Australian Academy of Science

NATIONAL COMMITTEE FOR SPACE AND RADIO SCIENCE | AUSTRALIAN ACADEMY OF SCIENCE | JANUARY 2022

Australia in Space

A DECADAL PLAN FOR AUSTRALIAN SPACE SCIENCE 2021–2030

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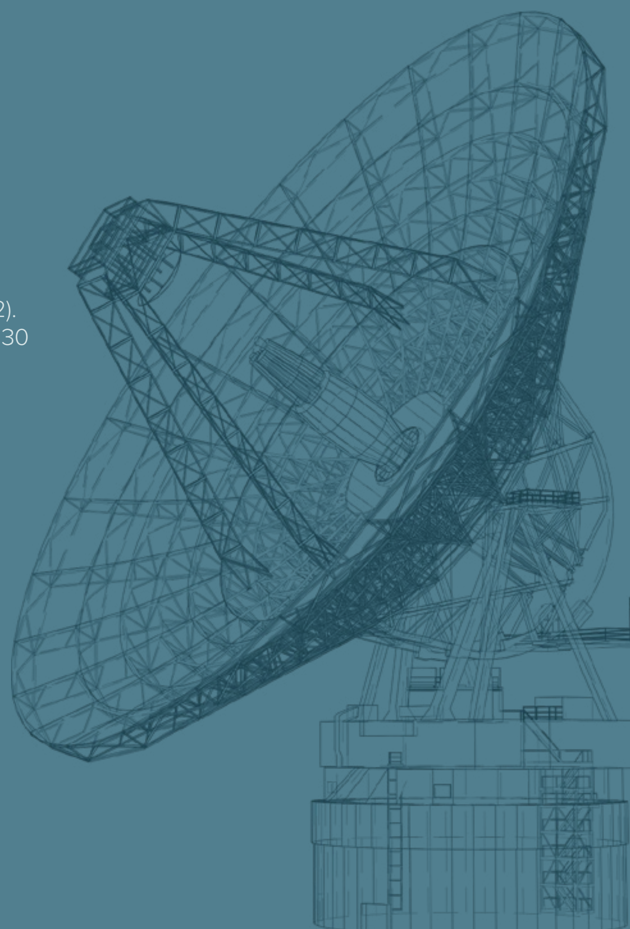
ACKNOWLEDGEMENT OF COUNTRY

The Australian Academy of Science acknowledges and pays respects to the Ngunnawal people, the Traditional Owners of the lands on which the Academy office is located. The Academy also acknowledges and pays respects to the Traditional Owners and the Elders past, present and emerging of all the lands on which the Academy operates, and its Fellows live and work. They hold the memories, traditions, cultures and hopes of Aboriginal and Torres Strait Islander peoples of Australia.



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Cover image: Joshua Steves / NASA Earth Observatory
'Iron-rich aerosols from the 2019-2020 fires fertilized huge phytoplankton populations in the far South Pacific.'

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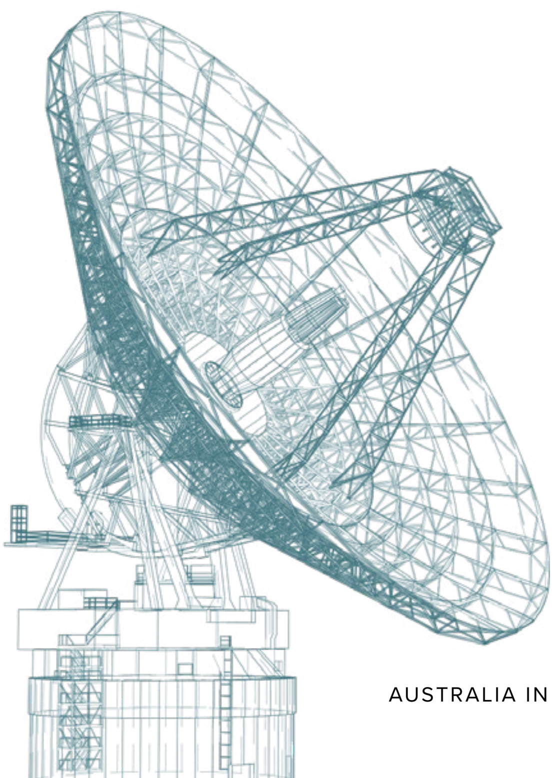


Foreword

Space-derived activities and services underpin much of Australia's economic, environmental and national security, yet are predominantly delivered by foreign entities.

Excellence in space-related science and technology is an important underlying platform for a sustainable, innovation-led Australia. The federal and state governments have implemented strategies and initiatives to stimulate the Australian space industry to develop sovereign capability and grow the innovation sector.

But we can achieve more.

Australia's future in space depends on a commitment to the underpinning science. Without the science we limit our options – an importer of the knowledge and technology we need for our own wellbeing.

We can drive innovation and discovery through Australian and transnational space missions by harnessing our space science expertise. We can lead breakthrough communications technologies, profoundly improve prediction of space hazards impacting critical infrastructure, improve health delivery to ageing and remote populations, contribute meaningfully to international efforts addressing major environmental challenges, and grow our science and technology workforce.

Australia's space research is excellent. This decadal plan presents a strategy, developed with community consensus and through extensive stakeholder consultation, to harness Australia's potential in order to achieve these goals and secure this important contributor to Australia's prosperity.

Professor Ian Chubb AC FAA FTSE

Secretary Science Policy
Australian Academy of Science

High resolution Satellite image of Sydney, Australia Elements of this image furnished by NASA.
CREDIT: SATELLITE STOCKS / ADOBE STOCK

SECTION 1
Executive summary

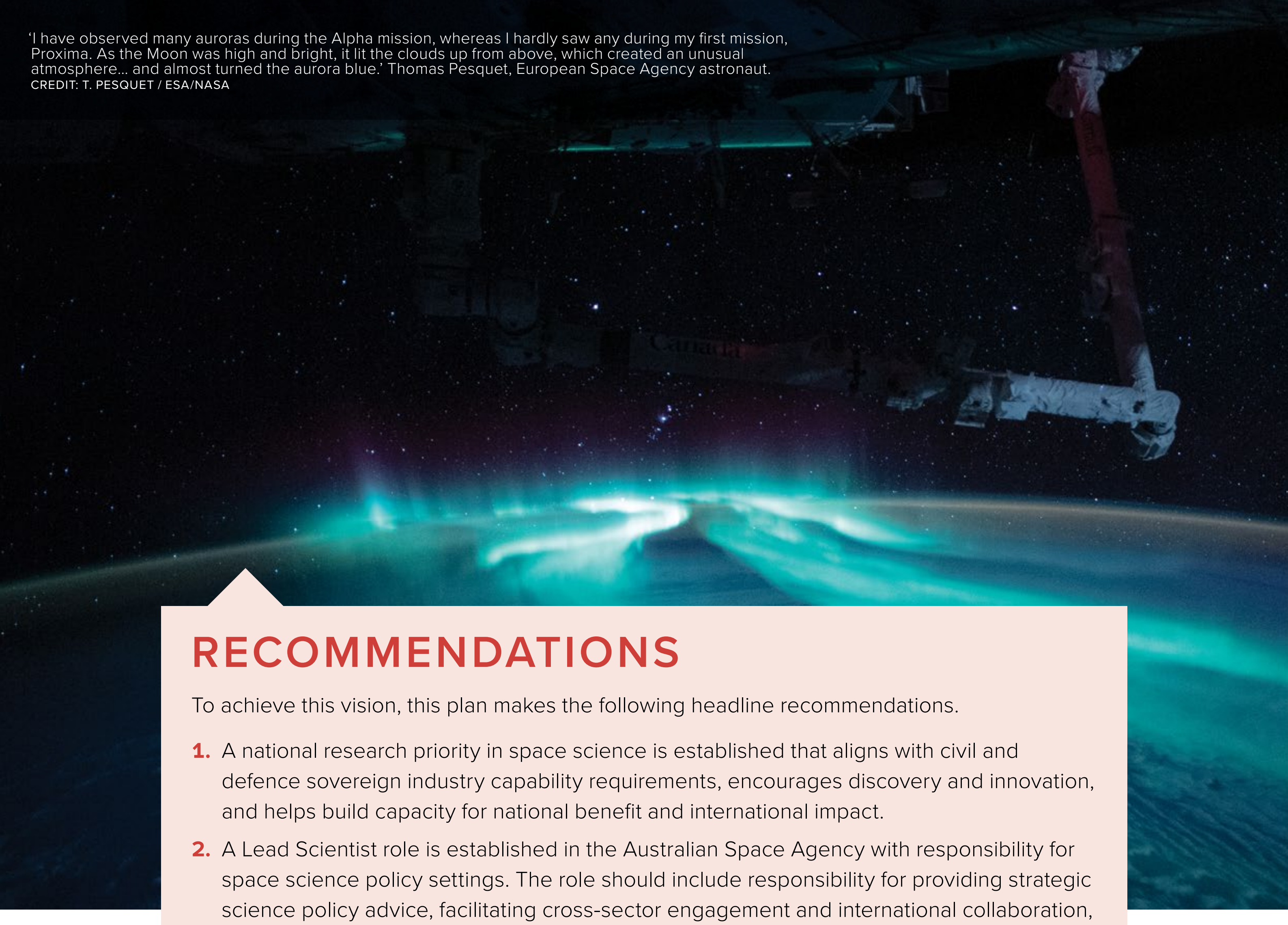
'Human knowledge and human power meet in one.'

FRANCIS BACON

Now is an exciting time to be involved with space. Space-derived activities and services are integral to Australia's economic, environmental and national security, with increasingly diverse and open-market participation in space activities catalysing transformative opportunities but also amplifying risks. Australia aims to exploit new opportunities by growing an internationally competitive space industry which will also build innovation capability and address strategic needs. Key to this is a sustainable space sector built on a foundation of excellence in science and technology.

Space science – the science of exploration and use of space to generate new knowledge, disruptive innovation and practical benefit – is a fundamental enabler for space industry and applications. It underpins the space programs of our partners and our own space aspirations. Australian space science research has established a world-class reputation in many areas. It engages with international space programs and is critical for growing our space capability and mitigating risks. However, Australia's space R&D sector faces several challenges which impact the development and competitiveness of our space economy.

Our vision is for Australia to be a respected partner in the global community of spacefaring nations, leading our own space missions with Australian science teams and Australian-built payloads and spacecraft systems. These missions will propel breakthrough science and technologies, and Australian expertise will contribute to the most significant international space missions. These activities will accelerate development of sovereign space capability and help train and grow a world-class workforce of professionals and technologists to feed the new opportunities arising in the burgeoning high value industry, research and applications sectors.



'I have observed many auroras during the Alpha mission, whereas I hardly saw any during my first mission, Proxima. As the Moon was high and bright, it lit the clouds up from above, which created an unusual atmosphere... and almost turned the aurora blue.' Thomas Pesquet, European Space Agency astronaut.
CREDIT: T. PESQUET / ESA/NASA

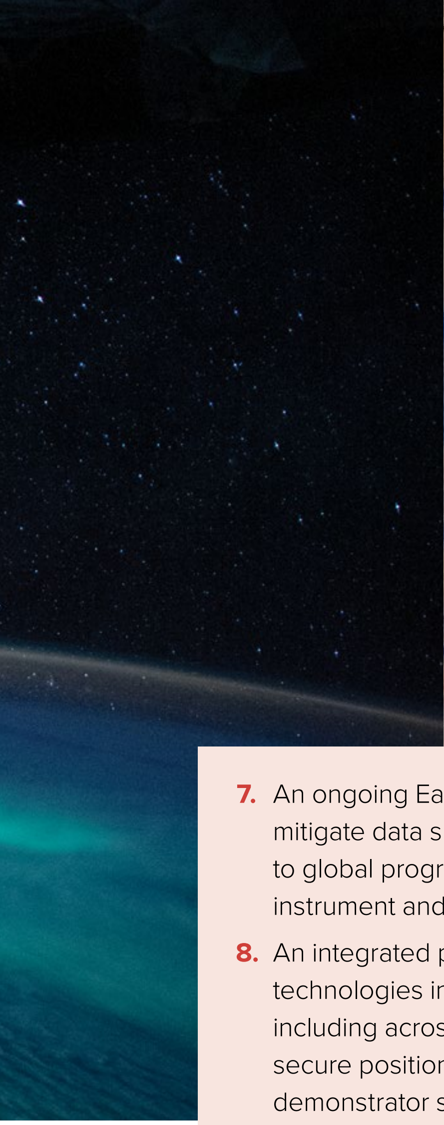
RECOMMENDATIONS

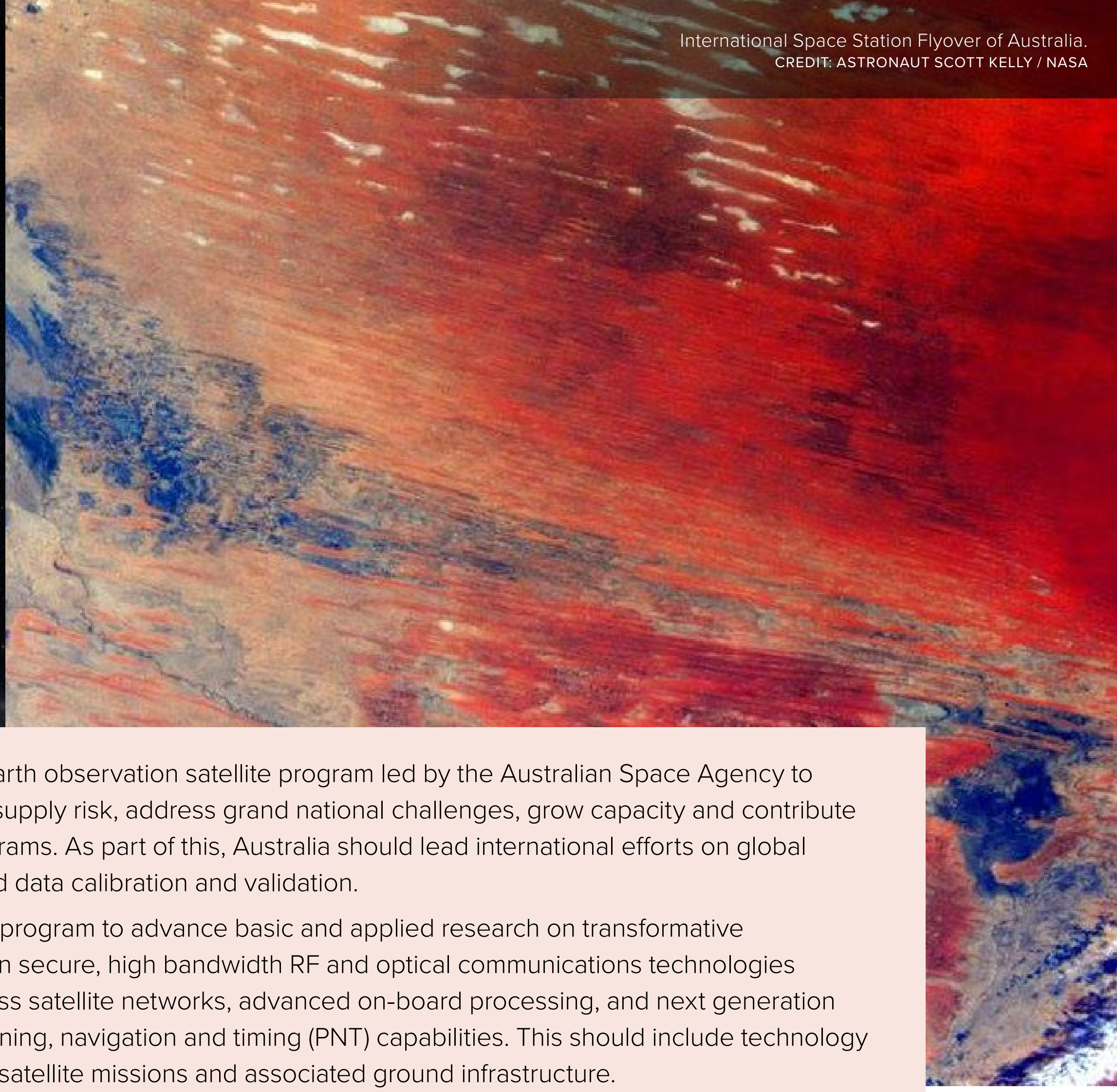
To achieve this vision, this plan makes the following headline recommendations.

1. A national research priority in space science is established that aligns with civil and defence sovereign industry capability requirements, encourages discovery and innovation, and helps build capacity for national benefit and international impact.
2. A Lead Scientist role is established in the Australian Space Agency with responsibility for space science policy settings. The role should include responsibility for providing strategic science policy advice, facilitating cross-sector engagement and international collaboration, and fostering capacity development initiatives.
3. Commitment to and investment in an ongoing national space program, enabled by space missions that advance science, stimulate technical innovation, address national priorities, grow capability and inspire citizens.

These headline recommendations underpin our plan, and are supported by six further recommendations, which seek to develop the following initiatives.

4. An integrated national space innovation and education strategy, led by the Australian Space Agency, that is consistent with the national curriculum, spans the primary, secondary, tertiary, VET and industry sectors, and aims to grow STEM participation, and improve career pathways and industry outcomes, cognisant of the values of diversity and equity.
5. A program of small space missions to advance knowledge and discovery, foster and leverage international collaboration, accelerate development of new technologies, applications and the skilled workforce, and help grow sovereign capability. This should be the responsibility of the Australian Space Agency, with NCRIS or similar support.
6. A national program focusing on space weather research activities to help protect critical infrastructure and advance space weather forecasting and space situational awareness activities. This program should be supported by observations from a diverse and extensive suite of sovereign ground- and space-based sensors.





International Space Station Flyover of Australia.
CREDIT: ASTRONAUT SCOTT KELLY / NASA

7. An ongoing Earth observation satellite program led by the Australian Space Agency to mitigate data supply risk, address grand national challenges, grow capacity and contribute to global programs. As part of this, Australia should lead international efforts on global instrument and data calibration and validation.
8. An integrated program to advance basic and applied research on transformative technologies in secure, high bandwidth RF and optical communications technologies including across satellite networks, advanced on-board processing, and next generation secure positioning, navigation and timing (PNT) capabilities. This should include technology demonstrator satellite missions and associated ground infrastructure.
9. A commitment of support to space life science research, including space medicine and human factors, and space agriculture and nutrition, engaging with international programs and providing translation of research to improve everyday life.

Successful implementation of the plan will result in a range of benefits, including:

- a sustainable national space science program
- enhanced innovation-led growth of the space economy
- more effective science-to-industry partnerships across the space sector
- enhanced STEM engagement and workforce capability
- sovereign capability to develop and operate small and medium satellite space missions
- ability to collaborate and contribute substantively to transnational missions
- an Earth observation program addressing national challenges and providing international leadership
- world-leading space weather forecasting helping protect critical infrastructure and contributing to space situational awareness capability
- next generation space-based communications and secure PNT services
- improvements in telehealth delivery and health outcomes
- improvements in sustainable agriculture and provision of plant-based nutrition.

University of Adelaide mechanical engineering and computer science student Melarn Murphy places an Inovor Technologies satellite into the vacuum chamber at the company's Lot Fourteen headquarters.
CREDIT: REBEKAH HOLLIDAY / INOVOR TECHNOLOGIES

SECTION 2
Space for Australia

'Curiosity and the urge to solve problems are the emotional hallmarks of our species.'

CARL SAGAN

2.1 OBJECTIVES

Australia's economic, environmental and national security depend on space-derived services and capabilities[1]. They enable our communications and data networks, environmental monitoring and management, weather forecasting and emergency services, and positioning information for the agriculture, resources and logistics sectors, and underpin Defence capability.

Globally, increasingly diverse and open-market participation is revolutionising the space domain. This is facilitated by dramatic technology transformation and will spawn new disruptive industries and applications[2].

Capitalising on these technological transformations requires a sustainable space sector built on a foundation of excellence in science and technology.

Australia's civil space priorities are presently industry-focused[3]. Australia aims to grow an internationally competitive space industry which will also build innovation capability and address strategic needs. However, there are many challenges including sustained declines in national manufacturing output[i], as well as in STEM capability[ii], expenditure on R&D[iii], economic complexity[iv], and skilled immigration[v], along with growing geopolitical tensions.

The Australian Space Agency's Civil Space Strategy identifies seven priority sectors for industry growth, with technical roadmaps outlining pathways to delivery. The Australian Government has also targeted space as one of six national manufacturing priority areas within a $1.3 billion Modern Manufacturing Initiative. 'Space' and 'surveillance and intelligence' (including over-the-horizon radars and SSA systems) are sovereign industry capability priorities necessary for the Australian Defence Force's tasks[4] and identified under the Australian Industry Capability plans[5].

These and other activities have led to significant new Australian Government investment in space. These are welcome developments, stimulating growth of the space industry sector. However, the space science research and innovation capabilities necessary to develop a sustainable national space ecosystem have not been similarly enabled.

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i Value added to the Australian economy by manufacturing has decreased from 13.8% of GDP in 1990 to 5.6% in 2019, level with Ethiopia. Source: data.worldbank.org

ii Measured by PISA performance scores in reading, mathematics, and science. Source: data.oecd.org/australia

iii Gross domestic expenditure on R&D has fallen from 2.25% of GDP in 2008 (level with the OECD average), to 1.8% in 2017, compared with the OECD average of 2.4%. Source: data.oecd.org/australia

iv In the Harvard University Atlas of Economic Complexity, representing diversity and complexity of knowledge-based industries, Australia ranks 87 out of 133, below Albania,Guatemala and Uganda. Source: atlas.cid.harvard.edu

v See *Interim report of the inquiry into Australia's skilled migration program*, Joint Standing Committee on Migration, Canberra, March 2021

Tropical Cyclone Harold illustration. Elements of this image are furnished by NASA.
CREDIT: SASA KADRIJEVIC / ADOBE STOCK

This plan takes a science-based approach. It focuses on the national role and importance of space science by drawing on data and defensible evidence. It is informed by the Australian Academy of Science's position statement which 'supports a vigorous and well-supported space industry, sustained by a strong space research sector'[6]. The objectives of this plan are to:

- advance excellence in space science research, enabling leadership and international engagement on challenging programs of exploration and discovery, generating knowledge and stimulating innovation and development of potentially transformative technologies
- grow world-class fundamental and applied research to advance the capabilities and applications which underpin the use of space for societal benefit and national security
- train scientists and technologists across a range of domains enabling growth of the innovation sector and the talent pool including traditionally marginalised groups.

Space science spans robotic and human space exploration; solar system planetary science; space weather science and mitigation of space weather events; remote sensing and Earth observation (EO); space-based positioning, navigation and timing; satellite-enabled communication; and space life sciences. In every case, basic space science discoveries and innovations underpin space technologies, industries and applications.

In countries with mature space programs the space economy value chain usually comprises:[7]

a. universities and public institutions which provide the scientific and technological foundations for space activity

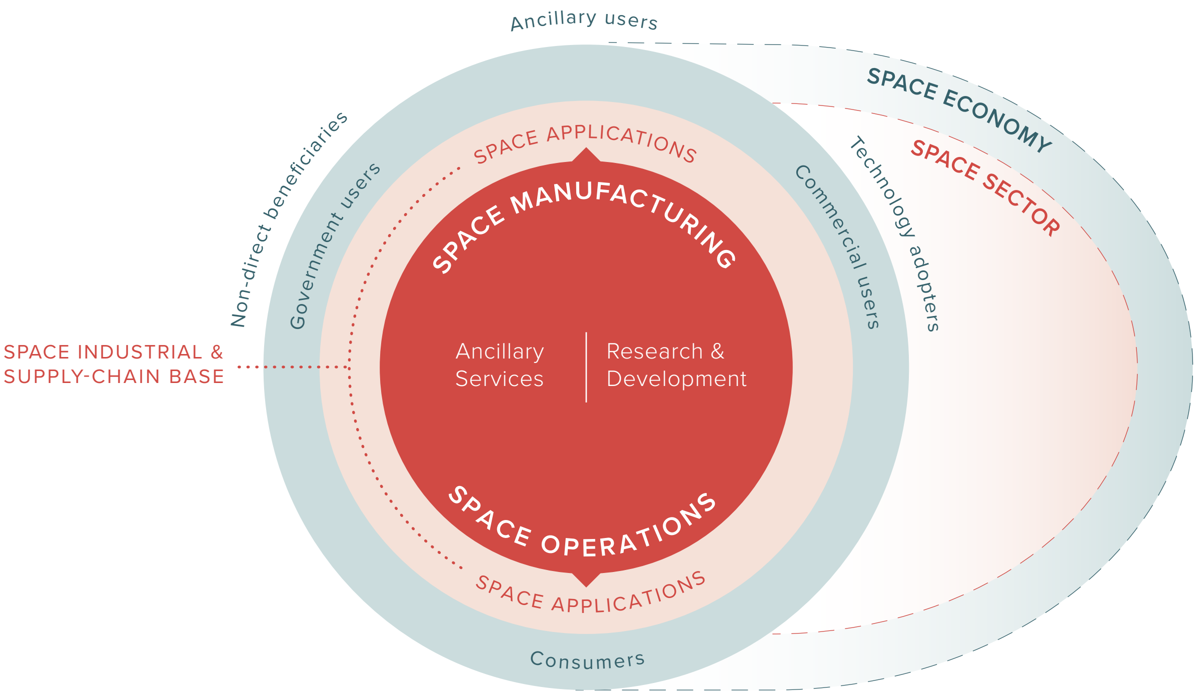
b. upstream sector providers such as spacecraft hardware manufacturers and launch providers

c. downstream sector providers such as satellite operators and Earth observation, PNT and telecommunications applications

d. space-derived activities in other economic sectors.

Relationships between the key elements of the space sector are illustrated in Figure 1. Sectors (a) to (c) are essential for sovereign capability.

Figure 1. Elements underpinning the space economy[8]



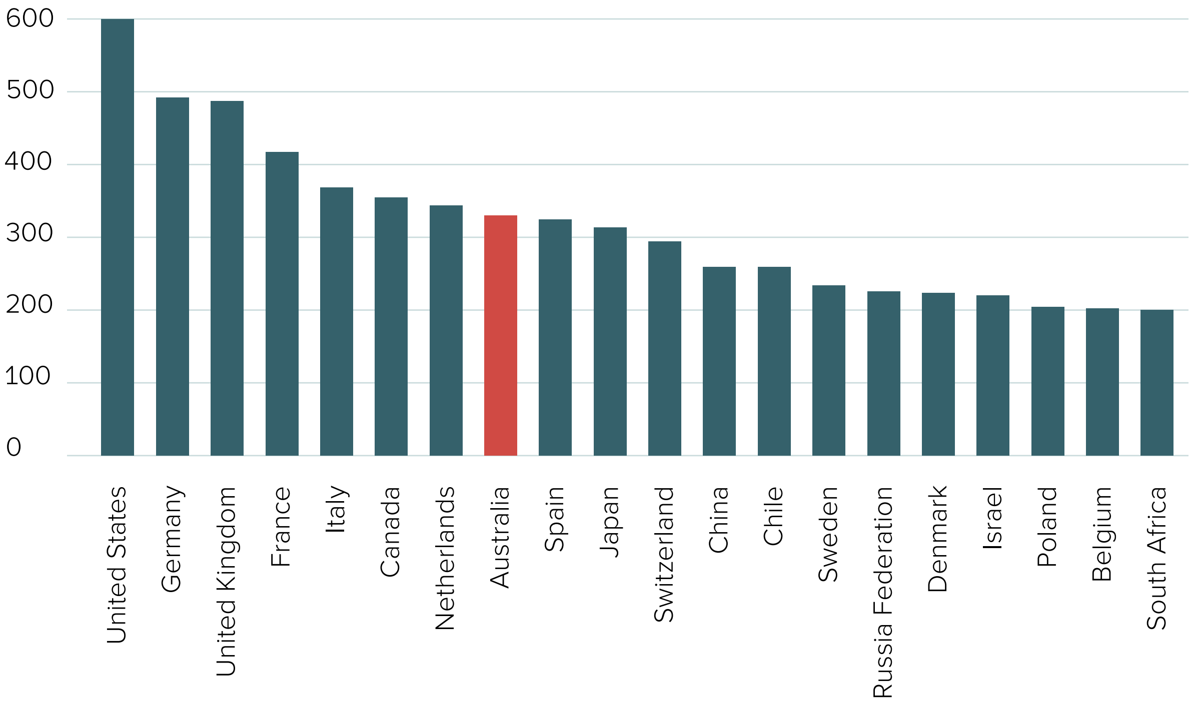
High-quality research and development is a core enabler of the space sector because it generates new knowledge, products and processes, allowing organisations to use the inputs available to them more efficiently and to supply improved products or services to the space sector and broader community. In order to realise new opportunities Australia needs a cohesive but innovative and agile space R&D sector effectively engaging in science-to-industry partnerships. However, institutional investors have yet to embrace this sector, government jurisdictions are risk averse, and institutional barriers within research organisations may inhibit effective application of R&D.

2.2 AUSTRALIAN SPACE SCIENCE

CAPABILITIES

Australian space science research is world class in many areas. This is evidenced by the international standing of peer-reviewed Australian space and planetary science publications, and by Australia's ability to attract major international space conferences[vi] and contribute to international space science programs and missions.

Figure 2. Global rankings in space and planetary science, measured by H-index[9].



In terms of the number and quality of publications, Australian space and planetary science is ranked 8th globally, comparable to Canada and well above China and Russia[vii] (Figure 2).

Australians have contributed to major international space missions since the Apollo era[viii], and continue to work at, and collaborate with, international space agencies, research groups and multinational consortia across all the key space science disciplines. These collaborations can leverage international expertise for national benefit.

There are also opportunities to develop synergies and collaborations between the space science and astronomy communities for future benefit. Areas of interest include atmospheric turbulence on radio and optical signals, space debris detection and developing space mission capability.

vi Space-related international conferences attracted to Australia include: Committee on Space Research (COSPAR, Sydney 2020/21); Asia-Oceania Geosciences Society (AOGS, Melbourne 2022); Asia-Pacific Radio Science Conference (AP-RASC, Sydney 2022); IEEE Geoscience and Remote Sensing Society meeting (GRSS, Brisbane 2025).

vii The OECD obtained the same ranking for Australian space science using a different methodology. Source: *Measuring the economic impact of the space sector, OECD, October 2020*

viii Stuart Ross Taylor (ANU) was NASA PI for lunar geochemistry, and Brian O'Brien (UWA) developed a lunar dust experiment which was deployed by Apollo 11-15.

Australia has provided satellite tracking support for US satellites since 1957. Currently the largest space science facilities in Australia are NASA (DSN, Canberra) and ESA (New Norcia) space tracking complexes, for which CSIRO provides operational support. These facilities play a significant role in support of international space missions.

Examples illustrating the scope of Australian space science activities appear in Appendix C.

INTERNATIONAL SCIENCE DIPLOMACY

Australian space scientists have long featured prominently in the leadership of major international scientific organisations. This provides an important seat at the table in discussions of international space priorities and has helped, for example, mitigate EO data supply risk to date (see Section 3.2). Strengthening our international relations can provide a range of other benefits, including Australian participation in joint missions, with associated opportunities for industry; provision of high-level services for international partners (e.g. EO satellite calibration and validation); participation in joint downstream activities (e.g. development of regional data cubes), and Australian capability development through knowledge transfer. A maturing national space strategy and capability also flags regional leadership in science and innovation domains and trusted partner status for international collaborations[10].

BARRIERS TO GROWTH

Community consultation undertaken to inform this plan (see accompanying volume) identified the following main limitations to growth of the space science sector. These findings complement a KPMG analysis of investment in Australia's space sector[11].

1. ENABLING THE SPACE R&D SECTOR

Australia's space science expertise and capabilities have developed largely through disconnected activities influenced by various institutional priorities and the availability of funding. A more coherent approach is needed to ensure that Australia's space research and innovation sector has the capacity to support national civil and defence sovereign industry capability requirements and growth of the space workforce.

Space science is not currently recognised in the National Science and Research Priorities or the National Collaborative Research Infrastructure Strategy, and was only recently recognised in the Field of Research classification[ix]. This hinders strategic planning and investment in basic space science research, funding for which has come principally for one-off projects from the Australian Research Council (ARC). Over 2016 to 2019 this averaged $2.0 million p.a[x].

New federal investment in civil space activities, such as the Moon to Mars initiative and SmartSat CRC, mostly aims to stimulate rapidly implementable mid-to-high TRL developments, and may require substantial commitments from industry partners. Competition between states and discrete grant schemes further confuses the picture.

ix Until 2021, the Australian Field of Research Classifications grouped astronomy, astrophysics and space and planetary science disciplines together under a common heading. Dependent applications such as satellite design, satellite-based communication, navigation and remote sensing, are separate fields.

x Based on projects identified as primarily space science (e.g. in the Astronomical and Space Sciences FoR classification and clearly dealing with space science research), or identified as including space science (often in other FoR classifications). Does not include the SmartSat CRC.

The result is an ad hoc funding environment, with new entities that have perceived or real overlapping remits with the ARC but insufficient support to sustain the necessary basic research.

More broadly, the overall Australian Government investment in space in 2019 was 0.003% of GDP[12], compared with Canada at 0.016% and South Korea at 0.03%. This is incompatible with Australia's national space ambitions and strategic priorities.

2. NATIONAL COORDINATION AND REPRESENTATION

Australia's space sector comprises many diverse elements across the defence, commercial and civil sectors but needs to be engaged more effectively with the research community to identify key goals and actions. This impacts growth of the innovation industry sector. The entire ecosystem should be working together to progress national space interests.

Much of the science R&D which enables the space sector is based in universities. However, science is not mentioned in the Australian Civil Space Strategy 2019–2028, beyond a call for 'leapfrog R&D'. In this regard the Australian Space Agency differs markedly from its overseas partner agencies, all of which identify science as a core strategic priority. This inhibits engagement with and leadership in international space programs and missions, with flow-on effects on domestic industry capability.

3. A SUSTAINABLE SPACE SECTOR

Australia has critical economic and strategic dependencies on space but no long-term plan to address knowledge and capability gaps. The widespread view is that there are many existing space-related strategies in various organisations but their alignment is poor and their awareness of each other is low. This hinders long-term decision-making by stakeholders, translation of basic research to commercial outcomes, development of sovereign capability and career pathways in the space workforce.

Development of a sustainable Australian space sector requires an overarching strategic plan that embraces all stakeholders and provides a detailed picture of the architecture, components and capabilities to a clearly milestoned timeframe.

4. WORKFORCE CAPABILITY AND CAPACITY

Australia's future depends on a highly skilled and diverse workforce.

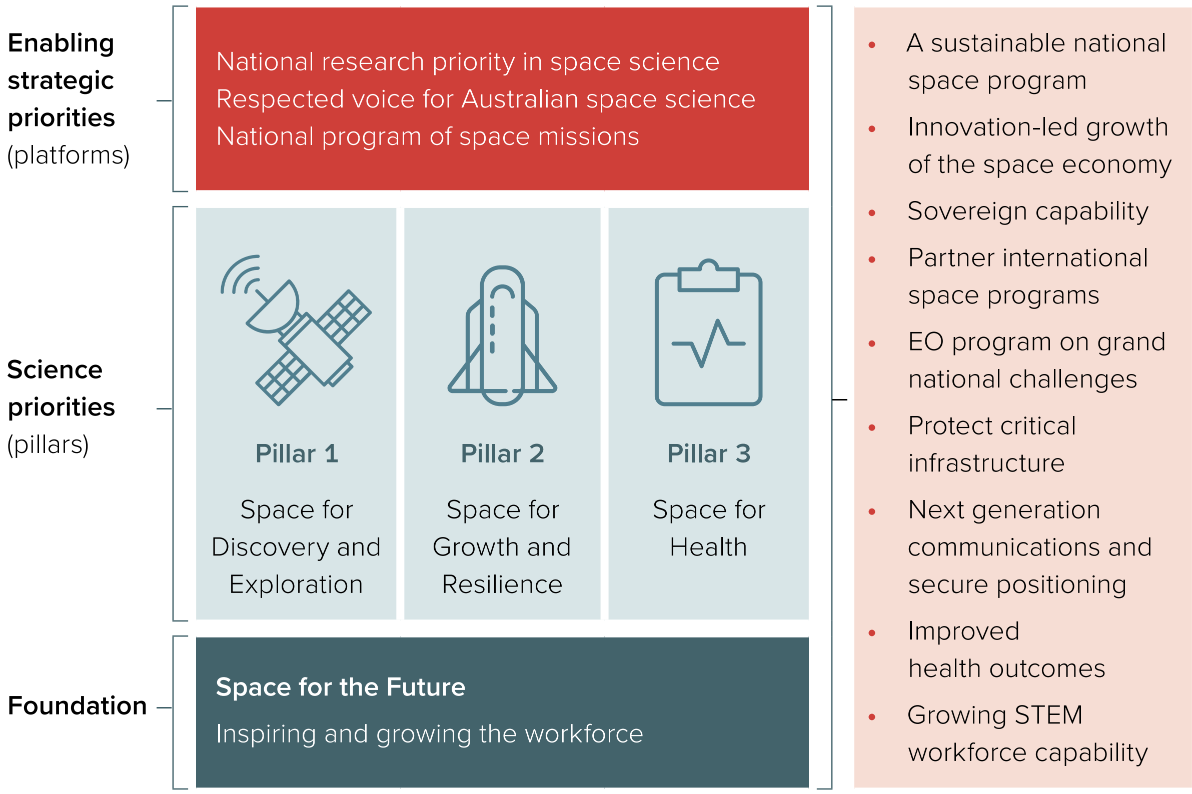
However, a profound workforce skills gap is impacting the space industry[13] and defence[14] sectors. In the downstream sector Australian companies and governments use highly skilled personnel to transform satellite-derived data to measurements and information. A much larger and rapidly increasing number of government, defence and private industries use information and services derived from these data, but would often be unaware of the satellite data pipeline. These sectors are growing rapidly, and failure to meet the skilled workforce capacity represents a risk to economic, environmental and national security.

2.3 STRATEGY

The 2010–2019 Decadal Plan for Australian Space Science brought together Australia's space science community for the first time to identify strengths, aspirations and imperatives. These were important achievements, but much has changed since then.

The present plan outlines a strategy to advance Australia's interests and priorities with a space science sector which drives innovation through mission-oriented capability goals. The strategy is outlined in Figure 3.

Figure 3. Strategy for growing Australia's space R&D capability to generate new knowledge, disruptive innovation, economic growth and practical benefit.



Three overarching strategic priorities form the platforms which enable the main science priorities. These science pillars focus on space science for discovery and exploration, and science-led innovation to benefit our economy, security and society. In reality, space science spans many sectors and disciplines, but this framework helps envision challenges and pathways to outcomes. Development of the workforce forms the underpinning foundation – without this Australia has no sustainable future space sector.

ENABLING PLATFORMS

Three overarching strategic priorities form the enabling platforms necessary to deliver plan outcomes.

1. A NATIONAL RESEARCH PRIORITY IN SPACE SCIENCE

High-quality research and development is a core enabler of the space sector value chain. Moreover, synergies between civil, defence and space industries mean that space R&D can benefit all these sectors[15]. Australian space science is world standard but must be more effectively engaged in support of national space priorities. This requires a national priority, and funding, to ensure a strong science research base with capacity to support Australia's space objectives into the future.

RECOMMENDATION

A national research priority in space science is established that aligns with civil and defence sovereign industry capability requirements, encourages discovery and innovation, and helps build capacity for national benefit and international impact.

2. A RESPECTED VOICE FOR AUSTRALIAN SPACE SCIENCE

A respected, authoritative voice is required to support engagement of Australia's space science expertise with the diverse elements of the domestic space sector and international science programs.

The role should encompass the following responsibilities.

a. Advocacy and strategic policy advice for a sustainable, innovative space R&D sector which can support Australia's space priorities. This would require expansion of the Australian Space Agency's current mandate and funding, for example as part of the review of its statutory basis to take place within four years of its establishment.

b. Enhance engagement between academia, government, the private and industry sector, and end users, to identify opportunities and foster translation of research to practical outcomes.

c. Foster international collaboration between Australian scientists and international space agencies to collaborate on projects and missions, promoting discovery and technology transfer for national benefit.

d. Advocacy to improve the capacity of the space R&D sector, including cross-sector conference and mentoring initiatives, and promoting equity, diversity and inclusion. Some of these activities are currently led by the Australian Academy of Science's National Committee for Space and Radio Science, which is not resourced for such work.

e. Support space-related education and training across national and state jurisdictions.

In line with international practice, the logical entity to perform this function is a Science Office, headed by a Lead Scientist, within our national space agency. While CSIRO is constituted to conduct scientific research to benefit Australian industry and the community, the Australian Space Agency has primary responsibility, under its Charter, for coordinating Australia's civil space matters and leading international civil space engagement.

RECOMMENDATION

A Lead Scientist role is established in the Australian Space Agency with responsibility for space science policy settings. The role should include responsibility for providing strategic science policy advice, facilitating cross-sector engagement and international collaboration, and fostering capacity development initiatives.

3. A NATIONAL PROGRAM OF SPACE MISSIONS

Australia needs to build the heritage and critical mass necessary for sustainable growth of the space sector and strategic sovereign capability. Commitment to an ongoing, challenging national mission-oriented space program would be a pivotal step. Our partner space agencies recognise this and have made science-focused space programs and missions core elements in their overall strategies[xi]. This is because science missions stimulate innovation[16] and bring interdisciplinary collaborators together to solve challenging problems, driving growth of the industry sector and promoting translation to practical outcomes across a broad range of sectors[17].

Commitment to a national ongoing space program would complement the Australian Space Agency's strategic priorities and provide confidence to overseas partners, funding agencies, industry and investors making long-term decisions.

The economic multiplier effects of such programs are well documented[18,19]. For example, the UK Space Agency investments in space science and innovation yield £3-4 in direct value to the space industry and additional spillover impacts of £6-12 for every £1 of public expenditure[20,21]. Spillover outcomes include job creation, revenue generation, productivity improvements, lives saved (or not lost), and lives improved[22,23]. Examples of mechanisms to facilitate development of spinoffs include NASA's highly successful Technology Transfer Program. The lag between investments and spillover impacts for space projects is around 3–5 years, a timeframe challenged by ad hoc and short duration funding schemes.

We propose a pragmatic, structured approach for iteratively developing Australian space capability to realise missions of national importance within a decade, and a vigorous, sustainable space ecosystem beyond that.

Challenging space missions are inspirational. They grow the future space workforce by motivating students to pursue STEM and space-related careers, and by providing the high-level training needed to embark on those careers. An exciting national space program will attract broad public appeal.

A national space program built around science missions will enable Australia to collaborate fully with overseas partners. Following international best practice, such a program should be led by the Australian Space Agency, with access to a specific competitive funding pool. This is compatible with the Australian Space Agency's current remit to grow the space industry.

RECOMMENDATION

Commitment to and investment in an ongoing national space program, enabled by space missions that advance science, stimulate technical innovation, address national priorities, grow capability and inspire citizens.

xi The Australian Space Agency has signed agreements with the space agencies of the UK, India, Italy, Germany, France, EU, USA, Canada, New Zealand and the UAE. All of these operate science-focused space programs and all the agreements mention cooperation on space science and research.

Close up of ISS orbiting Earth globe. 3D render.
Elements of this media furnished by NASA.
CREDIT: GOINYK / ADOBE STOCK

SECTION 3
Space science priorities

'Failure within the mission itself is an option. Failure to progress as a nation is not.'

OMRAN SHARAF, DIRECTOR OF EMIRATES MARS MISSION, MOHAMMED BIN RASHID SPACE CENTRE

3.1 SPACE FOR DISCOVERY AND EXPLORATION

ENABLING INNOVATION THROUGH SCIENCE MISSIONS

Decades of international space activity have shown that the needs of bold science and exploration missions, rather than more operational space activity, drive innovation[24,25]. Like Australia, our international partners are also interested in growing their innovation sectors and realising economic and strategic benefits. They recognise the importance of a challenging space program in this regard. For example, Canada's Space Strategy aims at 'growing the economy ... and ensuring that the benefits of a more innovative society are shared among all Canadians'[26]. Their strategy is called 'Exploration, Imagination, Innovation' and focuses on science and research excellence, delivered through space science and exploration missions; Earth observation, climate change science and communications missions; and using space activity to simulate STEM engagement.

Missions allow industry and research to collaborate around a common goal, are often focused on key national needs, and can leverage international collaborations and the purchasing power of government. Science-focused missions, involving concepts and advances from research groups incentivised by international collaboration and spin-off opportunities, must therefore be prominent in Australia's efforts to grow the industry.

Our vision for 2030 is to see Australia become a respected partner in the global community of spacefaring nations by leading our own science missions, with Australian-led science teams, and Australian-built payloads and spacecraft systems. These missions will propel breakthrough science and technologies. Australian hardware, software and scientific expertise will then contribute to the most significant international space missions. We will create a world-class workforce of scientists and engineers, trained on missions, to feed a burgeoning industry and research sector, and act as ambassadors for our nation as we engage with other agencies.

The development pipeline to realise this vision is based on:

a. significant numbers of highly innovative low-cost science-driven nano- and microsatellite missions which develop new technologies and grow collaborations and capability
b. smaller numbers of high-value small satellite missions focused on priority topics, growing our science horizons, industry capacity and practical applications
c. flagship missions addressing grand national challenges and delivering sovereign capability.

KEY OPPORTUNITIES FOR THE NEXT DECADE

The playing field for Australian space science has been redefined by enhanced access to space, strategic partnerships with international space agencies, and technological advances enabling small satellites to deliver big science. Specific opportunities arise from Australia's partnership with NASA on Moon to Mars projects under the principles of the Artemis accords, which facilitate exploration, science and commercial activities for humankind[27]. By harnessing and challenging our R&D capabilities, such projects can grow industry and improve broad areas of the economy.

Artemis is NASA's major program for human lunar exploration, providing an R&D stepping stone to future crewed missions to Mars. NASA is planning 72 missions to the Moon by 2030[28]. Many of the science and technology payloads will be delivered by private contractors. The continual flow of large payloads to lunar orbit and the lunar surface translates to multiple rideshare opportunities per year to cislunar space for secondary payloads over the next decade. There will be further opportunities for deep space missions.

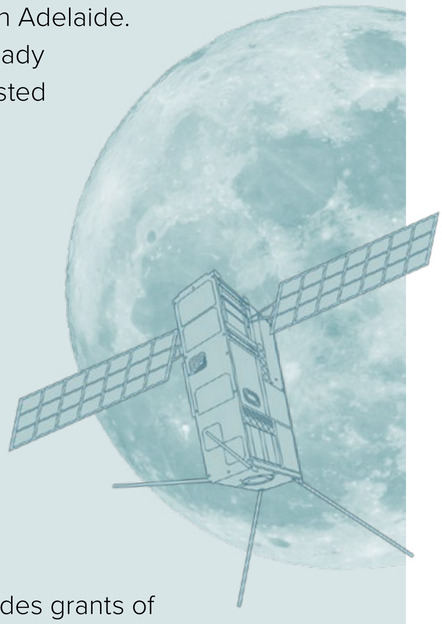
Artemis 1 will fly 13 low-cost CubeSat missions as secondary payloads. These will conduct science and technology research. This represents a radically different approach to science delivery, incorporating highly integrated miniaturised payloads into compact, lightweight, low-cost spacecraft. Australia can share the opportunities Artemis provides. There are further opportunities through, for example, NASA's SIMPLEx (Small Innovative Missions for Planetary Exploration) program.

But we can also be smarter.

NANOSATELLITE MISSION CASE STUDIES

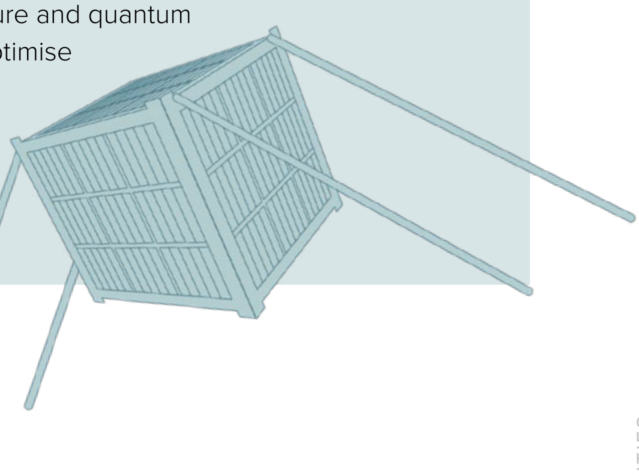
LUNAR ICE CUBE

Lunar Ice Cube is a small (6U) orbiter mission to prospect, locate and estimate the amount and composition of water ice deposits on the Moon for future exploitation by robots or humans. It will fly as secondary payload on the first Artemis mission. Lunar Ice Cube is led by Morehead State University, and the flight software is being developed by Vermont Technical College. Morehead State is a small regional US liberal arts university, similar in global rankings to Torrens University in Adelaide. Vermont Tech is one quarter the size of Morehead but has already developed its own CubeSat which operated for two years. It tested a robotic navigation system which can guide an autonomous CubeSat Lunar Lander. Both Morehead and Vermont began their CubeSat programs through NASA's CubeSat Launch Initiative, which provides opportunities for small satellite payloads built by schools and universities. With support from the State of Kentucky, Morehead State invested in spacecraft engineering as a new strategic area. Now they're leading an Artemis mission, and building spacecraft which can advance human exploration of the Moon. Australia has world-class university science and engineering departments which could also lead world-class missions.



CANADIAN CUBESAT PROJECT

The Canadian CubeSat Project, announced in April 2017, provides grants of up to C$250,000 to college and university research leaders to engage students in a real space mission, building a CubeSat to be launched from the International Space Station. Funded by the Canadian Space Agency (CSA), 15 projects were competitively selected involving 37 organisations and collaborations with universities in Europe, Australia and the USA. The projects involve researchers and students in all aspects of satellite design, fabrication, licensing, operation and data analysis (launches are organised by the CSA). The projects are science-driven and include space weather studies, Earth observation, technology development, precision agriculture, indigenous culture and quantum communications. CSA experts provide support to optimise mission success. This program increases Canada's space capacity and capability, advances Canadian space science and technology, and promotes STEM engagement, for a total cost of less than $3 million over four years.



Desert Fireball Network team members deploying a fireball camera system near to Mt Magnet, Western Australia. There are now 50 such autonomous digital observatories deployed across Australia, and this network is expanding with international partners to form the Global Fireball Observatory.
CREDIT: MARTIN CUPAK / DFN

Artemis and SIMPLEx missions are competitively selected for that one opportunity, meaning that some spacecraft systems and payloads are reinvented by multiple teams. Average cost per Artemis CubeSat mission is around US$10–15 million. Australia can improve on this model. There is a place for large flagship Australian missions, but the Artemis 1 CubeSats also suggest a role for a more agile approach, with fast turnaround missions and targeted science goals, small spacecraft with advanced highly integrated systems, smart payloads and onboard systems, and small teams enabling rapid innovation. The technology exemplified by these small spacecraft is eminently and rapidly achievable by Australia.

We envisage a program comprising multiple missions leveraging the space infrastructure being built by international partners. A mission R&D program of A$40 million over four years would build and validate a range of science payloads and spacecraft systems enabling modular mission design. This would be followed by a four-year A$80 million mission program which would see multiple Australian spacecraft exploring the solar system by 2030. These programs would deliver a unique, agile, sovereign space capability, and preferred partnership status for international space collaborations. The programs would stimulate innovation driving a thriving space science and advanced manufacturing and supply chain sector. They would inspire a generation of young Australians in STEM, and directly engage student scientists and engineers forming Australia's future space workforce.

KEY SCIENCE QUESTIONS FOR THE NEXT DECADE

Here we identify some key solar system science 'discovery' questions we can address. These build on Australian research strengths, international collaborations which help develop domestic capacity, and global research priorities. Some of these are discussed further later in this plan, as are other Earth-focused missions.

1. FORMATION AND EVOLUTION OF THE SOLAR SYSTEM

What were the initial processes of solar system formation and the nature of the interstellar matter that was incorporated? We understand much of how our Earth works – but how Earth and other terrestrial planets formed, and how and where the gas giant planets formed, is still a mystery. What governed the accretion, supply of water, chemistry and internal differentiation of the inner planets and the evolution of their atmospheres, and what roles did bombardment by large projectiles play? The Moon, Mars, asteroids (from which meteorites come) and comets contain a unique record of solar system formation. Australia is a world leader in the analysis and characterisation of extra-terrestrial materials, whether it be samples brought back by JAXA, NASA and CNSA missions, or meteorites. We can build on that, leading our own missions to these bodies.

2. HABITABLE WORLDS

How, why and where did life evolve in the solar system? Leveraging key Australian strengths in astrobiology and analogue site studies, there is an opportunity to develop Australian payloads around key science questions and knowledge gaps. Western Australia has the earliest and rarest evidence of life on Earth 3.8 billion years ago and an ancient hot spring environment, both of which attract space agencies and researchers from around the world. Key questions focus on the primordial sources of organic matter, whether Mars or Venus hosted ancient environments conducive to early life, and whether there are modern habitats elsewhere in the solar system with necessary conditions to sustain life. This is also an area where advanced Earth observation techniques can be further developed for detection and measurement of key variables.

3. HOW THE SUN INTERACTS WITH EARTH

How does energy transfer from the Sun through interplanetary and near-Earth space, driving space weather on Earth? The solar wind couples most directly to Earth's atmosphere at high latitudes, generating a wide variety of disturbances. How these reach low and equatorial latitudes is not well understood. This has important consequences for satellite-based positioning, navigation and timing systems, and operation of the JORN surveillance radar, for example. A different set of physical interactions generate 'killer electrons' which can damage spacecraft, affect atmospheric chemistry and ozone concentrations, and affect ground level temperatures at polar latitudes during large magnetic storms. An Australian space weather constellation program could provide critical data, addressing fundamental science questions while helping protect key infrastructure.

4. RETURN TO THE MOON

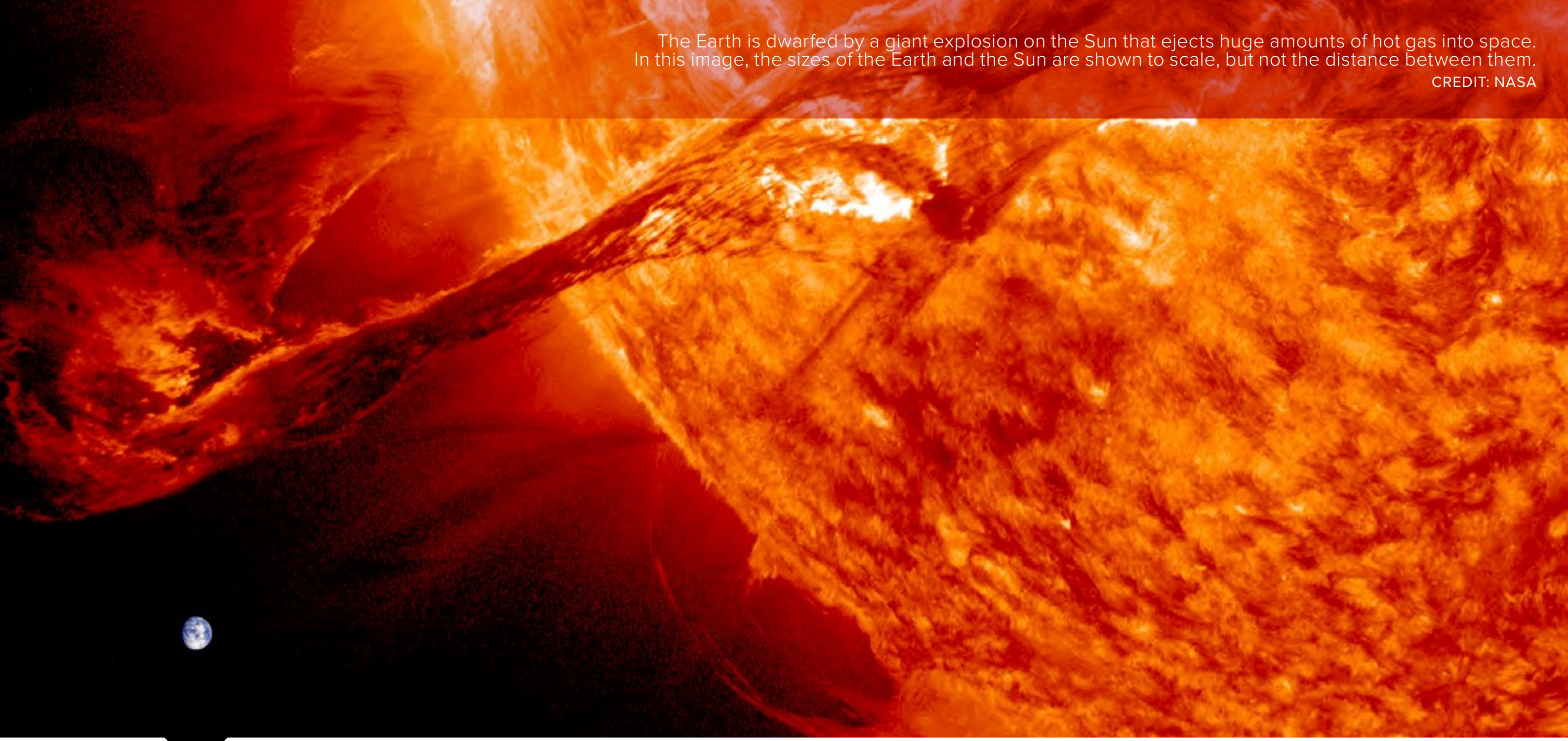
There is so much we still do not know about Earth's nearest neighbour. When did it form? What can its ancient surface, and record of impacts, tell us about the impact history of the solar system? The Artemis program allows Australia to participate in a new era for lunar science. The NASA Commercial Lunar Payload Services (CLPS) program offers an unprecedented opportunity, with low cost options to access the surface with lander or rover payloads, or via delivery of remote sensing platforms to orbit. Working closely with NASA on science projects as part of Artemis, Australian science teams can use hardware on the surface and in orbit to address key knowledge gaps[29]. We should develop nanosatellites to explore and deliver services from lunar orbit, and lunar science and exploration payloads.

5. ENABLING HUMAN EXPLORATION: IN SITU RESOURCE UTILISATION

Australia can partner with other agencies in characterising the composition of the lunar and Martian surfaces, their material properties, and dust environments – all key to determining the economic and ISRU potential of the Moon and Mars, and constraining hazards to human health. This area is the focus of a coordinated NASA program – the Solar System Exploration Research Virtual Institute (SSERVI), which supports domestic US science teams and collaborations with international partners on missions on the origin and evolution of the inner solar system. Australia is a key SSERVI partner, with 12 Australian institutions[30] participating in 19 international space missions. Relationships built within NASA SSERVI on projects to determine volatile content and distribution for ISRU, our track record in sample analysis, and Australian Government support for Artemis, potentially make us a preferred science partner with NASA in this area. Such activity would enhance and extend the Australian lunar rover project, which will provide complementary operational capability to NASA's in situ resources program.

RECOMMENDATION

Establish a program of small space missions to advance knowledge and discovery, foster and leverage international collaboration, accelerate development of new technologies, applications and the skilled workforce, and help grow sovereign capability. This should be the responsibility of the Australian Space Agency, with NCRIS or similar support.



The Earth is dwarfed by a giant explosion on the Sun that ejects huge amounts of hot gas into space. In this image, the sizes of the Earth and the Sun are shown to scale, but not the distance between them.
CREDIT: NASA

3.2 SPACE FOR GROWTH AND RESILIENCE

'Sometime in the future, science will be able to create realities that we can't even begin to imagine.'

ROBERT LANZA

Space science and technologies are profoundly dual use in nature. To date, Australia's critical economic and strategic dependencies on space have largely relied on global supply chains and strategic alliances. The ADF is now tasked with developing space situational awareness (SSA) capability and sovereign space-based geointelligence, surveillance, communications and control networks[31]. However, transformational change is catalysing new opportunities and risks.

Here we outline opportunities for Australian space science to advance national interests, by exploiting competitive advantages including R&D strengths.

3.2.1 ASSURING OUR CRITICAL INFRASTRUCTURE AND SUSTAINABLE USE OF SPACE

SPACE WEATHER RISKS TO CRITICAL INFRASTRUCTURE

All spacecraft and space-reliant services and much critical infrastructure are at risk from space weather and space debris.

Solar eruptions trigger magnetic storms and space weather events which can damage satellites and affect their orbits; degrade radio communications links, over-the-horizon radar operations and GNSS services; impact aviation; and damage long pipelines and electricity distribution grids. Space weather monitoring and forecasting is therefore critical to maintaining the integrity of space-related services in Australia[32]. The United Nations regards space weather as a global high-impact threat because of the interconnectedness of economies[33].

The benchmark extreme space weather event is the 'Carrington Event', which occurred in 1859. Such an event today would cause catastrophic failure across a range of critical sectors. Estimates of its probability range from 0.5-12% within the next 10 years[34]. However, collaborative work by the Bureau of Meteorology's Space Weather Services, Geoscience Australia, academia, and transmission and distribution network service providers, has highlighted risks to Australian and New Zealand power grids from more moderate scale events which may occur many times per year during the active phase of the solar cycle.

Current capability provides around a one-hour warning of major space weather events, with general indications of potential events over the preceding day or two.

SUSTAINABLE USE OF SPACE

The space environment is becoming increasingly commercial, congested and contested. Around a million pieces of space debris over 1 cm in size currently orbit Earth, but only about 22,000 objects are tracked. The number of satellites in orbit will grow by a factor of 10 within a decade. The concepts of space situational awareness (SSA – detecting and tracking objects), space domain awareness (SDA – knowing about factors that affect the use of space), and space traffic management (STM – ensuring safe use of space) span military and, increasingly, civil and commercial domains. Legacy approaches to SSA, SDA and STM are challenged by the vast growth in the number of space objects and in-orbit capabilities, and the need to incorporate physics-based models including space weather effects.

The resultant growing risk of collisions jeopardises all space assets and threatens the sustainable use of space[35].

Australia has an international commitment to action on space debris management through membership of the UN's Committee on Peaceful Uses of Outer Space. Specifically, UN Resolution 74/82 highlights the significance of space science and technology and applications to provide long-term solutions for sustainable development, expresses deep concern about the challenges posed by space debris, and calls for continuing national research and improved technology to tackle this problem[36].

NATIONAL NEEDS AND ASSETS

Australia requires a tightly integrated and sovereign space weather and SSA capability across the defence, civil and commercial space sectors. However, basic space weather research has not been identified as a priority area by the Australian Space Agency, CSIRO or the ADF, and is mostly undertaken by insecurely funded university groups. The Bureau's Space Weather Services is responsible for operational space weather forecasting (see box page 30) but not the underpinning research.

Australia assumes responsibility for geophysical monitoring over one seventh of the world's surface, spanning polar to equatorial latitudes and strategically important time zones. Australian assets across this region include world-class monolithic and distributed sensors spanning optical, passive and active RF, radar, infrared, laser ranging and spectrum monitoring. These are operated more or less independently by various organisations including the ADF, the Bureau, CSIRO and the MWA/SKA consortium, industry groups and university groups. Under Project JP9360, the ADF aims to develop a multi-technology, multi-layered sensor network to collect sovereign-controlled SSA data through partnerships with Australian industry focusing on mature, ready-to-go technology. This may incorporate space weather and in situ observations in time, but the ADF is not tasked with basic research or responsibility for protecting critical civilian infrastructure. Instead, Australia's core SDA product needs will be sourced from the US.

We can and should do better than this.

Several Australian university groups are at the forefront of international research in solar and near-Earth space physics. By exploiting our geographical advantages and growing our space science and SSA capability, Australia can become a medium to major player in managing the global commons of space, while building resilience for space-dependent services, growing sovereign SDA and STM capability, exploring new commercial opportunities and supporting NASA's deep space and lunar SDA programs.

KEY SCIENCE QUESTIONS AND OPPORTUNITIES

Despite intense international research efforts, we are still a long way from high fidelity prediction of severe, or more frequent less severe, space weather. However, there is a window of opportunity for Australia to advance globally important space weather science and operational outcomes. Here we identify topics which Australia can lead.

- **Characterising extreme space weather.** Our Sun is much less active than other Sun-like stars[37]. Is this a permanent condition, or does solar activity vary over long time scales? What are the implications for planetary habitability?
- **Predicting solar activity.** Can helioseismology (imaging of the far side of the Sun), physics-based modelling and data-driven simulation provide transformative improvements in the prediction of solar activity? Australia has significant expertise in these areas.
- **Tracking space weather triggers from the Sun to Earth.** Current state-of-the-art predicts arrival times of major space weather events within 12 ± 12 hr. This can likely be significantly improved with new observations, including from the MWA/SKA radio telescopes, combined with simulation models.
- **Space weather effects in the ionosphere.** By combining our expertise in ionospheric physics, extensive sensor networks, international collaborations, and operational tools used by the Bureau's Space Weather Services, Australia is exquisitely placed to improve understanding of space weather effects in the mid- to low-latitude ionosphere. These regions are not well understood but affect GNSS systems including SouthPAN, HF radio and defence surveillance radars, low frequency radio astronomy, and synthetic aperture radar measurements by EO satellites.
- **Impacts on LEO satellites**. Current orbit determination algorithms use statistical optimisation techniques. However, LEO is a complex and dynamic environment. Australia can play a key role in developing more sophisticated physics-based models informed by innovative laboratory and in-orbit experiments and taking into account space weather effects. This would also complement and enhance Defence's SSA program, and allow Australia to offer services into the new commercial SDA market.

- **Predicting effects on power grids and pipelines.** Australia's expertise in space physics, geophysics, power line network modelling and industry support position us as an international leader in the understanding of space weather causes of geomagnetic-induced currents in the ground. With further work, reliable models can be developed to predict the impact of geomagnetic storms on power networks and corrosion of long pipelines across Australia. This is a vital step for protecting our critical infrastructure.
- **Space weather and SDA for cislunar, lunar and deep space missions.** Long duration crewed space missions require advanced capability in space weather prediction and deep space surveillance. Blue-sky research built on existing capabilities should be exploited to secure Australia as a preferred partner in lunar and deep space SSA, SDA, STM and space weather.

ENABLERS

1. **Research program.** Realising the above opportunities requires a collaborative program of fundamental and applied science on space–environment interactions. This would build on existing capabilities spanning sensor networks, data processing and analytics, physics modelling and machine learning, and harness collaborations with trusted international partners. A mechanism to achieve this is through establishment of a research institute or centre tasked with developing breakthrough space weather science and collaborations with industry and government partners, to mitigate risks to critical infrastructure, support Australia's strategic goals and promote translation to outcomes.
2. **Expanded ground-based and in-orbit sensor network.** The manner in which solar wind disturbances arriving at high latitudes generate space weather effects at lower latitudes is not well understood. Furthermore, LEO altitudes are critically undersampled from the space weather perspective. Therefore, the research program requires:
   a. augmentation of the existing suite of ground-based sensors (e.g. HF radars, magnetometers, GNSS receivers) to sample latitudes poleward and equatorward of Australia. These would also complement and enhance operational aspects of JORN.
   b. a regular cadence of space science and SSA spacecraft missions to generate benchmark quality truth data to verify and validate ground-based sensors, data processing, modelling and simulation tools. These missions would provide a low-risk pathway for the development of operational space-based space surveillance and space weather payloads, and support strategic objectives. Australian groups have the necessary capability, and these satellites could also form elements of global multinational constellations.

   Such infrastructure will provide globally significant space weather and SSA capability, but to ensure viability should be funded as a national facility.
3. **Virtual observatory and analysis centre.** The complete space weather and SDA picture only emerges when many diverse sources of data are intelligently combined, analysed and acted on. This requires a single, coordinated and curated virtual observatory and analysis centre, providing access to a multitude of Australian and international ground- and space-based datasets, and data assimilation, visualisation and machine learning analysis tools. This will connect the capabilities of the Australian space

weather and SSA community, enabling rapid developments that lead toward operational capability. Its aim is to support new breakthrough research outcomes, and ADF's SSA program via suitable protocols. To remove financial and technical barriers this should be a well-funded national facility. It could operate alongside or as part of the Australian Space Data Analysis Facility.

RECOMMENDATION

Develop a national program focusing on space weather research activities to help protect critical infrastructure and advance space weather forecasting and space situational awareness activities. This program should be supported by observations from a diverse and extensive suite of sovereign ground- and space-based sensors.

AUSTRALIAN SPACE WEATHER RESEARCH

The Bureau of Meteorology's Space Weather Services (SWS; formerly Ionospheric Prediction Service) provides space weather predictions to the public and specialised services for a range of customers, the largest being Defence. It has been proactive in developing new products supporting a variety of sectors. The SWS also operates the Australasian regional warning centre and hosts the World Data Centre for Space Weather on behalf of the International Council for Science. Its forecasts are based on data assimilation and nowcasting and it engages in research through collaborations mostly with university groups. Although a small unit, the SWS was found by a 2014 external review to be 'in the top tier of global space weather centres'[38]. The SWS sources data from its own and other Australian infrastructure and collaborating international organisations.

Ground-based space weather sensors are operated more or less independently by the SWS, the Australian Antarctic Division, DST Group (to support JORN operations), GA, and various university research groups. The latter includes over-the-horizon research radars operated by a consortium headed by La Trobe University, the members of which are technology leaders in a global research radar network. Support for the various Australian observing networks depends on institutional priorities.

Australia's disjointed approach to space weather research contrasts with international efforts, such as the US Center for Space Environment Modeling, and China's Meridian Space Weather Monitoring Network. The latter comprises a heavily instrumented ground sensor network monitoring the geospace environment along the 120° meridian extending from northern China across Australia and to Antarctica, and also along the 30°N parallel, plus sounding rockets. Data are analysed at China's Center for Space Science and Applied Research, informing China's space weather integrated model (SWIM) and multiple space weather prediction centres.

NOVEL IN-ORBIT CUBESAT SURVEILLANCE SSA EXPERIMENTS

M2 is an Australian-technology capability demonstration and R&D platform for RAAF and in turn for Defence, with the primary purpose being optical and RF maritime surveillance as an example of space-based remote-sensing capabilities developed and built in Australia.

It incorporates in-house technology building blocks including optical telescopes; software defined radios; best-in-class fully-reprogrammable-in-orbit flight computers; CPU/FPGA/GPU-based on-board processing; formation flying technologies; attitude determination and control system; GPS and star trackers to assist navigation and pointing; and intersatellite and ground-space radio and optical links.

The mission also carries an events-based neuromorphic optical sensor from Western Sydney University, a hosted attitude control payload for Technical University Munich, and an ionospheric aerodynamics experiment to validate the science needed to control and de-orbit propulsionless spacecraft at and from higher orbits than previously thought possible.

M2 is designed as a 12U CubeSat which splits into two 6U halves to facilitate in-orbit attitude control experiments based on different cross-sections. Successful separation was achieved in September 2021. Further activities include space-based space surveillance employing its on-board technologies.

Launched in March 2021, M2 represents the most significant Australian space technology capability to date, and will be a world-leading pathfinder for the Australian space sector.

The M2 mission, a collaboration between UNSW Canberra Space and the Royal Australian Air Force (RAAF), brings together emerging technologies that deliver advanced capabilities in Earth observation, maritime surveillance and satellite communications. The craft is able to split into two separate satellites and fly in sequence, enabling significant mission flexibility..
CREDIT: UNSW CANBERRA

3.2.2 UNDERSTANDING AND MANAGING OUR CHANGING ENVIRONMENTS

SIGNIFICANCE

Earth observation (EO) data are essential for managing our environments and resources, forecasting weather, understanding climate change, responding to natural disasters and supporting urban planning. Satellites furnish the bulk of EO observations: for example, delivering around 95% of the observations used by the Bureau in its weather, hydrological and ocean models. The economic benefit to Australia of space-based EO data in 2020 is estimated at $2.5 billion[39].

All satellite data used by Australia comes from foreign sources. All jurisdictions, from government to defence to commercial, require long-term continuity and security of supply of EO data and derived products. Australia is an active member of the World Meteorological Organisation (WMO), which under Resolution 40 provides free and open exchange of satellite data to members. However, there is no guarantee all necessary data sources will always be freely available, optimal, or meet specific and evolving needs. This imposes a sovereign risk, especially if Australia is regarded as an unequal contributor to the global EO community. Defence project DEF799[40] recognises some of these risks by seeking to provide 'direct and more timely access to commercial imaging satellites... [and] the possible acquisition of a sovereign GEOINT space surveillance system', but this does not fill the civilian gap.

Australia's EO data requirements will increase in the face of growing environmental, commercial and geopolitical stresses.

OUR COMPETITIVE ADVANTAGES

Australia's important advantages include the following.

- Respected membership of the WMO, the international Group on Earth Observations (GEO) and the Committee on Earth Observation Satellites (CEOS), and an authoritative voice on space-based Earth science research and applications. Partly this arises from Australia's expertise in development of innovative EO applications, platforms and products (e.g. the Open Data Cube).
- Strong collaborative partnerships with international agencies such as NASA, USGS, ESA, DLR, JAXA, Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA) and the Chinese Academy of Sciences.
- World-class Earth observation research centres such as the Earthbyte group hosted by the University of Sydney; CSIRO Centre for Earth Observation; University of Queensland's Remote Sensing Research Centre and associated research-to-operations programs in governments and industry; ANU's Centre for Water and Landscape Dynamics; the Bureau's Earth system modelling; and FrontierSI.
- National infrastructure facilities including AuScope (services, data and analytics for geoscience research) and TERN (collecting and providing terrestrial ecosystem research data), IMOS (collecting and providing oceanic ecosystem research data), along with digital research infrastructure such as the Pawsey Supercomputer and the Australian Research Data Commons.
- Australia's large and diverse territory comprising almost every single climatic zone and diverse soil types and biodiversity, extensive infrastructure over this region, and scientific and technical expertise, providing unique opportunities for ground truthing of satellite observations[xii].

xii Such activities are currently conducted, for example, by CSIRO.

OPPORTUNITIES AND ENABLERS

Monitoring, understanding and effectively managing our environments, resources and security in the climate change era poses grand national challenges. Addressing these requires:

- ongoing access to a broad range of international data sources and platforms, through active participation in the global observing system
- appropriate sovereign capability to mitigate supply risks in the evolving commercial and geopolitical landscape
- enhanced science, observations, analysis and modelling capability. For example, reducing the detection time of bushfires by 30 minutes can result in an economic benefit of around $3 billion over 30 years, rising to more than $8 billion if all fires are detected within 30 minutes[41].

Ultimately, meeting Australia's future EO needs requires an ongoing national science-focused civil space program, aligned with Australian Space Agency and GA priorities and roadmaps, and potentially dual use programs. Such a space program would support sovereign data capability, grow EO expertise and capability, engage local industry, and help grow global market share in niche areas where we could be world leading. Australia's expertise in delivering decision-ready, scientifically and legally valid information from EO data analytics can be exploited further to allow Australians to lead domains transitioning scientific research to commercial and government applications.

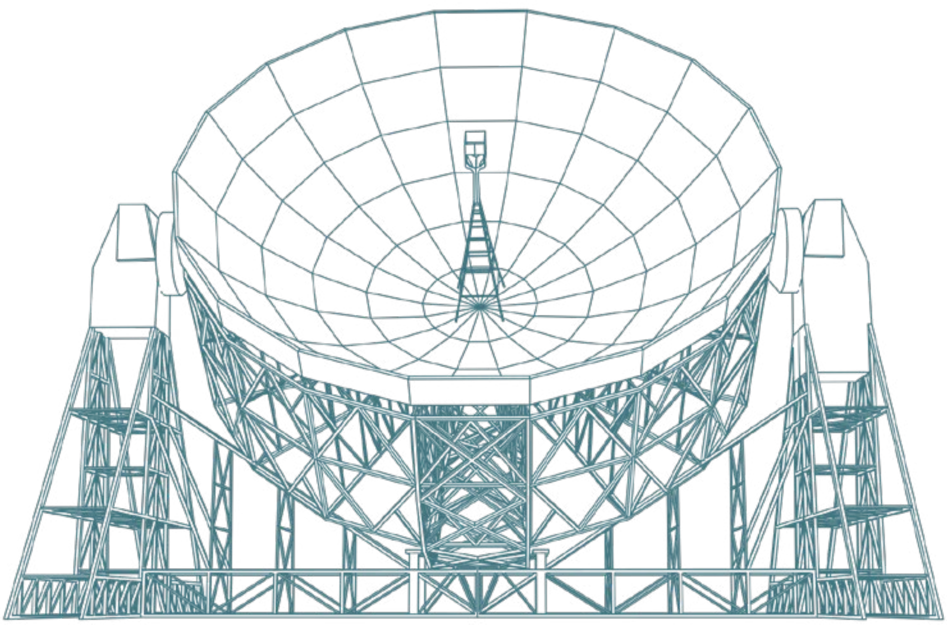
A useful analogy for such a program is the NASA Earth Venture Program (see box page 35). This consists of innovative, low cost and competitively selected science-driven missions which produce new research and applications that enhance understanding of the Earth system, improving the prediction of future changes and building a skilled workforce with technical capacity.

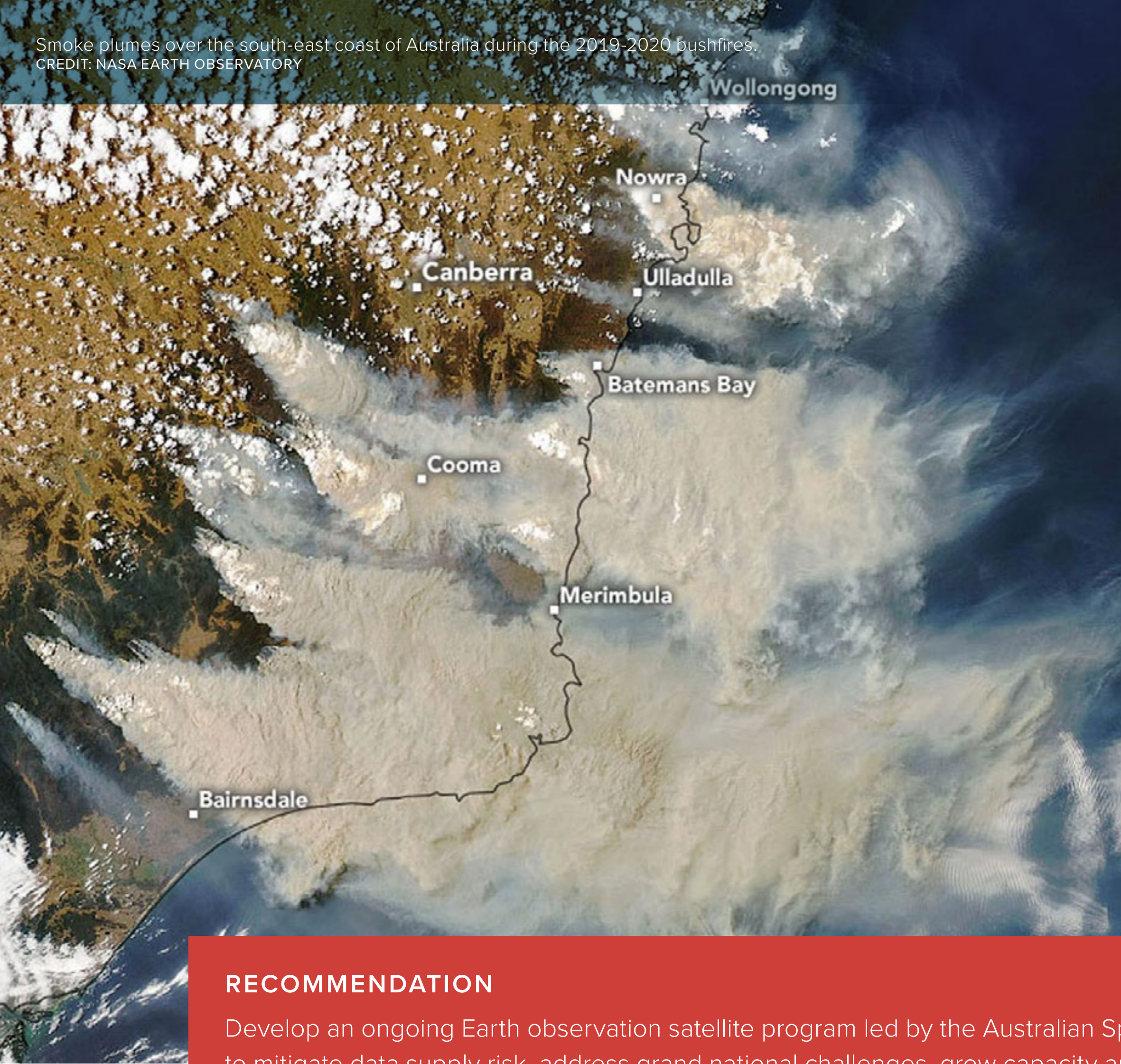
A compelling economic argument for a sovereign, continuous launch small satellite EO program, costing around $36 million per year from 2023 to 2040, has been produced by Deloitte for GA[42].

Here we identify stepping stones to realising a national EO program.

1. **Nanosatellites and constellations in LEO to improve understanding of a range of topics**, such as atmospheric temperature and moisture dynamics, wind and wave directions, ground-level water volumes and quality, evapotranspiration and agricultural water consumption, crop development and impact of pests and diseases, development of bushfire fuel loads and fire occurrence, impacts of infrastructure on urban microclimates and identification of potential mineral deposits. The emphasis is on 'pre-operational', low-TRL but challenging science missions by research groups and SMEs to stimulate development of new sensors, smart payloads including on-board processing, reconfigurable low-cost platforms and novel data analytics. Relevant technologies include optical imaging (visible, thermal and reflected infrared, hyperspectral), radio (real and synthetic aperture radar, radio occultation, microwave hyperspectral imaging), and high-precision gravity measurements with laser range finding. Cross-sector collaboration will be important; for example, a University of Melbourne team is leading development of a low noise infrared telescope for a 12U CubeSat astronomy mission called Skyhopper.

2. **Small (some 10's kg) high-value satellites with enhanced capabilities**, engaging and advancing industry capability and supporting the growth needed for delivery of strategic requirements such as Defence's DEF799 program, and help industry realise new market opportunities. Examples of EO missions of this calibre include the Canadian Space Agency's RADARSAT constellation and WildFireSat, and the Argentina Space Agency's SABIA-Mar marine science mission.
3. **A national quality assurance capability for satellite Earth observation instruments**, data and derived measurements, products and services. This would use ground- and water-based quality assurance infrastructure and a continuous series of Australian cross-calibration radiometer satellites to assure scientific veracity and data interoperability between various EO datasets. Australia would be positioned as an international leader and global resource for remote sensing calibration and validation advancements, also helping assure the long-term supply of critical EO data streams and enabling new science applications. A scoping study to inform the Australian Space Agency's Earth Observation from Space Technology Roadmap has detailed such a calibration and validation program[43] and is strongly supported by the US Geological Survey (responsible for the Landsat program). This would also complement other programs such as ESA's TRUTHS mission.
4. **Complex, high value payloads on the orbiting space stations and large geostationary platforms**, in conjunction with other space agencies, to provide high cadence weather and environmental data specifically for Australian applications. One example is NASA's GeoCarb instrument to monitor CO_2 sinks and sources, and plant health and vegetation stress through the Americas.
5. **Accessible and interoperable data networks and sophisticated processing algorithms and methods** to ingest and break down vast and growing volumes of EO data into smaller more dedicated chunks for less technical end users. This can open new markets for products and services. The Australian Space Data Analysis Facility is already providing some of this capability. FAIR (Findable, Accessible, Interoperable, Reusable) data principles are elements of the NHMRC's Open Data Access Policy[44] and the Australian Government's National Collaborative Research Infrastructure Strategy[45].





Smoke plumes over the south-east coast of Australia during the 2019-2020 bushfires.
CREDIT: NASA EARTH OBSERVATORY

RECOMMENDATION

Develop an ongoing Earth observation satellite program led by the Australian Space Agency to mitigate data supply risk, address grand national challenges, grow capacity and contribute to global programs. As part of this, Australia should lead international efforts on global instrument and data calibration and validation.

NASA CYGNSS MISSION

The Cyclone Global Navigation Satellite System (CYGNSS) is an element in NASA's Earth Venture program. It comprises a constellation of eight 29 kg satellites in LEO measuring ocean surface winds using GNSS reflectometry – direct and reflected signals from GPS satellites – to determine location and surface roughness. The project is led by the Southwest Research Institute at the University of Michigan and has been highly successful, with mission life extended from an initial two to nearly six years. Outcomes to date include soil moisture measurements for eastern Africa, used by the World Health Organization; better location of storm centres and movement; imaging coastal flooding after hurricane landfall; and establishing river flow rates and widths following extreme weather events. Similar GNSS reflectometry receivers will now be deployed by NASA on Air New Zealand aircraft to collect environmental science data over New Zealand.

The Australian Centre for Space Engineering Research (ACSER) at the University of New South Wales has built and flown CubeSats and developed a GNSS reflectometry receiver payload with CubeSat form factor. These can also be modified to provide radio occultation data, which can significantly improve weather forecasting. Australia could fully develop a sovereign CYGNSS program and, given that the UNSW receivers are also being deployed experimentally on aircraft and UAVs at low to very high altitudes, fly such receivers on operational Australian aircraft missions.

The Western Australian Optical Ground Station will be part of a national network of next-generation space communication facilities using lasers to overcome data bottlenecks and improve security between orbiting satellites and the ground, allowing an increase in data transmission rates critical for crop monitoring, mapping, bushfire and disaster response, financial market transactions and many other applications.
CREDIT: ICRAR

3.2.3 NEXT GENERATION GLOBAL COMMUNICATIONS

Satellite communications and dependent services accounted for 76% of Australian space industry revenue in 2018[46]. Currently all satellite services are enabled through radio communication. However, spectrum space is limited and increasingly congested, already impacting some EO missions[47]. Furthermore, services delivered via satellites in geostationary orbit are too slow for some applications[xiii]. Seamless global, high capacity, low latency communications can transform economies and society, enabling 'big data' and machine-to-machine IoT.

The dual use nature of space means that needs and developments overlap the defence, civil and commercial sectors.

Future high capacity global communications will likely be facilitated by resource sharing across relays and multiple satellite systems in GEO and networked constellations in LEO; smart and adaptive on-board and on-ground processing, and advances in hybrid RF and optical communications technologies.

New science and technology are required to exploit opportunities.Considerable heritage and expertise exists across government agencies such as CSIRO and DST Group, university-based groups, institutes and centres including the SmartSat CRC, industry groups and SMEs.

xiii The communications latency for satellites in GEO, such as the NBN-Co Skymuster satellites, is limited by the speed of light to 600 ms. LEO satellites, such as SpaceX Starlink system offer latency around 20 ms. The speed of light in free space is also higher than in optical fibres used in terrestrial communications.

Pathways for development of technologies offering greatest opportunity for Australia are outlined in the Australian Space Agency's Communications Technologies and Services Roadmap 2021–2030. However, research topics and specific actions to achieve outcomes including the necessary research funding commitments are not identified.

RESEARCH NEEDS AND BREAKTHROUGH OPPORTUNITIES

Areas of research need and opportunity, complementing aims of the roadmap, include:

- mitigation of optical channel degradation due to atmospheric effects, such as adaptive optics, diversity and channel coding
- advanced signal processing and waveform standards for interference mitigation of RF channels
- advanced satellite on-board electronics, including development of millimetre wave devices and circuits, allowing higher throughput communications payloads
- advanced antenna research and design to improve performance and flexibility, such as contoured and adaptive beamshaping, multifeed applications and CubeSat antennas
- high speed hybrid RF-optical, and free space laser optical communication to significantly improve bandwidth, data capacity and security (see also 3.2.4).

Quantum technologies offer breakthrough improvements in secure communications but corresponding risks to public-key cryptography. Research topics relevant to Defence[48], industry and civil applications include investigation of coherent optical links between satellites for extended quantum sensing (which can increase the precision of gravity measurements), and distributed coherent optical imaging between satellites to improve imaging resolution ('sparse aperture synthesis').

An important step would be demonstration of in-orbit optical communication between a small constellation of nanosatellites and to the ground, paving the way for more ambitious quantum-capable assets including networked swarms (with smart sensors) in LEO, and eventually in cislunar orbit supporting Artemis and planetary missions[49]. Such a project should be achievable at modest cost using a modular platform approach. Research activities for a suitable optical ground station network are under way[50].

Some of these activities are currently supported under the Australian Space Agency's Moon to Mars Initiative, but program funding and timeframes will constrain development of potential breakthroughs. There should also be collaboration with the astronomy community, which has expertise in large and complex data handling and processing capabilities, and correction for atmospheric distortions of optical signal paths.

3.2.4 RESILIENT POSITIONING, NAVIGATION AND TIMING (PNT) SERVICES

SIGNIFICANCE

PNT services derived from global navigation satellite systems (GNSS) such as GPS, underpin commerce and business activity, personal user applications, new technologies including precision agriculture and IoT, mission- and safety-critical applications such as autonomous machines and vehicles, and much defence capability.

Many science applications are also enabled by PNT services. These include meteorology, geodesy, geodynamics, geophysics, space physics, oceanography, and land surface and ecosystem studies. These embrace domains such as environmental and climate change monitoring, resources exploitation and space domain awareness. Techniques include direct and reflected GNSS signals, differential measurements, phase measurements and radio occultation measurements.

Australia's reliance on accurate, available and reliable PNT information will continue to expand, amplifying concerns about vulnerabilities and risks, particularly those impacting national security such as cyber attacks, jamming and spoofing.

BUILDING RESILIENCE

Measures necessary to build resilience in our PNT infrastructure involve a convergence of conventional solutions with emerging science and technologies. These include developing, testing and implementing back-up or alternative GNSS-PNT technologies such as multi-sensor systems, and development of classical and quantum technologies to provide GNSS-independent PNT capability. The DST Group's STaR Shot program 'Quantum assured PNT' has this focus.

Such efforts will depend on cross-sector collaboration to ensure interoperability of technologies, translation of research to implementable outcomes, and measures to grow workforce skills and capacity. Opportunities to commercialise resilient PNT products and services may also emerge.

Fundamentally, science underpins all PNT technologies and applications. For example, the deployment of SouthPAN (formerly SBAS) as part of Australia's national positioning infrastructure will provide decimetre positioning precision enabling new applications and improved productivity. However, there are important limitations which need to be better understood and mitigated through basic and applied research. Future PNT may involve signals of opportunity from a combination of services delivered by commercial operators of satellite constellations, 5G/6G, and internet-enabled ground technology. Future developments will also focus on next generation GNSS real-time absolute navigation at sub-centimetre level, such as using real-time kinematic, precise point positioning and smart post-processing technologies.

It is important that Australia leverages first-mover advantage gained through SouthPAN to further advance PNT expertise and capability as technology continues to develop. This requires a focus on research topics offering particular opportunity, including:

- aspects of metrology, such as on-board and ground clocks to improve precise time synchronisation and real-time kinematic applications
- advanced signal processing, for example to reduce interference and jamming impacts
- precise orbit determination, including space weather effects
- handling difficult signal propagation conditions
- enhanced, real time tropospheric and ionospheric corrections to improve positioning and provide vital data for weather forecasting and ionospheric tomography
- antenna science, such as phased array and reconfigurable reflectarray antennas
- smartphone-based positioning
- multi-constellation aspects, such as multi-frequency precise point positioning offering centimetre positioning accuracy, enhanced robustness and near real-time convergence times
- multisensory integration, such as GNSS, communications, camera and inertial.

RECOMMENDATION

Australia commits to an integrated program to advance basic and applied research on transformative technologies in secure, high bandwidth RF and optical communications technologies including across satellite networks, advanced on-board processing, and next generation secure positioning, navigation and timing capabilities. This should include technology demonstrator satellite missions and associated ground infrastructure.

3.3 SPACE FOR HEALTH

WHY ARE SPACE MEDICAL AND LIFE SCIENCES IMPORTANT?

Research in space medical and life sciences enables human space exploration but also provides important practical benefits to society. Australia has a unique advantage by pairing internationally acknowledged medical, health and behavioural science research with experience in delivering health services to harsh rural and remote environments, from the outback to Antarctic expeditions. Capitalising on these strengths opens the opportunity for Australia to contribute to international programs such as NASA's Artemis, and translate research to improve health outcomes in everyday life.

Space biomedical sciences expertise is a prerequisite for long-duration crewed space missions and space tourism. As part of its Human Research Roadmap (HRR), NASA has identified 28 overarching medical risks for crewed spaceflight, mapping to 230 knowledge gaps. The risks include exposure to ionising radiation, cognitive and behavioural effects of spaceflight, physiological consequences of long-term exposure to microgravity environments, and long-term storage and stability of food and medications. As just one example,

Researchers at the University of Wollongong have invented, developed and successfully tested silicon microdosimeters to measure radiation dose for astronauts for prediction of cancer during their mission.
CREDIT: UNIVERSITY OF WOLLONGONG / NASA ASTRONAUT GARRETT REISMAN

radiation exposure for a human mission to Mars substantially exceeds NASA's current permissible limits for exposure-induced death due to radiation carcinogenesis and associated risks[51]. Research to understand and ameliorate radiation exposure in space is closely related to research in clinical radiation oncology settings to improve dose delivery, verification and outcomes for cancer patients. There are similar synergies between space medicine and life science R&D and practical benefits across other areas.

A survey conducted for this plan by the Space Health and Life Sciences Working Group (see accompanying volume) identified specific areas of Australian expertise and mapped these to NASA HRR knowledge gaps. Seventy-seven percent of survey respondents reported current or previous collaborations with international space agencies, most commonly NASA (30%), ESA (21%) and DLR (12%). A range of domestic capabilities can be developed or enhanced to support such international agency collaborations. These may include parabolic flight programs, head-down bed rest laboratories, short- and long-arm centrifuges, radiation laboratories, microgravity simulators and hypobaric facilities. Establishment of a desert-based space analogue research program can supplement existing Antarctic analogue research to enhance understanding of psycho-social and human factors aspects of the risks identified.

There are clear opportunities and compelling reasons for development of Australian space health and life sciences research, with benefits across the following four domains.

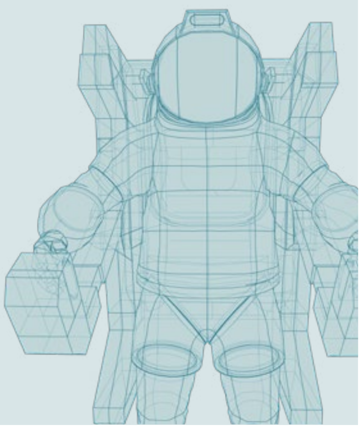
CONTRIBUTING TO INTERNATIONAL SPACE MISSIONS AND PROGRAMS

Australia can provide significant contributions to international space programs and missions. For example, the Centre for Medical Radiation Physics at the University of Wollongong is leading research in the development of microdosimeters for use in radiation therapy and space missions (see box), while teams at CSIRO's Health and Biosecurity unit and Manufacturing unit respectively lead medical image analysis research, and development of novel radiation shielding materials.

Many Australian academic and clinical institutions are involved in a wide range of space-related disciplines, including fatigue and circadian physiology, somatosensory physiology, microgravity countermeasures, radiation microdosimetry and shielding, musculoskeletal effects of space flight, neurophysiology, nanotechnology, environmental monitoring, cellular biology, psychology/psychophysiology and bioethics. Private industry is already collaborating with international space agencies, for example in the novel use of virtual reality for space applications, data analytics, wearable biomonitoring and antimicrobial nanotechnologies. These existing areas of expertise position Australia well to expand its contribution to future human space flight programs through space medicine education, medical support for long-term exploratory missions, and developing countermeasures for the physiological challenges of space flight. In turn, collaborations with overseas partners will grow Australian capability and international profile. Australia can indeed play a key role in human spaceflight programs such as Artemis and Moon to Mars.

RADIATION SENSORS FOR SPACE AND CLINICAL APPLICATIONS

The Centre for Medical Radiation Physics at the University of Wollongong is internationally recognised as a leader in the field of radiation sensors for use in space exploration, medicine, aviation and homeland security. The centre's director, Professor Anatoly Rozenfeld, has patented a microdosimeter for use in space to protect astronauts and systems from hazardous radiation – a consequence of space weather. Supported by funding from ESA, the centre is partnering with the Norwegian research organisation SINTEF to develop a tissue-equivalent sensor for real-time measurement of radiation at the cellular level. These activities are part of a substantial research effort at the centre focusing on semiconductor detectors and dosimeters for clinical applications in radiation protection, radiation oncology and nuclear medicine. The microdosimeters heading for space are also being tested in radiation oncology centres around the world where new radiation treatments are being used to treat cancer.



ACCELERATING BIOMEDICAL TECHNOLOGY

There has never been a better time to accelerate Australia's innovative biomedical technology industry. The importance of this sector and its potential to drive productivity and growth is recognised through the National Innovation and Science Agenda. There is a key intersection between space technologies and biomedical technologies through human spaceflight missions, but beyond this, space also provides a unique microgravity laboratory that can be used to develop novel biomedical technologies which can be commercialised purely for the benefit of human health.

This includes manufacturing of pharmaceuticals and food products in, and suitable for, space and hence austere and arid environments, and environmental engineering systems (for space life support systems) which can improve waste management, water purification and treatment, bioregenerative systems, air filtration, toxin monitoring, and biosecurity and infection control.

To date, Australian space life and health science researchers have mostly worked independently in small groups without the benefit of a national priority or framework (including Field of Research classification) to support the development of research, collaborations and partnerships domestically and internationally. This impedes the growth of research and translation of research into useful applications.

The Australian Human Research Institute for Space and Extreme Environments (AHRISEE) was recently formed to drive collaborative translational research spanning international space agency and industry challenges, space mission support, and Australian space life sciences education and training. The institute can also assist the Australian Space Agency in providing a point of liaison and coordination with the biomedical community and international agencies. Initial support to establish the institute has come from the University of Tasmania, CSIRO, the Australian Antarctic Division and the Tasmanian Government. To harmonise and grow activities at the national level, the institute requires a suitable commitment of ongoing support.

ADVANCING PLANT AND FOOD SCIENCES

Australia is an international leader in agricultural sciences, ranking fourth globally in terms of quantity and quality of publications in agronomy and crop science[52]. Five Australian universities are in the top 50 AWRU ranking of global universities in this discipline. Agriculture is also a vital sector of the Australian economy, currently worth around $71 billion per annum, with 70% of production exported. The downstream food and beverage sector is our largest manufacturing sector, worth an additional $50 billion annually. The combined agriculture and food sector aspires to grow to $200 billion by 2030[53]. The agriculture and food industries therefore represent significant scale and critical mass that the space industry can leverage, both in terms of an abundance of research expertise but also downstream markets stemming from space-focused research.

With remote space missions timetabled in the coming decades, it will be essential to provide a varied and nutritious food supply to sustain long-term physical and mental wellbeing. There are many challenges, with current capability not able to provide the required nutrition for such missions. A three-year return trip to Mars for four people is estimated to require 10 tonnes of food, yet current technology can only land 6 tonnes of material on the Moon, and one tonne on Mars[54]. The delivery of food in advance will require a five-year shelf life, but essential nutrients are degraded within months[55]. Long-term space missions will also require on-demand generation of pharmaceuticals and construction materials. Development of suitable space biotechnology can therefore have widespread applications for Earth[56].

Higher plants are the ultimate source of all life on Earth due to their photosynthetic production of oxygen and nutrition. Prokaryotes, algae and fungi are relatively inefficient sources of nutrition. Plants are a sustainable alternative that can be used in space to deliver continuous nutrition or be processed into multiple food types or other materials. The enabling technologies that will provide adapted plants for multiple space applications are globally nascent. Australia possesses the skillsets, global networks and leadership in advanced plant-based molecular sciences and in food engineering, that are required to adapt and optimise plants as a nutritional and biomaterial source which will enable missions to Mars and beyond. Such developments would also provide important knowledge and improvements in terrestrial controlled environment agriculture.

PLANTS AS AN ENABLER OF CLOSED SYSTEM HABITATION

The fully sealed Yuegong-1, or Chinese 'Lunar Palace' for Permanent Astrobase Life-support Artificial Closed Ecosystem (PALACE) has completed several long-term missions – the latest supporting a crew of four for contiguous missions of 200, 60 and 105 days. This experiment demonstrated that it is possible to rely on higher plants as a major component of diet and as a source of sustainable and essential nutrition in closed systems. CO_2 levels were also controlled, with plant growth to levels similar to those on the ISS. However, because this experiment was conducted on Earth, plants were not exposed to constraints such as microgravity or cosmic radiation.

Experiments on the ISS have shown that plant growth is suboptimal in space. However, molecular sciences can adapt plant form and stress tolerance. For instance, gene editing technology, classified as non-GM in Australia, has been used by US-based scientists to re-domesticate wild tomato and to make compact forms with extended fruiting periods, which may after further modification be suitable as a space crop. GM lettuce has also been developed that contains pharmaceuticals that, for instance, can be used to treat bone density loss. These are proof of principle examples of how plants can be adapted for purpose. Further work is needed to improve nutrient use efficiency, reduce potential waste streams, improve processability and adapt plants to space conditions. Australia's experience and skillsets in the required sciences provide the potential to lead this sector.

LEVERAGING BENEFITS FOR HUMAN HEALTH

Human spaceflight programs can provide spin-offs with substantial economic and public health benefits. For example, developing countermeasures for the physiological and mental challenges of space flight has direct practical application to Earth-based public health challenges and may result in breakthrough improvements to public health outcomes, particularly in elderly, underserved, remote and indigenous populations.

The areas of greatest benefit in the short term are likely to come from:

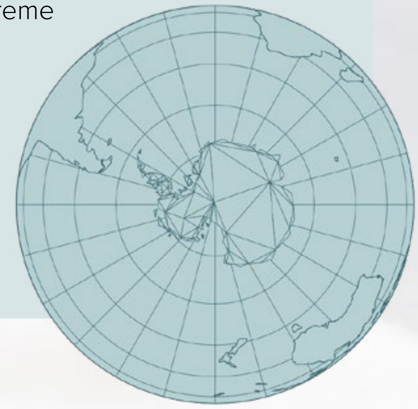
- bone density research for osteoporosis – suffered by over 6 million Australians over the age of 50 and costing $3.8 billion by 2022
- exercise development and reconditioning for people with musculoskeletal conditions – these conditions contribute 12–14% of the total burden of disease in Australia
- sleep and circadian physiology research – inadequate sleep cost Australia an estimated $66 billion in 2016–17
- neuro-vestibular research for falls prevention – falls resulted in 1.4 million patient-days of hospital treatment in 2014–15
- miniaturisation of medical diagnostics, sensors and technologies
- telehealth and remote medicine training and support – inhabitants of remote and very remote areas of Australia experience a total disease burden 1.4 times higher than major cities
- psychological care for isolated populations – bushfire and pandemic crises have highlighted the need for mental health support to physically and socially isolated populations
- antimicrobials to combat increasing antibiotic resistance
- space-hardened pharmaceuticals
- improved agricultural sustainability, including the supply of new plant-based products to feed the boom in controlled environment agriculture (30% growth globally per annum) and provision of new foods with enhanced nutrition.

ANTARCTICA AS A SPACE ANALOGUE

The Scientific Committee on Antarctic Research Expert Group on Human Biology and Medicine sets priorities for research on, and healthcare of, humans in Antarctica involving the fields of biomedical sciences, social and behavioural sciences, and medicine. Areas of particular interest include research into the effects of isolation, cold, altitude, and light and dark. Antarctica has been used as a space analogue for human research for some time.

Australia's Antarctic Program uses 'Life in a Freezer' to offer a high fidelity space analogue for operational medicine, training and research for 'ICE' (isolated, confined and extreme) environments. Antarctic expeditioners can spend up to nine months isolated from sophisticated medical support. They live in small populations in shared habitats surrounded by an extreme environment adding to psychological stressors. These hazards are just as life threatening as those found in space.

Antarctica has provided an analogue platform for Australian research in physiology, epidemiology, behavioural health and psychology, and photobiology. It has also provided training in clinical and operational medicine for extreme environments, and delivery of advanced telehealth and other technologies for isolated populations. These activities are part of a formal research program between the Australian Antarctic Division and NASA which since 1993 has facilitated cooperation to advance basic research, develop advanced capabilities for space flight, and advance operations management in isolated, confined and extreme environments.



Antarctica can be used as an analogue for space environments due to its isolation and extreme conditions.
CREDIT: TONGUY324 / ADOBE STOCK

The COVID-19 pandemic has demonstrated the importance of even simple telehealth consultations and mental health services[xiv]. The capability needed to meet the comprehensive medical requirements of long-duration space missions could revolutionise the efficacy and cost of virtual health delivery across all areas of Australia.

To maximise benefits to the domestic community and opportunities to participate in international space programs, Australia should prioritise and grow research in areas of expertise including:

- **technology-based healthcare delivery, training and clinical support for isolated, remote and extreme environments**, including leapfrog telemedicine technologies for imaging, patient monitoring and AI diagnostics
- **radiation**, to help solve a range of key knowledge gaps including cognition, behaviour and health
- **microgravity,** in particular musculoskeletal and neuro-vestibular physiology, where the biggest population health benefit can be derived from innovation and where dedicated facilities, human centrifuge, head-down bed rest laboratory and parabolic flight would greatly enhance capability
- **life support systems**, such as photosynthetic bioregenerative environmental systems to provide innovative solutions to problems of agriculture and nutrition, water recycling, microbial countermeasures, and waste management
- **suborbital flight** physiology and safety, spinning-off into a potentially lucrative commercial space tourism market
- **analogue space research,** using a remote desert environment to explore the physiology and psychology of isolation and confinement, human factors and psycho-social risks. These are key NASA knowledge gaps but areas of Australian expertise could form a niche international strength.

RECOMMENDATION

Commit support to space life science research, including space medicine and human factors, and space agriculture and nutrition, engaging with international programs and providing translation of research to improve everyday life.

xiv From March 2020 to April 2021, $2.9 billion in Medicare benefits were paid for Covid-19 MBS telehealth services. Source: The Hon Greg Hunt MP, Minister for Health, 26 April 2021.

Earth from space at night. Elements of this image furnished by NASA.
CREDIT: MARCEL / ADOBE STOCK

SECTION 4

Space for the future

'If you think in terms of a year, plant a seed; if in terms of ten years, plant trees; if in terms of 100 years, teach the people.'

CONFUCIUS

4.1 THE AUSTRALIAN SPACE WORKFORCE

SKILLS GAPS

Science, technology, engineering and mathematics (STEM) skills are essential for Australia's future workforce[57]. Surveys and working group reports commissioned to inform this plan, and other reports[58,59], point to workforce planning and development as the top strategic risk to the sustainable growth of the Australian space industry.

Australia's STEM workforce currently lacks the scientific, engineering and technical skills capacity to support our space needs[60]. Many of these require degree or higher-level training in disciplines such as physics, mathematics, electronic and software engineering, and data science. There is also a need for skills in human intersections with space technology, such as human cognition, performance, decision-making, and governance frameworks.

These capability gaps are mirrored in international jurisdictions, further pressuring our domestic supply. Agencies such as NASA and the UK Space Agency are reporting persistent skills shortages, lack of a STEM and humanities and social science workforce, and concerns about a wave of generational retirements[61,62]. In 2018, 58% of Canadian space companies had difficulties hiring STEM personnel to the extent that positions went unfilled.

Defence is currently the largest entity in Australia's space sector. It has been obliged to develop strategies to grow its STEM workforce[63], including internships and in-house training of STEM graduates and postgraduates[64]. Industry also performs specialised on-the-job training locally or overseas. The Australian Space Agency's aim is to triple the size of the industry, with up to 20,000 new jobs by 2030.

BENCHMARKING PROJECTIONS OF WORKFORCE REQUIREMENTS

The Canadian space sector has been building and operating spacecraft since 1962. In 2018, its workforce numbered just under 9,600 FTE, of which 61% were STEM qualified and 64% had a bachelor degree or higher[65]. One-third of the workforce comprised engineers and scientists. The space workforce was evenly divided between upstream (R&D, manufacturing, launch) and downstream (infrastructure, applications) sectors, and supported another 11,300 jobs in the broader economy.

Extrapolation against the structure of the Canadian space industry suggests that Australia's jobs target will require at least 1,000 new space sector employees including around 330 newly qualified scientists and engineers each year for a decade. This pipeline must be in addition to meeting existing shortages. Some specialists may be recruited from overseas but mostly Australia will need to depend on recruiting domestic students currently at university or VET, or in secondary school.

HARNESSING THE TALENT POOL

Our survey results reveal a mix of hesitancy and confidence about space sector careers. The most common concerns are instability of employment and poor ongoing career prospects. On the other hand, most respondents believe their prospects of space-related employment are good to excellent, but (especially for younger people) often think these need to be pursued overseas. Mid- and later-career women reportedly find this a barrier for family reasons. Only 19% of survey respondents were women, and one (0.5%) identified as Indigenous. The proportion of female researchers in engineering and physical sciences is also just 19%[66] while 75% of girls of school and higher education age don't find STEM careers are of interest[67]. The VET sector overwhelmingly provides engineering-related training but women comprise only 8% of the VET STEM qualified workforce[68].

It doesn't have to be this way.

An OECD report[69] points out that Russia and Ukraine have near gender parity in the space manufacturing sector, while in the UAE Space Centre and the South African Space Agency women form 40% and 39% of engineers and scientists respectively. The Australian astronomy community has targeted activities to increase public outreach and diversity, setting a goal for at least 33% participation by women across all levels of employment by 2025[70]. The proportion of women researchers in astronomy positions in Australia has risen from 21% in 2015 to 27% in 2019[71].

CAN THE UNIVERSITY SECTOR MEET THE NEEDS?

Undergraduate completion data show that bachelor degree graduation rates in some space skills areas such as physics, areas of engineering, and geographical sciences have been decreasing and are well short of meeting space workforce demand. Completion rates in some other areas such as mathematics and electronic and computer engineering have been increasing but are also below future space workforce demand.

Some universities have recently developed new space science degree programs, specialised master degree programs[xv] and research initiatives[xvi]. Space industry focused centres are also emerging in Australian universities[xvii], as well as industry PhD scholarships and internships such as with CSIRO and the SmartSat CRC. Various universities are also rapidly developing short courses and microcredential training aimed at stakeholder needs across the space sector, including Swinburne, ANU, SmartSat CRC, and University of South Australia in collaboration with the International Space University in France.

All these capabilities are small and discrete. Moreover, pandemic-related restrictions on international travel to Australia are also impacting the STEM workforce and the tertiary research and training sector[72]. The tertiary sector shed 20% of its workforce (around 40,000 positions) over the year to May 2021[73] with around 80% of these from public universities. These cuts will impact space science research and training. For example, two of Australia's three world-standard planetary science groups were effectively disestablished in 2021.

ROLE OF THE VET SECTOR

VET training provision is largely industry-led and there are few bespoke VET training courses. In the space industry, demand from either Defence or inclusion of space-applicable occupations in national or state and territory skills needs lists, helps guide training provision in VET. There are, at present, no space industry-specific courses listed on myskills.gov.au. Some VET training options could be applicable to the space industry, such as robotics, electronics, and communication engineering and computer systems engineering.

It is not currently known to what extent the space workforce requirements in Australia will be met by offering space-specific courses. However, in the UK technicians comprise around 20% of the space industry[74] while for Canada this is around 11%.

xv RMIT, University of Southern Queensland, University of NSW Canberra
xvi e.g. Curtin University Space Science and Technology Centre, UNSW Canberra Space, UWA International Space Centre
xvii e.g. CUAVA training centre at University of Sydney, Swinburne Space Technology and Industry Institute, RMIT Space Industry Hub, UNSW Australian Centre for Space Engineering

4.2 A NATIONAL SPACE WORKFORCE STRATEGY

The above discussion shows that Australia's STEM training and skills sector is currently incapable of meeting expected future demand for the space workforce.

Building this future workforce requires an overarching multi-faceted strategy to grow the skills pipeline. It should complement the Defence Industry Skilling and STEM Strategy (2019) and span the school, tertiary and industry sectors. A key plank of the Australian Space Agency's Civil Space Strategy is the pillar 'Build future workforce: Partner in a vision to build an Australian space sector that inspires industry, researchers, government and the Australian community to grow the next generation of the space workforce'. The Australian Space Agency should therefore carry lead responsibility for growing capacity, capability and diversification of the space workforce.

Below we focus on three enablers for such a strategy.

ENGAGEMENT: GROWING THE STEM FOUNDATION

Relative to international benchmarks, performance of the Australian school system in core STEM subjects has been steadily declining for some years[75]. However, space exploration inspires, and space science can be a valuable vector to STEM engagement. The school level provides the largest audience to encourage young Australians of diverse backgrounds to pursue STEM and space-related studies. International space agencies understand that aspirational space missions and hands-on space-science themed activities are important motivators for young people to engage with STEM programs[76]. Accordingly, they provide opportunities for students to watch, learn from and even participate in space-based research.

Various aspects of space science are included in Australian state, territory, and national curricula, but there are few dedicated facilities and teachers who are subject matter experts. Teachers seeking online space-related resources often use NASA sites and materials, which ignore the Australian context. The mission of the Australian Space Discovery Centre, located at Lot Fourteen in Adelaide, is to inspire the next generation of the space workforce, targeting 12–23 year olds who are considering career options. Visits require prepurchased timed tickets, and online teaching and learning resources are currently very limited.

Programs to increase engagement in space studies have been developed by a variety of government groups, NGOs, industries, fee-for-service businesses and individuals. While many of these may be excellent, this ad hoc approach is confusing, risks gaps or duplication of effort, does not provide for quality audit and evaluation of performance or outcomes, and does not ensure diversity and inclusion aspects are effectively incorporated.

Successful camps for high school students have operated for many years in South Australia (South Australian Space School) and Queensland (Australian Youth Aerospace Forum), and several small businesses offer space science expertise on a fee-for-service basis. CSIRO also provides extensive educational activities and resources related to space science engagement.

One stand-out organisation, the Victorian Space Science Education Centre (VSSEC), uses space science content and examples which are fully integrated with the school curriculum (see box). VSSEC has provided IP to help establish similarly themed facilities at Hamilton Secondary College in South Australia, and Wallington Schools District in Connecticut, USA.

The International Space Education Board (ISEB), founded in 2005, brings together 10 space agencies with the aim of increasing STEM literacy and supporting the future space workforce needs of member countries. ISEB provides a range of education initiatives including specialised events and opportunities for students. Australia is the only ISEB member not represented by a space agency, this role instead being championed by VSSEC, which is not tasked or resourced for such activity. This is a missed opportunity.

SPACE SCIENCE AS A STEM VECTOR: VSSEC

The Victorian Space Science Education Centre, hosted on the campus of Strathmore Secondary College in Melbourne, is one of six specialist maths or science centres established more than a decade ago by the Victorian Department of Education and Training. It uses space science as the teaching vector to introduce basic concepts in mathematics, physics and chemistry in hands-on, scenario based contexts. VSSEC's signature program is a Mission to Mars, aimed mainly at students in years 7–9. All activities are fully integrated with primary and secondary curricula. VSSEC caters for around 15,000 face-to-face students annually but also provides online programs and professional development resources.

The centre has achieved international recognition and is at the forefront of educational practice because of the way in which it combines a deep understanding of pedagogy (the science of teaching) with the teaching of science (and technology, engineering and mathematics). VSSEC represents Australia on the International Space Education Board, alongside nine space agencies including NASA, ESA, CNES and JAXA.

We identify the following actions to improve engagement in space-related and hence STEM topics at school level.

- **Mapping:** research to map the space science education ecosystem, to understand the gaps and the most successful levers, particularly for under-represented groups. This should include evaluation of the role of museums, observatories, planetariums, exhibitions, and science festivals such as National Science Week in contributing to space science education. Such mapping should also aim to build stronger connection, information sharing and coordination across Australia.
- **Commitment:** a national level commitment to developing, curating and providing curriculum-relevant Australian space-related material to stimulate STEM engagement, and related educator professional development resources. The materials should be diverse and inclusive, and be developed in consultation with the Australian Science Teachers' Association (ASTA). Ideally this would include hands-on science-driven space-related projects, including participation in mission design (see below: 'Retention and diversity: harnessing the talent pool'), with support from the Australian Space Agency and industry.

- **Access:** space-related resources must be widely and freely accessible through a respected, suitably maintained portal, readily accessible to remote communities, students with a disability, and those with poor digital inclusion.
- **Quality assurance and evaluation:** an evaluation plan is developed to allow space and education professionals to measure the effectiveness of their STEM outreach, in line with the Women in STEM Ambassador's National Evaluation Guide for STEM Gender Equity Programs[77], to improve programs and delivery.
- **Scope:** teaching resources and classroom activities highlight the breadth and cross-disciplinary and collaborative nature of space science activities.
- **Context:** Australian examples of space activity and achievement are used where possible, including Australian role models and leveraging the Australian Government's Girls in STEM Toolkit.

RETENTION AND DIVERSITY: HARNESSING THE TALENT POOL

A survey of nearly 1,500 Australian scientists in May 2020[78] found that 16% of men and 22% of women were planning to leave the workforce, that there is a 17% wage gap for all sectors, and that one in five women had reported sexual harassment at least once in their careers. Women with postgraduate STEM qualifications earn significantly less than men. Women are more likely to be working part-time or not at all and providing unpaid childcare to their children[79]. They have also been disproportionately impacted by the COVID-19 pandemic[80] through differential impacts of job losses and increased challenges of balancing paid work with family and caring responsibilities[81]. Inflexible parental leave schemes also affect paternity leave.

Australia is home to the world's longest established Indigenous cultures, which have a close affinity with the land, water and sky. Space-related infrastructure is increasingly being deployed across traditional homelands. However, Aboriginal and Torres Strait Islander people are under-represented in the space sector. This is a lost opportunity for Aboriginal and Torres Strait Islander peoples, and for other Australians to better understand and connect with this rich knowledge and history.

The benefits of diversity in the workforce are well known. The lack of representation of women and Aboriginal and Torres Strait Islander people in STEM have been highlighted as national problems by many groups, including the Australian Government and the Chief Scientist. The Women in STEM Decadal Plan developed by the Australian Academy of Science in collaboration with the Australian Academy of Technology and Engineering, identified strategies and actions to help address these inequalities through to 2030, and work is ongoing through the Women in STEM Ambassador. A global summary of policy instruments used by various jurisdictions to improve gender equity and STEM education in space-related fields is given in the OECD report.

The following additional recommended actions aim to improve retention, diversity and inclusion to benefit the capacity and productivity of the Australian space workforce.

- Advocacy by senior leaders promoting engagement and role models of preferred practices, managed through a Diversity and Inclusion Office within the Australian Space Agency.
- Data collection and research supported by this office on the experiences of people with diverse backgrounds in the space science and industry sector, in order to inform strategies.
- Encouragement of adoption across the space sector of principles supporting equity, diversity and flexible working environments. Suitable models may include the Gender Action Toolkit of the Centre for All-sky Astrophysics (CAASTRO)[xviii], the Science in Australia Gender Equity (SAGE) program, and recommended actions in the Australian Academy of Science report, Impact of COVID-19 on women in the STEM workforce.
- Digital accessibility and support is equally available to all.
- An award scheme, similar to the Pleiades Awards by the Astronomical Society of Australia, to recognise Australian space organisations which take active steps to promote equity and inclusion of all people, and to actively support currently marginalised groups.
- Encouraging space-related organisations to become Champions of the Women in STEM Decadal Plan, supporting organisations advocating for gender and diversity inclusiveness, and collaborating with organisations such as the Australian Institute of Physics, the Space Industry Association of Australia, the Astronomical Society of Australia and Astronomy Australia Limited.

IMPROVING OUTCOMES: CROSS-SECTOR COLLABORATIVE EXPERIENCES

Universities are the engine-room for basic, enabling research, and the supply chain for the highly skilled workforce. However, Australia has a poor record of translating research to industry outcomes[82]. From the space perspective, a key factor that would improve this situation is a strategy to bring together disparate elements of the space sector to collaborate on challenging space missions and projects, from conception through to operation, to develop essential capability and infrastructure.

We identify the following actions which may be part of such a strategy.

- A program such as the Canadian CubeSat Project (see section 3.1) designed to grow innovation and capability through engaging tertiary students in developing scientifically valid CubeSat space missions. An Australian ground-based example is the Monash Nova Rover (see box page 55).
- A program similar to NASA's Technology Transfer Program[83], which provides a central resource for technology access and commercialisation.
- A seed funding scheme supporting collaborative projects, for example with the Australian Space Agency partnering on ARC Linkage type grants. While the CRC program also aims to build collaborations, it does not support new or innovative projects outside the scope of existing CRC partnerships.

xviii http://caastro.org/gender-action-toolkit/

Monash Nova Rover is a team of university students designing, fabricating and testing the next generation of Mars rovers, and inspiring future generations along the way.
CREDIT: CAROL OLIVER / UNSW

NOVA ROVER

Monash Nova Rover is a team of Monash University students who have been designing, fabricating and testing Mars rovers in their Melbourne laboratory. Comprising (in 2020) almost 50 students (one third women) from commerce, design, engineering, IT, medicine and science, the team has been taking its rovers to compete in the international University Rover Challenge (URC) since 2017. The machines are highly sophisticated, featuring autonomous navigation, a robotic arm, several cameras, a comprehensive sensor suite, and life detection capability.

URC is the world's premier robotic competition for tertiary students, held annually in the Utah desert. In order to qualify teams need to present a science plan, pass a preliminary design review and a system acceptance review, and produce a detailed financial report. Nova Rover is an outstanding example of how space science empowers engagement with STEM technology, producing young scientists and engineers with skills to drive the innovation economy.

- A professional development and mentoring program to support career development for young space scientists and engineers across the academia–industry nexus. Many prime contractors and government agencies such as Defence and CSIRO already offer development opportunities but a program of national scope, with cross-sector focus and funded to defray industry participation costs, is needed to address workforce skills gaps[xix].
- Standardised IP agreements and other arrangements between state governments and the Australian Government to reduce inefficiency and promote engagement, and a national framework to help protect domestic IP.

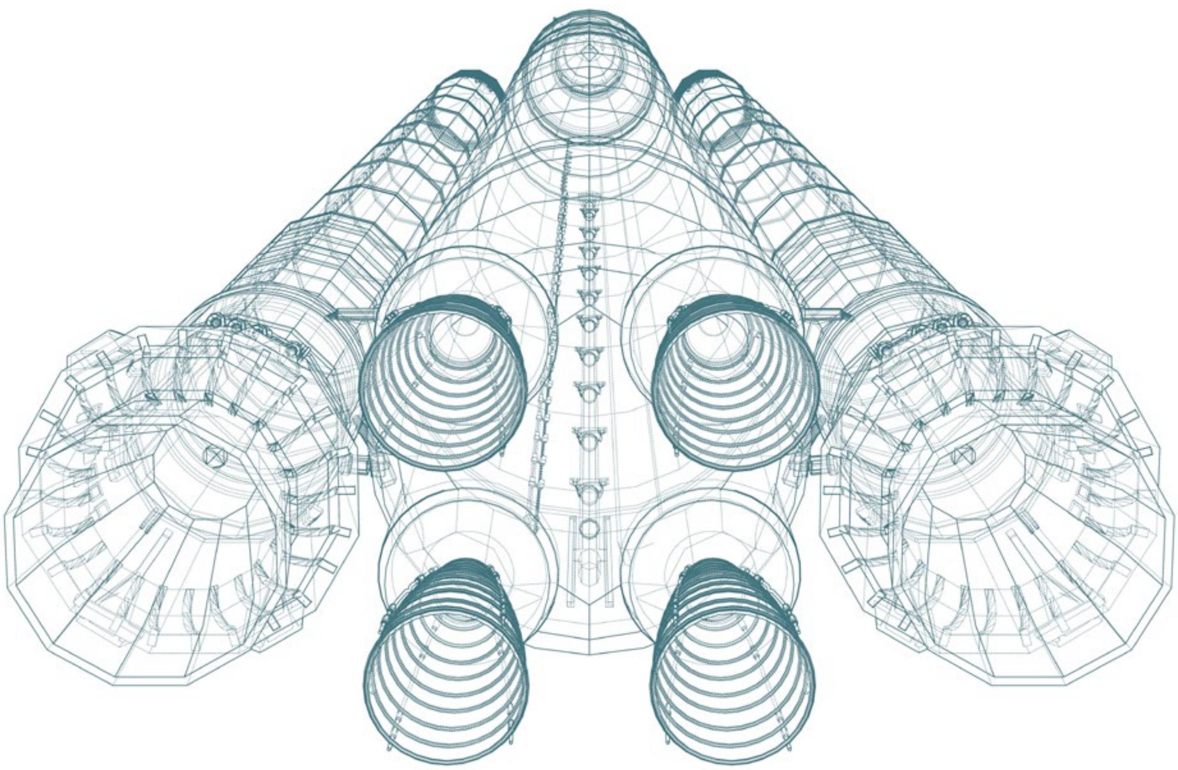
xix A pilot program of this nature has been funded by the Australian Academy of Science's Theo Murphy Initiative for 2021–2022.

- Removal of the discrimination between university- and industry-based R&D groups, who all need to develop IP to sustain and grow their activities. For example, the Canadian Space Agency regards academic organisations as core elements of the space industry, comprising 20% of the workforce (almost all in STEM), 21% of registered patents, and engaging with international partners.
- Regular science–government–industry workshops to promote information sharing and collaboration[xx]. Pricing must allow student attendance.
- Mechanisms to encourage and reward staff flexibility between academia and industry, such as encouraging industry-based academic study leave and academic co-appointments for industry fellows.

RECOMMENDATION

Develop an integrated national space innovation and education strategy, led by the Australian Space Agency, that spans the primary, secondary, tertiary, VET and industry sectors, and aims to grow STEM participation, and improve career pathways, and improve industry outcomes, cognisant of the values of diversity and equity.

A high priority of this strategy should be a national taxonomy of space-related skills (this does not presently exist) and an audit of the current space course offerings at tertiary level. This will provide critical baseline data to systematically plan improvements to overcome the skills gap. It is important that this overall strategy is led by the Australian Space Agency, as a whole-of-government organisation.



xx The biannual Space Forum run in Adelaide has not to date included a science focus, while the Avalon airshow is principally a Defence event.

Appendix A

ABBREVIATIONS

ADF	Australian Defence Force
ARC	Australian Research Council
Bureau	Bureau of Meteorology
COPUOS	[United Nations] Committee on the Peaceful Uses of Outer Space
COSPAR	Committee on Space Research, a member of the International Science Council
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CubeSat	A microsatellite based on a 10 x 10 cm size format, e.g. 3U = 30 x 10 x 10 cm, etc.
Defence	Australian Government Department of Defence
DST Group	Defence Science and Technology Group
EO	Earth observation
GA	Geoscience Australia
GDP	Gross domestic product
GEO	Geostationary orbit
GNSS	Global navigation satellite system
IoT	Internet of things
ISRU	In situ resource utilisation
JORN	Jindalee Operational Radar Network
LEO	Low Earth orbit
MEO	Medium Earth orbit
MWA	Murchison Widefield Array
NCRIS	National Collaborative Research Infrastructure Strategy
OECD	Organisation for Economic Co-operation and Development
PNT	Positioning, navigation and timing
R&D	Research and development
RF	Radio frequency
SBAS	Satellite-based augmentation system
SDA	Space domain awareness
SouthPAN	Southern Positioning Augmentation Network, in effect SBAS for the Australasian region
SSA	Space situational awareness
STEM	Science, technology, engineering and mathematics
STM	Space traffic management
TRL	Technology readiness level, a scale of 1–9 (basic research to fully operational)
WMO	World Meteorological Organization

Appendix B

THE PLAN PROCESS

This plan has been informed by the activities of several expert working groups, listed below. Each working group comprised up to 10 expert members. Reports from these working groups appear in a separate volume of accompanying papers.

The plan document was developed by the Executive Working Group also listed below.

Broad community input to the plan was obtained through a number of mechanisms: town hall meetings at the Australian Space Research Conference in October 2019 and the COSPAR conference in February 2021; calls for submissions in December 2020 and to the exposure draft in August 2021; and solicited peer review in December 2020 and August 2021.

All participants have given their time generously and freely, despite competing and challenging priorities. The views represented in this document do not necessarily reflect the views of, nor imply endorsement by, any individual or any working group members' affiliated organisations.

EXECUTIVE WORKING GROUP FOR THE DECADAL PLAN

Emeritus Professor Fred Menk *Chair,* National Committee for Space and Radio Science

Professor Phil Bland *John Curtin Distinguished Professor,* Curtin University

Dr Brett Biddington AM *Principal,* Biddington Research Pty Ltd

Dr Kimberley Clayfield *Leader, Space Technology Future Science Platform,* CSIRO

Professor Stuart Phinn *President, Earth Observation Australia Inc.* University of Queensland

Imogen Rea Department of Industry, Science, Energy and Resources (now at Rocket Lab, New Zealand)

Adam Seedsman *Executive Director,* Australian Space Agency

EXPERT WORKING GROUPS AND CHAIRS

Australian space research and industry community survey **Associate Professor Carol Oliver** University of NSW

Australian space science research capacity and priorities **Emeritus Professor Fred Menk** University of Newcastle

Communications technologies **Professor Bill Cowley** University of South Australia

Earth observation **Professor Stuart Phinn,** Earth Observation Australia, **Professor Simon Jones** RMIT University

Education, training and careers **Dr Sarah Baker** South Australia Department of Education

Heliosphere science **Professor Colin Waters** University of Newcastle

Planetary sciences **Professor Phil Bland** Curtin University

Space-based PNT **Emeritus Professor Chris Rizos** University of NSW

Space health and life sciences **Associate Professor Gordon Cable AM** University of Adelaide

Space situational awareness and space weather **Dr Melrose Brown** University of NSW Canberra

Space technology **Nick Carter** CSIRO Space and Astronomy

Workforce capacity and capability **Louise Moes** Australian Academy of Science

Appendix C

EXAMPLES OF CURRENT AUSTRALIAN SPACE SCIENCE ACTIVITIES[xxi]

- Detection and tracking of near-Earth objects by combining the capabilities of the Canberra Deep Space Communication Complex and the Australia Telescope National Facility (CSIRO)
- Development of innovative, low cost, small research satellites and associated technologies at many universities and CSIRO
- The Binar program at Curtin University, developing highly integrated reconfigurable CubeSat platforms providing low cost, agile scientific exploration mission options
- The Melbourne Space Program, founded by team of students in 2014, a breeding and training ground for space technologists and entrepreneurs such as Troy McCann, founder of Moonshot Space Co.
- Space-based remote sensing to improve horticulture, livestock and irrigation management, forecasting and mapping, identify the presence of pests and diseases, and improve nutrient use efficiency and yields (University of New England and others)
- Development of user-friendly applications for visualising global and regional geophysical and geological data through time (EarthByte consortium led by University of Sydney)[84]
- A partnership between DLR and La Trobe University to develop the DESIS hyperspectral camera, built by Teledyne Brown Engineering and operating on the ISS[85]
- Development of an optical space situational awareness sensor array spanning Australia (Curtin University and Lockheed Martin)
- Expertise in ionospheric physics in universities and DST Group underpinning development of JORN, backbone of Australia's long range surveillance capability
- Using advanced physics and mathematics to image the far side of the Sun and improve understanding of disruptive solar events (Monash, Sydney, Newcastle universities)
- Using GNSS for geodesy applications to measure crustal deformation and kinematics, Earth orientation and rotation (e.g. GA, UNSW, ANU)
- Remote sensing of the atmosphere and surface (via radio occultation and reflectometry techniques), substantially improving weather forecasting (Bureau, RMIT, UNSW)
- Precise gravity measurements from orbit to investigate sea level rise, floods, droughts and earthquakes (University of Newcastle)
- A national consortium of 12 Australian institutions partnering with NASA in 19 international space missions to address basic and applied science questions through the Solar System Exploration Research Virtual Institute (SSERVI)
- Space-derived Earth observation science to better understand and monitor our land, water and atmosphere, and better manage resources and mitigate, map and manage disasters (CSIRO)
- Provision of satellite calibration and validation services, and access to NovaSAR-1 synthetic aperture radar data, to support Australian EO activities (CSIRO)
- Investigation of superflares at other stars and possible effects on planetary habitability (USQ)
- Development of high speed microwave chips and circuits for advanced satellite communications (Adelaide University and local and international collaborators)

xxi This is a selected, not exhaustive, list.

- Collaboration with DLR (German space agency) on optical and quantum communication capability (University of South Australia and ANU)
- Research into adaptive optics and quantum technologies for the Australian Optical Ground Station Network (ANU, UWA, CSIRO, with international partners)
- Research on in situ resource utilisation to support lunar exploration, including resource modelling, characterisation and extraction, robotics, remote operations, and materials for lunar dust mitigation (CSIRO)
- Development of machine learning and data visualisation software for NASA's Perseverance Mars Rover Mission (QUT)
- Research on the world's oldest land-based fossils, in the Pilbara region, providing new insight on origins of life on terrestrial planets (University of NSW)
- Skinsuits to mitigate bone and muscle loss on long duration space missions, with potential application in everyday sedentary situations (RMIT with local and international partners)
- Research into food for long-duration human spaceflight missions, including packaged food and in-space food production (CSIRO)
- Expertise in advanced materials, space medicine and radiation physics at CSIRO, ANSTO and Wollongong University leading to internationally important research projects on radiation protection for space missions
- Using a Mars Analogue research facility at Arkaroola, South Australia, for field science and engineering, evaluation of exploration methodologies, education and outreach (various university groups and Mars Society of Australia)
- Research on living in Antarctica as an analogue for long duration space flight, by the Australian Antarctic Division in conjunction with NASA since 1993[xxii]
- A partnership between the University of Melbourne, multiple Australian industry partners, and the Italian Space Agency to develop and launch an innovative technology and science demonstrator satellite, the SpIRIT 6U CubeSat. This hosts an X-ray detector developed by the Italian National Institute for Astrophysics, and is the first space mission funded by the Australian Space Agency
- Studies to test alternate radio and radiometer configurations for sensing soil moisture from satellites, such as the NASA SMAP and ESA Soil SMOS missions (Monash University)
- Delivery of NASA's Global Learning and Observations to Benefit the Environment (GLOBE) educational program (partnership between CSIRO and the Australian Space Agency)
- Establishment in 2021 of an annual Australian Rover Challenge, bringing together teams of university students to design, build and operate semi-autonomous rover vehicles in a simulated lunar environment (South Australian Space Industry Centre, Australian Space Agency, SmartSAT CRC)

xxii Dr Des Lugg was appointed Chief of NASA's Medicine of Extreme Environments division in 2001 on retirement from Head of Polar Medicine at the Australian Antarctic Division

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