth.gsfc.nasa.gov/geo/missions/grace
[4] https://coldatomlab.jpl.nasa.gov/

Next steps and closing

Dr Foley reiterated the estimated worth of the space industry and the importance of identifying and understanding the market needs of both upstream and downstream users of space, such that quantum technologies have a clear vision of the potential value-add. She summarised opportunities for quantum in space explored throughout the day, including PNT, gravity mapping, deep-space communications for science exploration and space situational awareness. She acknowledged the challenges of ensuring quantum technologies were space-ready and suggested that leveraging international partnerships to create dedicated space quantum test beds could accelerate the growth and uptake of these technologies in Australia.

Dr Foley also noted the power of quantum and space as future thinking and inspiring realms in their own right. Bringing the two fields together would attract young people to develop the much-needed workforce for the future and to foster an interdisciplinary culture where the two sectors need not be mutually exclusive.

To ensure the quantum sector was aware of the opportunities in the space domain, stakeholders should be informed of existing space programs that could benefit from the integration of quantum technologies alongside classical systems. Missions that served a public good, such as those that involved environment and climate monitoring, could also serve to make a lasting impact on public perception, further boosting the profile of quantum and delivering on government priorities.

Dr Foley concluded that quantum engagement was an imperative and an opportunity for Australia to lead. Commercialising emerging technologies was challenging but could be overcome through collaboration between quantum researchers, industry and government.

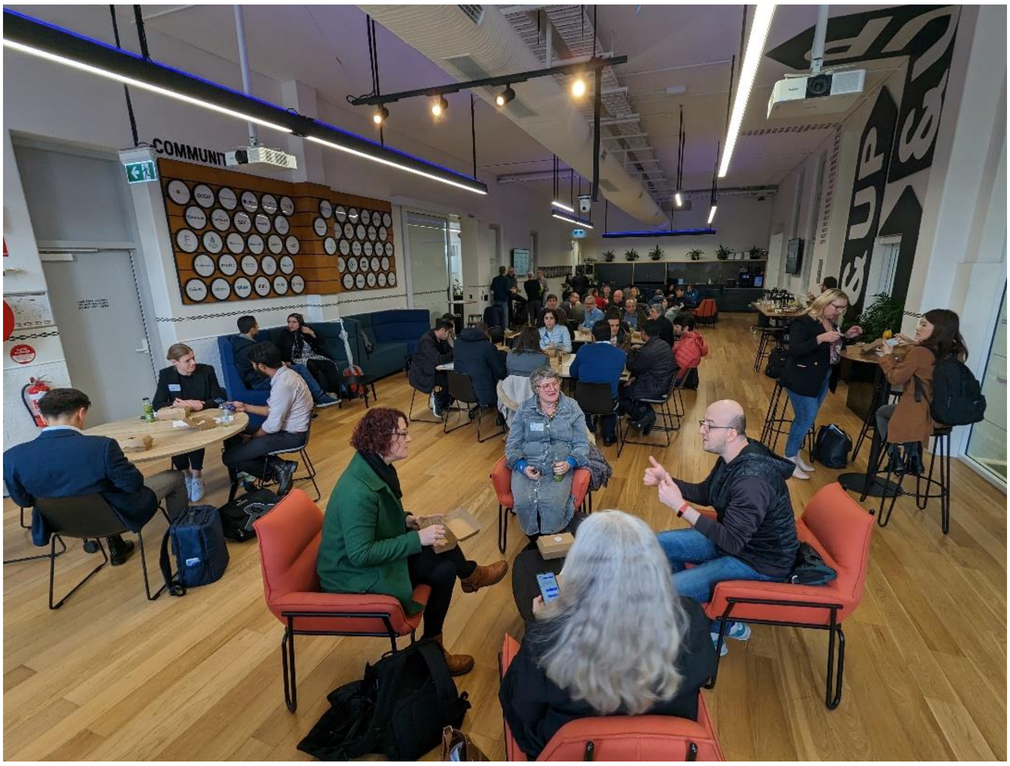


Image 6. Discussions continuing over lunch.

Appendix: case studies

Case study 1: Australia paving the way for future quantum communications infrastructure

Background

The significance of quantum communications in supporting critical market sectors is becoming increasingly prevalent in widely held discussions across Australia. Following the Quantum Communications Forum held on 21 March 2024 in Canberra, it was projected that the industry would have an estimated value between US$1 billion and USS7 billion dollars by 2040[5].

The space domain is undergoing a rapid transformation. With the rise of commercial launch and service providers, lower costs and availability of commercially available, off-the-shelf components, more industries are looking to establish their place in space.

The NASA-led Moon to Mars program, encompassing the Artemis missions, seeks to achieve a suite of scientific goals and technical challenges, many of which have never been undertaken in the history of humankind, including landing the first woman and person of colour on the south pole of the Moon. Deep-space communications are critical in ensuring the success of these missions. NASA's Glen Research Centre is already investigating the application of entangled photons for enabling deep-space communication, resulting in enhanced security, lower signal-to-noise ratio and representing "a breakthrough for a wide variety of terrestrial, scientific, military and field deployable applications".[6]

It's recognised that space is a key enabler of quantum communications and its underpinning technology. Australia has a long history in deep-space communications, including supporting the Apollo missions and the first Moon landing. Space-based infrastructure is a necessity to effectively realise the goal of establishing a truly global quantum internet. Such a network would have vast implications across finance, health, defence capabilities, logistics and transport, and energy services.

Significant investments have already been made, including the $10 million dollar investment from the Australian Government for optical ground stations through ANU ($6.2 million) and UWA ($4.4 million).

Australia's competitive advantage

"Australia's geographical size and minimal cloud cover, together with strong optical communications research have set the foundations for competitive advantage in the provision of optical ground station segments"[7]

ANU is seeking to develop the first Australian deep-space communication-capable optical ground station, ensuring that it is compatible with NASA's Optical to Orion mission. This will pave the way for a future commercial optical communication service by supporting laser links to missions in low Earth Orbit, lunar and deep-space orbits.

[5] https://www3.weforum.org/docs/WEF_Amplifying_the_Global_Value_of_Earth_Observation_2024.pdf
[6] https://technology.nasa.gov/patent/LEW-TOPS-108
[7] https://www.industry.gov.au/sites/default/files/2024-02/communications-technologies-and-services-roadmap-2021-2030.pdf

It will also demonstrate cross-continental optical networking between the ANU optical ground station (OGS) and TeraNet, a three-node commercial OGS which will support low-Earth-orbit communications. As these technologies mature and develop, with Australia at the forefront in quantum technologies, there are opportunities for the quantum industry in Australia to reach cross- cutting sectors and end-user markets as they become increasingly reliant on space-based communication.

As space exploration missions become more ambitious, with an increase in crewed missions and crewed space flight, there is an opportunity to elevate our technology on the world stage: supporting deep-space communications; relaying critical, time-sensitive astronaut heath data to ground crews; and optimising decision and mission planning.

Opportunities also exist in developing security for quantum communications. Researchers at Griffith University's Centre for Quantum Communication are leading an international effort to demonstrate how "networks can be utilised to overcome noise in quantum communications",[8] developing an experiment that aims to simulate a future quantum internet.

The ANU, in collaboration with Nanyang Technological University in Singapore, has demonstrated a proof-of-principle CV-QKD system on a silicon photonic chip, creating a stabilised, miniaturised, and low-cost system that is compatible with existing fibre-optical communications infrastructure.

Continued international collaborations, along with mechanisms for fast turnaround times, are critical to accelerating Australian technology readiness levels for quantum technologies.

Image 7. TeraNet, one of the first optical communications networks to be built in Australia. ***Photograph courtesy of University of Western Australia***

[8] https://www.cqc2t.org/a-breakthrough-step-towards-noise-robust-quantum-networks/

Opportunities

- Showcasing Australia's significant quantum communications capability to substantially contribute to international space missions. This includes support for NASA's Artemis Program.
- Increased visibility for quantum industries in cross-cutting sectors, via space-enabled services. Accessing end-user markets that are becoming increasing reliant on space-based communication services is key to determining market gaps and value add.
- Establishing secure foundations and infrastructure for a global quantum internet would drive demand for security measures. This would open the door for Australian-international partnerships (current and future) to further accelerate achievements in quantum key distribution and quantum memory.
- Leveraging partnerships between Australian industry, academia and defence in quantum communications.

Challenges

- Understanding the impacts of quantum key distribution over long transmission distances.
- Developing the coherent exchange of information between quantum systems.
- Enabling seamless integration between classical and quantum systems.
- Elevating technology readiness levels of current Australian quantum technologies and effectively translating the seemingly large research and development effort in Australia into an uptake of commercialisation.
- Reliance on equipment/infrastructure from overseas.
- Understanding the impacts of quantum key distribution over long transmission distances.
- Developing the coherent exchange of information between quantum systems.
- Consolidating a mechanism for faster turnaround times when engaging with international collaborations.

Case study 2: Integrating quantum technologies with Earth observation services

Background

Earth observation (EO) has become increasingly important worldwide as a major data stream source for real/near time climate and environmental monitoring. Additionally, for providing crucial insight for those sectors dependent on up-to-date models, including agriculture, fisheries and disaster management.

NASA is focusing on a new Earth Systems Explorers[9] program, while the European Commission's Joint Research Centre (JRC) has recently outlined a new Strategic Research and Innovation Agenda for Earth Observation, focusing on the Copernicus missions. A major component of the EU space program, the agenda places particular emphasis on incorporating quantum gravity field measurements as part of its Space Component Long Term Scenario, and fostering a Quantum Space Gravity Pathfinder mission, developed through Horizon Europe.[10]

Australia's opportunity

In Australia alone, EO services are used across various sectors of government, industry and society. The Australian Earth Community Plan 2026 states that the minimum impact of EO from space-borne sensors alone is approximately $5.3 billion each year.[11] The World Economic Forum (WEF) insight report on amplifying the global value of Earth observation further suggests that EO could add $703 billion to the global economy while eliminating 2 gigatons of greenhouse gas emissions in 2030.[12]

According to Geoscience Australia, Australia has one of the largest exclusive economic zones in the world, with 10.2 million square kilometres of ocean.[13] Managing, using, and responding to the natural environment, climate change and population growth are critically reliant upon EO from space.

Australia has niche EO requirements that afford the opportunity to develop new capabilities and data streams. For example, Australia needs unique combinations of spatial, spectral radiometric and temporal resolutions that allow collection against the typically small inland bodies and narrow rivers found across the Australian land mass.[14] EO missions can have a significant part to play in addressing several government priorities to ensure economic resilience, growth and productivity, including the monitoring of renewables and low emission technologies, transport and value-add in agriculture, forestry and fisheries.

Existing and future EO missions may hold the potential to address key market gaps both in a national and international context, while serving as a driving force to increase technology readiness levels (TRL) of both space and quantum-based technologies.

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[9] https://www.nasa.gov/news-release/new-proposals-to-help-nasa-advance-knowledge-of-our-changing-climate/
[10] https://publications.jrc.ec.europa.eu/repository/handle/JRC136730
[11] https://static1.squarespace.com/static/59b76501914e6bd226708d7a/t/5d8d9b9a59c029599d11504f/1569561572570/AEOCP+final_web.pdf
[12] https://www3.weforum.org/docs/WEF_Amplifying_the_Global_Value_of_Earth_Observation_2024.pdf
[13] https://www.ga.gov.au/scientific-topics/national-location-information/dimensions/oceans-and-seas
[14] https://www.industry.gov.au/sites/default/files/2024-02/earth-observation-from-space-roadmap-2021-2030.pdf

Australia's competitive advantage

The Quantum Meets Space event found that EO could address several key themes with potential opportunities for the space and quantum industry. These include:

- The need to clearly identify market gaps, specifically those where quantum technologies could provide a significant advantage over classical systems.
- Identifying investments that serve a public good.
- Clear links to government priorities.

Clear market gaps exist with regard to advanced sensors with a need from end users for higher resolution data. Quantum sensing provides a significant advantage in terms of resolution over its classical counterparts. At the event speakers mentioned that Australia's quantum industry is making significant headway in this field and highlighted a few companies including:

- Sydney based **Q-CTRL**,"building a new generation of software-defined atomic sensors for magnetic and gravitational signals, high sensitivity and best-in-class, long term stability to enable new observational techniques".[15]
- **Nomad Atomics**, developing quantum sensors for commercial geological surveying applications.[16]
- **Quantum Brilliance**, developing a "few-qubit systems test bed designed to enable research and innovation in quantum computing and sensing".[17]

Australia's EO community already has deep knowledge on how to best utilise EO data, specifically in the context of land sand sea monitoring, agriculture and climate. **Geoscience Australia** has been working closely with the United States Geological Survey (USGS) Landsat Sustainable Imaging program data for more than 40 years. [18]

As the volume and complexity of EO data is only set to increase, those in the space sector should seek to integrate upcoming technologies, such as quantum, which can potentially support the processing, analysis, visualisation and distribution of these diverse data sets. Additionally, enhanced protocols to handle data sensitivities are needed. **Quintessence Labs**, based in Canberra, has previously partnered with a number of Australian universities as well as defence to provide a suite of cybersecurity measures, including QKD and quantum random number generation.

Australian researchers from the **ANU** have been extensively involved in GRACE (the Gravity Recovery and Climate Experiment), which has been instrumental in providing data to address gaps in the understanding of hydrology. The research team developed "a retroflector that uses lasers to measure the world's water reserves from space with unprecedented accuracy".[19] Laser ranging interferometry measures the change in speed of the two GRACE spacecraft, caused by subtle changes in the Earth's gravity due to landscape deformations from large bodies of water. This method can detect changes down to 10 nanometres in separation.

Measuring changes in gravitational fields can also open new opportunities for mineral exploration, and critical resources needed for renewable technologies. Q-CTRL is working with Transparent Earth to explore the use of onsite and potential space-based exploration of Earth's mineral composition

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[15] https://q-ctrl.com/our-work/earth-observation
[16] https://www.nomadatomics.com/
[17] https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/future-industries/quantum
[18] Geoscience Australia, http://www.ga.gov.au/news-events/ features/40-years-of-landsat-in-australia 17 For example, ground-based sensors can link wat
[19] https://www.abc.net.au/news/2018-06-23/australians-space-mission-to-measure-world-groundwater-reserves/9899730

through quantum gravity gradiometers, in partnership with USGS and funded by the Australian Government CRC-P program.

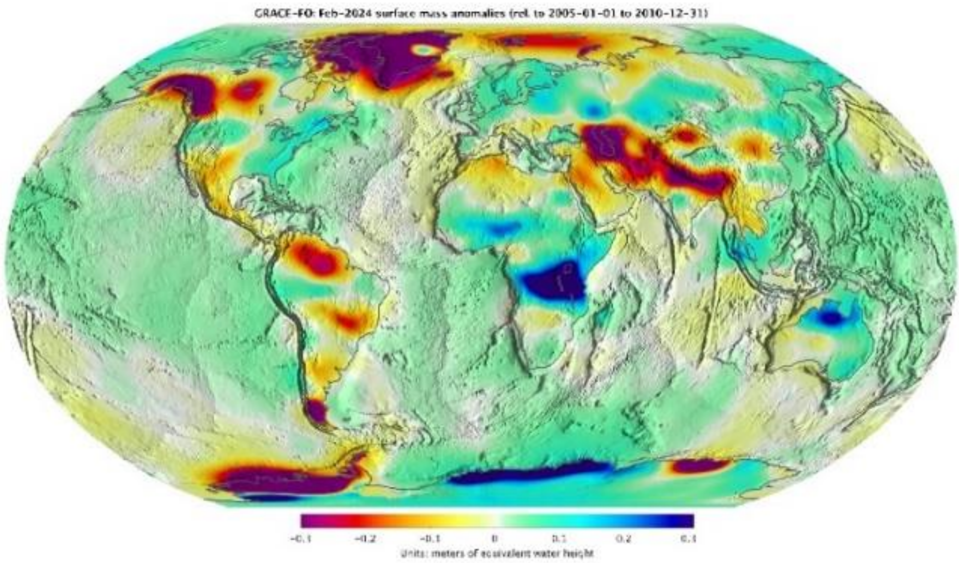

Image 8. Global surface mass anomalies observed by the GRACE-FO satellites. Image courtesy of NASA, JPL

Opportunities

- The Australian EO from space sector directly contributed $283 million in value to the Australian economy and employed 15,720 full time equivalent people in 2020.[20] Augmentation of quantum technologies with current capabilities could support quantum stakeholders to tap into a growing market.
- Increased visibility for quantum stakeholders to downstream uses, which are increasingly dependent on space-enabled technologies.
- Applicability of quantum-enhanced adaptive optics sensing to enhance trace gas measurements, particularly methane, to monitor Earth carbon emissions and contribute to international climate monitoring efforts facilitated by EO.
- Ability to effectively address size, weight and power concerns for the space industry over classical systems.
- As well as sensing, quantum key distribution and post quantum cryptography have a role to play to address security concerns and data sensitivities, integrated over various stages of the lifecycle of the missions.
- Establishing a coordinated network between the space and quantum sectors to inform stakeholders of existing and upcoming space missions where quantum technologies could augment existing capabilities.
- Leveraging upcoming missions, such as the 2028 launch of the next GRACE mission. Hybrid accelerometers and more precise PNT, using quantum noise limited lasers, could add value to current classical systems.

[20] Deloitte Access Economics, Economic study into an Australian continuous launch small satellite program for Earth observation, 2021, p. 7

Challenges

- Quantum sensors need to have minute thermal control with limited variability, to reduce noise and interference. However, spacecraft are designed to withstand the harsh environment and extreme swings in temperature, depending on which part of the spacecraft is facing the sun, and which is exposed to the cold depths of space. Addressing this dichotomy of temperature profiles is one of the key challenges for deploying quantum technologies in space.
- There is a need for specific laser and detection technologies to meet current requirements, evolving current TRL's and a reliance on international partners. The coordination of a dedicated quantum-space technology test bed was one such suggestion to mitigate this issue.
- The European Space Agency has noted that "the quality, availability and reliability of Earth Observation products need to improve in order to increase customer take up and detention".[21] While the improvement of sensors can be seen as a challenge, it is also an opportunity to build on current Australian capability to fill a clear market gap.

[21] https://www.esa.int/Applications/Observing_the_Earth/Six_trends_to_watch_in_commercial_Earth_observation