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

COMPANION DOCUMENT: EXPERT WORKING GROUP REPORTS

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Acknowledgements

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Contributors to each report are listed in alphabetical order. Care has been taken to ensure the lists are complete, however please notify nc@science.org.au of any omissions.

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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.

Prepared by the National Committee for Space and Radio Science on behalf of the Australian Academy of Science.

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Foreword

Space-derived activities and services support much of our economy and society. New technologies and burgeoning commercial activity are transforming the space sector. These changes offer incredible opportunities and risks.

Science underpins knowledge and use of space. Space science and technology are also exciting areas for educators, students and innovation driving the new economy. Australia must therefore evolve and grow existing research strengths in fundamental and applied space science research in support of national priorities.

The first national plan for space science, developed by the Australian Academy of Science's National Committee for Space Science and published in 2010, outlined a vision for a long-term, productive Australian presence in space underpinned by internationally engaged space science and technology, and education outreach. In 2015 the Academy's National Committee for Space and Radio Science surveyed the national space science community to assess views on the value of and progress toward the goals of the 2010 decadal plan. This informed a vision statement that outlined opportunities and priorities for Australia to best utilise and innovate in space science and technology to generate economic growth, deliver societal benefits and enhance national security.

Much has changed in the national space narrative since these documents were published. These changes include establishment of the Australian Space Agency in July 2018 and release of the Australian Civil Space Strategy 2019–2028; the rollout of the of the satellite-based National Positioning Infrastructure and the Digital Earth Australia Earth observation data platform; and major commitments to space-based capability by the Department of Defence.

The purpose of the new decadal plan is to identify strategies for Australian space science to generate new knowledge, drive innovation, support growth of the space industry, enhance our social capital and advance national needs.

Development of the current decadal plan was informed by the activities of ten expert working groups and two specially designed surveys. These aimed to identify areas of strength; key trends and scientific challenges in international and national contexts; opportunities for space science to contribute to national priorities including education and training; and strategies on how those opportunities may be realised. The working groups roughly covered those disciplines of concern to the Committee on Space Research (COSPAR), the main international body dealing with scientific research in space, except for astrophysics.

This volume contains reports summarising the findings of these working groups and surveys. These are the result of careful, detailed expert consideration. Very many people contributed their time generously and freely to the plan process, despite competing and challenging priorities in a pandemic-impacted environment. However, the views represented here do not necessarily reflect the views of, nor imply endorsement by, any individual or any working group members' affiliated organisations.

Emeritus Professor Fred Menk
Chair, National Committee for Space and Radio Science 2017–22

Australian space research and industry community survey

June 2020

WORKING GROUP MEMBERS

Chair: Associate Professor Carol Oliver

Members:

- Dr Brett Biddington
- Dr Eriita Jones
- Isabelle Kingsley
- Professor Fred Menk

DISCLOSURES OF INTEREST

None

INTRODUCTION

The above Working Group met in 2019 at the Australian Academy of Science for a one-day workshop on creating a short survey to assess the shape of the Australian space research and industry community. A survey of 13 questions was developed and discussed at a Town Hall meeting at the Australian Space Research Conference in September 2019. Revisions were made, and in late December 2019, the survey was launched on the Australian Academy of Science's website. The survey ran until March 23, the same day as COVID-19 closed Australia. The survey therefore reflects the pre-pandemic community.

The survey was distributed via several electronic address databases and invited responses from 'those studying, employed in or otherwise contributing to the Australian space science community'. Organisations which distributed the survey include the Academy of Science, the Australian Space Agency, the Australian Space Research Conference, the Australian Space Industry Forum, the National Space Society of Australia, the Australian Youth Aerospace Association, the Mars Society of Australia, the Australian Institute of Physics, the CSIRO, the Space Industry Association of Australia, the Engineers Australian National Committee on Space Engineering, and various university groups (e.g. ANU Institute of Space, UNSW Australian Centre for Space). While there is overlap between these various databases the survey is likely to have reached most of the target audience.

A copy of the survey instrument appears in the Appendix.

The survey was analysed by Carol Oliver by hand, except for the word pictures and frequency of words, which was undertaken by Isabelle Kingsley using the qualitative analysis software NVivo. The raw database of 212 respondents had one duplicate and one person from outside of the Australian space community. These were eliminated, leaving a database of 210 respondents. The previous Space Decadal Plan survey, in 2015, posed 82 questions and elicited 72 fully completed and 45 partly completed responses.

Responses to the 2020 survey came from all areas of the sector, undergraduates through to very senior researchers and administrators. Answers to open-ended questions were mostly thoughtful, carefully considered, and often pessimistic regarding future prospects for growth of the research sector. One notable outcome of the 2020 survey is that not much has not improved since 2015 despite an almost 100% larger sample. Five years have elapsed, and nearly two years of these having an Australian Space Agency – one of the most pressed-for needs in the 2015 survey. There are some exceptions, one being the coalescing of opinion around Australia positioning itself on its strengths within international needs and missions, perhaps galvanised by the Moon and Mars contract to which the Australian Government has committed.

Some areas were not covered in the 2015 survey, so there is nothing to compare them to – for instance, the four open-ended questions about jobs, willingness to go overseas, and what Australia should focus on going forward. Following is a discussion of demographics and employment results followed by an analysis of four open-ended questions.

1. DEMOGRAPHICS

Of the 210 respondents, 86% identified as Caucasian and 9.5% non-Caucasian, 4% preferred not to say, and just one person identified as Aboriginal.

Respondents were evenly split into the three age categories: 18–35 (35%), 36–50 (28%) and 51–65 (31%). The remaining group, 66+, consisted of 13 male respondents (6%).

Almost a third of respondents came from New South Wales (33%), with a relatively even split between Queensland (12%), Victoria (14%), South Australia (13%), Western Australia (14%) and the ACT (12%). The smallest number of respondents were from Tasmania (3%). There were no respondents from the Northern Territory.

Just under a fifth of the respondents were female (19%), slightly less than in the 2015 survey (21%). It is remarkable and concerning that the gender proportion has not improved. Of the remaining respondents, 79% were male, and 2% preferred not to say. Females comprise 24% of both the 18–35 and 33–50 age groups, but only 14% of the 51–65 category, with none in the 66+ group.

Most of the respondents are in their mid-career (39%) with 20% identifying as late career. However, in the pipeline categories, 19% are in their early career or post-docs, 17% are PhD students, and 5% are undergraduates.

Most respondents believe space-related career skills are transferable (73%) or somewhat transferrable (20%) to other careers.

2. EMPLOYMENT

Three-quarters of respondents currently have space-related jobs (74%). Of the remainder, some are retired, and the remaining cohort consists of volunteers. There is no indication among the volunteers that they are currently seeking space-related paid employment.

As in the 2015 space survey, universities are the biggest employer, which is unsurprising given the research, development and teaching nature of higher education. Of the 210 respondents, 56% work in universities (72% in 2015), 15% in for-profit companies, 9% in Government departments, 8% in Government funded bodies (in 2015, these were grouped together and accounted for 15% of respondents); 4% in non-for-profit companies and 8% in other employment (contractors and volunteers). The number of contractors and those working in for-profit and not-for-profit companies together equals 22% of respondents in the commercial world in 2020, compared to just 5% in the 2015 survey. While this could indicate growth, there are other factors to consider, including the broader reach of the 2020 survey.

About 8% of the respondents have casual jobs, and a smaller number are on contracts (5%). The majority (39%) have full time or part-time (24%) ongoing work. However, 17% of the respondents identify as volunteers, and 7% do not give any employment.

One stand-out feature was that of the 11 respondents on contracts, almost half of them were female – which is disproportionately high, given the respondent cohort is more than 80% male.

3. OPEN-ENDED QUESTION 1

Please add comments if you wish to expand on the answer to the question 'Do you think there are impediments to remaining in the space-related area and if so, what are they?'

The most common concerns regarding ongoing employment in the sector were 'lack of funding' (38%), 'instability of employment' (22%), and 'poor career prospects' (13%). Of the 15% who reported no such impediments, many were in high-level government or university positions, students, or retired. Of lesser concern, but mentioned a few times was 'work-life balance' (almost 2%).

The negativity concerning employment relates specifically to Australia; for example:

> '*...there are few space-related postdoctoral opportunities in Australia*'.
>
> '*The majority of space-related opportunities are based overseas and can involve relatively high barriers for entry for foreigners*'.
>
> '*...there are very few available opportunities for people to obtain jobs in the space industry in Australia and often jobs that do become available require at least some experience overseas*'.
>
> '*The Australian space industry is still quite small and fragmented. If you lose an existing space job, it can be difficult finding another role in the industry*'.

A claim made by one respondent is that tenders by other nations are limited to national companies, but Australian bids are open to anyone.

A word cloud generated in NVivo underscores majority thinking on the 'lack of funding' perspective, with funding in Australia mentioned 57 times. Lack of opportunities in industry and research also top the word count and is reflected in the word cloud.

In contrast to negativity on funding and job stability in Australia, the view of job prospects in the space industry generally is relatively strong, including in the critical beginning of the pipeline, the PhD students. Of the 36 PhD student respondents, almost 60% thought that their prospects of space-related employment were good to excellent. Another 27% of respondents thought there were 'some' job prospects, with only 13% of students (representing five individuals) believing their prospects of space-related employment were 'little to none'.

The positive attitude toward prospects is not limited to the beginning of the pipeline – it reflects across early, mid and late-career respondents with 61% saying that prospects of space-related employment were good to excellent. Another 29% thought there were 'some prospects' with only 9% saying prospects were 'little to none'.

Nearly three quarter (74%) of respondents believed they had skills transferable outside space science employment.

Figure 1. Open-ended question 1 word cloud

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4. OPEN-ENDED QUESTION 2

Where do you see Australia developing a role in space in the next five to ten years?

Participation in international missions was the most commonly anticipated space role for Australia in the next five to 10 years, with many respondents citing areas in which Australia has, or could have, niche capability. In the NVivo word cloud (Figure 2), missions stand out as the fourth most used word after space, Australia and development, being used 57 times by respondents. Industry and satellites were the fifth and sixth most used words – and often with associated phrasing in sensors and other instruments, remote sensing, Space Situation Awareness, GNSS, the geography of Australia's location, Earth observation, communications, mining, medicine and robotics. There were at least 37 mentions of launch capability among respondents, as reflected in the upper right quadrant of the word cloud.

A common thread of satellites, services and instrumentation ran through a number of comments, for example:

> '*Niche capabilities in technology and manufacturing, enhanced satellite and debris tracking, aerospace medicine, environmental management*'.

> '*Niche sensors, CubeSats, systems/concepts, taking advantage of our geographic location (testbeds, collaboration with overseas entities)*'.

> '*In extremely niche areas of space with very focussed technologies. Piggy backing onto NASA missions*'.

> '*...our niche competitive advantage in various domains of space-related technology. Global leadership therein should be a key strategy*'.

Geographical position came up frequently, for example:

> '*Australia's main strength is geopolitical*', and '*Using our geographical advantage and our strong research expertise*'.

There were opposing views on launch capability such as:

> '*We do not have the infrastructure to support large scale launch and rocket manufacturing*', but...

> ...'*Launch site and infrastructure, CubeSats, satellite scientific payload design and build, Australian science leads on international Earth observation and interplanetary missions*'.

Although not mentioned as often, some respondents felt very strongly that STEM education and outreach was necessary to keep an open pipeline for future talent, for example:

> '*Some publicly-funded science/exploration missions will be necessary to inspire the next generation to do the learning necessary to provide the future workforce*'.

Figure 2. Open-ended question 2 word cloud

5. OPEN-ENDED QUESTION 5

Would you go, or have you gone, overseas to pursue a career in space-related activities?

Willingness to seek a space-related career overseas is sharply marked by age – the younger, the more like a person is open to the idea. Indeed, some point to it as almost a necessary rite of passage:

> '*There are very few available opportunities for people to obtain jobs in the space industry in Australia, and often jobs that become available require at least some overseas experience*'.

Others point to most jobs being overseas:

> '*The majority of space-related opportunities are based overseas and can involve relatively high barriers for entry to foreigners*'

Some respondents point to lack of opportunity in Australia:

> '*...there are few space-related postdoctoral opportunities in Australia*'..

Females express the same willingness as males to go overseas in the 18–35 age group but this diverges in the other age groups, unlike males. The key reason cited from females only is family, for example:

> '*No, not in the short to medium term, due to family constraints*'.

> '*No, due to family commitments, I have not pursued a career overseas.*'

In the word cloud generated by NVivo (Figure 3), the most used word after space, Australia, and overseas is 'yes' – used 63 times while 'no' is not in the top 20 most-used words. Work is used 51 times, career, 45 times, and opportunities, 40 times. The word family is used 14 times, and most likely associated with a resistance or simple 'no' to the idea of uprooting the family to take up a position overseas. One theme threading through responses is a preference for Europe as a destination for space-related opportunities rather than the US.

Figure 3. Open-ended question 3 word cloud

6. OPEN-ENDED QUESTION 4

What is your area of space-related work and/or study?

The respondents represent a very wide number of careers within the broader areas of science, technology, engineering and education. The most common word used after 'space' was engineering, mentioned 31 times and in phrases of up to 11 words, closely followed by satellites, research, science, and systems. Communications, instruments, education, observation, development, space policy and space weather, were also commonly used words. Some of the correspondents work in astrophysics (mentioned 21 times), planetary studies and – although not regarded as being in the space science category, astronomy.

Figure 4. Open-ended question 4 word cloud

SUMMARY

The 2020 survey shows little change with respect to those areas covered in 2015. In the remainder, apart from a few minor surprises, views are expressed in four open-ended questions. In Question 1 and Question 3, it is clear that the community views job prospects in Australia to be very low, funding opportunities limited and where available not aligned to the timelines required in space-related activities. Given the low job prospects in Australia, there is a general willingness to seek positions overseas except where family commitments prevent that consideration.

The space science research workforce remains predominantly mid-career Caucasian men, while females are mostly in the youngest age group.

In Question 2, the Australian Space Agency's commitment to NASA's Moon and Mars missions may be partly responsible for an international outlook. This is coupled with the recognition that Australia's key advantages are its geography and niche capabilities in instrumentation, satellites, software, SSA and GNSS. There is an appetite for launch capability but this is not currently on Australia's horizon.

Question 4 confirms that the community is largely space-related science, technology and engineering. Education is recognised as the way to inspire the next generation.

APPENDIX

RESEARCHER/INDUSTRY SURVEY

Q1. What is your gender? (M, F, other or prefer not to disclose)

Q2. What is your age group? (18–35, 36–50, 51–65, 66+)

Q3. How do you identify? (Caucasian, non-Caucasian, Aboriginal and Torres Strait Islanders)

Q4. What state or territory do you or study in? (NSW, Victoria, ACT, Queensland, South Australia, Western Australia, Northern Territory, Tasmania)

Q5. Which organisation do you work or study with for space-related activities? (Government departments or operational agencies; Government-funded research agencies; University; for-profit company; not for profit; other)

Q6. What is your career stage? (select more than one if applicable) (undergraduate student; higher degree student; postdoc; early career; mid-career; late-career)

Q7. Outside of your studies, how would you characterise your space-related activities? (Ongoing full time; Ongoing part-time; Contract; Casual; Voluntary; N/A)

Q8. How do you regard your prospects for entering or remaining in space-related employment? (Little to none; Some; Good; Excellent)

Q9. Do you think the space-related skills you are gathering or have are transferable outside of space-related employment? (No; Somewhat; Yes; I don't know)

Q10. Do you think there are impediments to remaining in the space-related area and if so, what are they? (Stability of employment; Poor career prospects; Lack of funding; Location; Work-life balance; Work culture/discrimination; N/A). Please add a comment if you wish to expand on the answer.

Q11. Where do you see Australia developing a role in space in the next 5 to 10 years? (Open-ended)

Q12. Would you go, or have you gone, overseas to pursue a career in space-related activities? Please explain response or say if this question is not applicable to you. (Open-ended)

Q13. What is your area of space-related work and/or study? (Open-ended)

Australian space science research capacity and priorities

Data analysis report

July 2020

AUTHOR

Emeritus Professor Fred Menk

DISCLOSURES OF INTEREST

Chair, National Committee for Space and Radio Science

INTRODUCTION

To inform development of the next strategic plan for space science, the National Committee for Space and Radio Science undertook a survey of current and future space science research capacity and priorities. The survey comprised 5 short answer questions plus one open-ended question and was conducted using an invitation-only Academy of Science website over 22 May – 12 June 2020. A copy of the survey instrument appears in the Appendix.

The survey specifically and solely targeted heads of space science research groups in universities, government divisions, and SMEs, 50 of whom were invited to respond via personal emails. Thirty detailed responses were received, 5 from government divisions or departments, 5 from SMEs, and the remaining 20 from university groups. All areas of space science research are more or less evenly represented except for space life sciences, which was featured in only 7 groups.

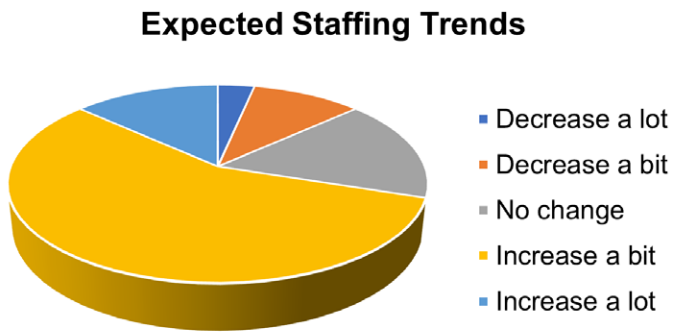
Responses to open-ended questions in particular provided valuable insight on current capabilities and future priorities for space science research. Individual responses are confidential but main points and trends are summarized below. Since conducting this survey the university sector in particular has experienced pandemic-related capacity reductions.

PERSONNEL

Altogether over 600 employees, around 120 higher degree research (HDR) students and over 60 honours students are represented by the respondents. About 25% of these employees and 70% of the HDR students are attached to university groups.

Respondents were optimistic about staffing trends, with 70% expecting employee numbers to increase a bit or a lot over the next 2–3 years (especially in industry), and 17% expecting no change (mostly in universities). These results are depicted in Fig. 1. Expectations were similar for HDR student numbers. All but one respondent confirmed the presence of a gender equity policy in their institution, although 20% claimed no resources were provided for its implementation.

Figure 1. Anticipated staffing trends over next 2–3 years



RESOURCES

Heads of groups were asked to identify their principal sources of research funding, in order of importance. The responses varied by sector, as seen in Fig. 2. For university groups the main sources were ARC grants, recurrent (institutional) funds, and other government support, in that order. Not surprisingly, government departments relied overwhelmingly on recurrent funding, while government funds were important sources for industry.

When asked about the adequacy of their research funding, all government groups, 75% of university groups, and 60% of industry groups stated that their funding was inadequate. All university research groups whose main source of funding is ARC grants find this inadequate. Nobody reported having more than adequate funding.

However, the pattern for anticipated funding over the next 2–3 years is more optimistic. Most industry and some university groups expect significant increases in their research funds, while government departments expect no change or small increases. These trends suggest general belief in growth of the space sector.

Regarding research infrastructure, 80% of government and industry groups reported this is adequate at least, while 35% of university groups find this inadequate.

Figure 2. Relative importance of funding sources for government departments (green), industries (orange), and universities (grey).

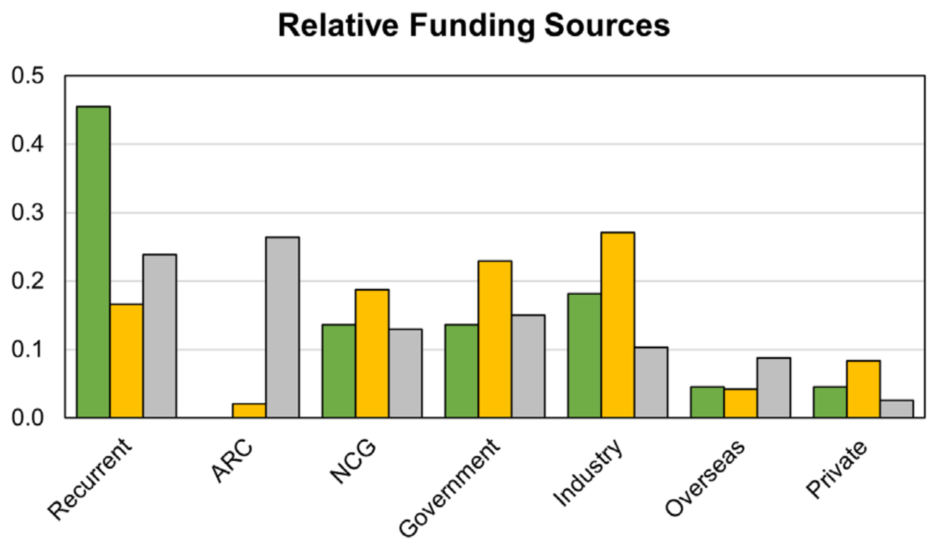
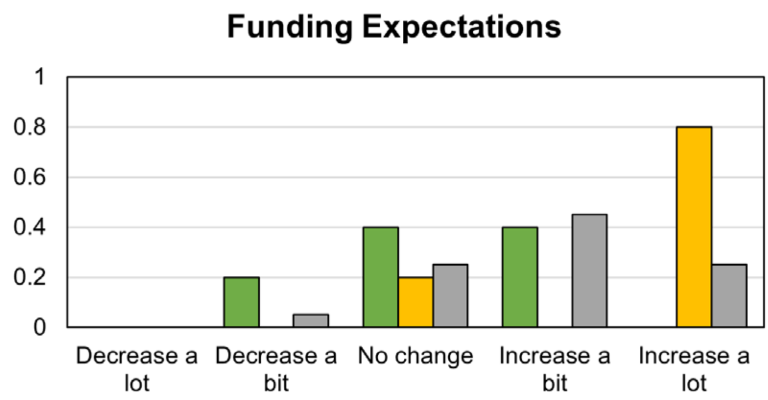


Figure 3. Anticipated funding trends over next 2–3 years for government (green), industry (orange) and university (grey) groups.



COLLABORATIONS

All respondents reported that their research is strongly influenced by international collaborations, and all but two university groups stated that industry–university collaborations are important.

These results suggest that Australian space science researchers are well connected with international researchers and groups, and that most seek to form collaborative linkages with industry.

BARRIERS TO RESEARCH

Heads of groups were invited to identify the main barriers to growing their group's research activities through an open-format question. A variety of responses was received but in essence there were three areas of concern: funding (80% of all responses), workforce (30%), and strategic policy supporting space science development (30%). Twenty-five percent of university group heads also expressed critical difficulties around their personal workload.

Responses about funding highlighted barriers due to the very competitive and limited funding streams which only cover short-term projects and contracts: for example 'short term nature of funding', 'no funding stream for space science missions', and 'no funding avenue for larger groups who develop substantial capacity'. All government department heads reported difficulties due to funding restraints. Workforce constraints were also expressed across all sectors and focused on 'lack of skilled people' and 'difficulty attracting students'. Responses related to strategic policy included 'lack of support for building basic space capabilities', 'lack of [institutional or government] strategic focus', 'competition between state governments', and 'lack of government support for local industry'. University groups cited problems with 'convincing large industries to invest' and 'industry linkages difficult'.

The above barriers all point to a common problem: lack of a national strategy or program for development of a sustainable space-related R&D system through provision of support, beyond limited short-term measures, to encourage growth of and collaboration between government, university and industry groups.

IMPROVING COLLABORATION

The survey invited respondents to identify measures to improve industry collaborations, and new areas for collaboration. Responses mostly focused on two critical areas: more effective mechanisms for establishing linkages between researchers and industry; and access to funding sources to support cross-sector collaborations.

Responses regarding the first topic highlighted aspects such as the need for institutional business development expertise, difficulty in understanding industry strengths and needs, mobility or alignment of staff between academia and industry, and better mechanisms for shared PhD students. There were calls for 'an information sharing platform to bridge R&D barriers', and 'annual Space2.0-type workshops' to bring government, academia and industry together to identify areas of mutual interest. One rather candid comment, 'eliminating ineffectual enthusiasts and research mafia, with no proven ability, who hinder productive interactions between academia & industry', highlighted the stresses felt by some researchers in obtaining effective business development support.

Many group heads identified a need for an R&D seed funding scheme: e.g. 'long term sustainable program to develop government–academia–industry collaborations and projects', 'government co-investment in research-industry activities', 'Australian Space Agency partnering ARC-linkage type grants', and 'collaboration scheme not requiring industry cash contribution'.

Some areas for policy improvement were also identified: need for 'standardised IP agreements', need for 'government policy to buy local', and 'the government needs to view substantial research groups & centres in same way as industries: developing IP to sustain their own development roadmap rather than adjuncts to industry'.

New areas for collaboration include in-orbit astronomy, off-Earth mining and related operations including in-orbit manufacturing, and advanced data analytics and AI.

AUSTRALIA'S MAIN ADVANTAGES

Respondents were very clear about Australia's main advantages in the context of international space science: geography and geopolitics (70%); and scientific and technical expertise (53%). Typical responses include 'strong university research and political stability', 'strong academic research base', 'skilled workforce', and related views such as 'collaborative and innovative spirit'.

Other advantages identified by more than one head are 'strong demand for Earth Observation services', and 'strong primary industries with ability to develop secondary space industries'.

RESEARCH AND INFRASTRUCTURE PRIORITIES

Respondents were asked to identify key developments including infrastructure which would provide Australia with international leadership in space science and significantly benefit society.

While responses spanned several topics, one very clear theme emerged. The overriding 'discovery or development' theme was sovereign capability to develop, manufacture, launch, operate, use and distribute data from a satellite mission or constellation. This was also the most common 'infrastructure' priority.

Eleven respondents (37%) specifically identified sovereign capability to develop an Earth observation constellation with associated data assimilation infrastructure: e.g. 'national EO program including space infrastructure, science teams, utilisation teams, calibration and validation, ideally led by the ASA'; 'user-driven sovereign EO satellite suite and data processing with support for research and industry groups to develop high TRL sensors and hardware'.

Nine respondents similarly identified a sovereign space situational awareness/space traffic management/space weather capability as an area in which Australia could lead internationally. For example: 'leadership in STM'; 'SSA/STM supremacy (cops of space)'; 'funded, coordinated Team Australia (e.g. Defence funded CoE) combining all relevant areas of science and legals underpinning SSA/STM. Should include dedicated Australian missions coupled with ground based radar and AI'.

Some respondents suggested that such a mission or missions could accomplish more than one task: 'integrated studies of solar-terrestrial system coupled with EO, GPS, improving space weather predication and environmental monitoring, e.g. Murray-Darling basin, Barrier Reef'. However, a third of all respondents identified the capability as the goal rather than specific missions; e.g. 'vibrant service-focused nationally collaborative microsatellite development & launch centre'; 'national space industry hub', and 'at least one substantial science focused mission under ASA flag, e.g. NASA explorer-class, or CubeSats'.

Other important developments mentioned by respondents include: optical and quantum communications; space medical and life support technologies; investment in developing human resources; and space agency funding for science.

SUMMARY AND RECOMMENDATIONS

A survey of heads of government, industry and university heads of space science research groups undertaken in June 2020 has revealed the following points.

1. Research staffing levels are generally expected to increase but there is already difficulty in finding suitably skilled personnel. Given that one of Australia's key advantages is its scientifically and technically skilled workforce this is a worrying trend.

RECOMMENDATION 1.

Develop a national strategy for recruiting and training students, researchers and technologists into space R&D areas.

2. While individual SMEs are optimistic about future funding, all sectors report considerable funding stress, which is the single major impediment to growing research capacity. A critical problem is that funding sources, e.g. through the National Competitive Grants scheme, are limited to relatively short duration projects and do not allow development of sustainable capacity.

RECOMMENDATION 2.

Articulate a funding mechanism facilitating the development of substantial cross-sector space R&D projects as part of a national space strategy or program.

3. Australian space science researchers are well linked with international collaborators and seek to develop linkages across the Australian government–university–industry system. However, they are hindered by lack of a coordinated framework for establishing and growing such opportunities.

RECOMMENDATION 3.

Develop coordinated mechanisms to facilitate establishment of linkages between researchers and industry, such as information sharing platforms or conferences, and a seed funding scheme including government or ASA co-investment supporting cross-sector collaborations and projects.

4. Australia's main advantages lie in its geography and geopolitics. The most important pathway for asserting international space leadership would be development of sovereign capability to manufacture, operate and analyse data from a science-based small satellite constellation, for example for Earth observation and/or space situational awareness purposes. This entails a coordinated approach to development of space infrastructure, science teams, calibration and validation, utilisation teams, and international data exchange, ideally led by the Australian Space Agency. Such growth is necessary if Australia is to develop competitive market products and strategic sovereign capability.

RECOMMENDATION 4.

Articulate a program to develop space-based missions supporting national science and strategic goals, providing international leadership, and leading in time to sovereign space capability.

Note: Role of Cooperative Research Centres.

The purpose of a CRC, such as the SmartSat CRC, is to foster industry-led collaborative research to solve industry identified problems, increase R&D capacity in SMEs, improve the competitiveness, productivity and sustainability of Australian industries, and encourage take up of research. This is an important function but does not replace the need to support and grow the basic research necessary to generates discoveries, disruptive innovation, and engage with international science programs and partners. In the words of a research group leader: 'the CRC's focus is on industry problems, it will not meet space science needs or the opportunity of Australian SSA capability'.

APPENDIX

Research Capacity Survey

The National Committee for Space and Radio Science is managing development of the next decadal/strategic plan for Australian Space Science. This short survey aims to assess current and future research capacity in space science. One response is sought from the head of each research group.

The survey will close on 8 June 2020. All responses will remain anonymous. An email address is requested only to track responses. The survey contains 5 multiple choice questions and one question inviting longer responses, and should take 15 minutes to complete.

1. **Type of institution [select one of the following]**
   - University
   - Government department or operational agency
   - Government-funded research agency
   - Industry
   - Other (please outline)

2. **Area(s) of space science research [select one or more]**

- Space situational awareness
- Space weather
- Solar system planetary sciences (not including geology)
- The heliosphere (Sun, solar-terrestrial science, magnetospheres, aeronomy)
- Remote sensing and Earth observation
- Precise positioning, navigation and timing
- Communications technologies
- Space technology (satellites, launch or propulsion systems, sensors, etc)
- Space medicine and life sciences
- Education and training
- Other (please outline)

3. **Personnel**

   a. Number of full time equivalent staff employed in your group who are active in space science research (do not include students).
   b. Number of higher degree research (PhD, Masters) students.
   c. Number of honours students.
   d. Over the next 2–3 years do you expect the number of staff in your group to:
   e. Increase a lot / Increase a little / Stay the same / Decrease a little / Decrease a lot
   f. Over the next 2–3 years do you expect the number of students in your group to:
   g. Increase a lot / Increase a little / Stay the same / Decrease a little / Decrease a lot
   h. Does your institution have a strategy to actively support gender equity and diversity in groups such as yours?
   i. Yes / Yes but no resources provided / Not aware of any

4. **Resources**

   a. Principal sources of research funding [number in order of importance, where 1 is most important]

      Recurrent (internal) funds (including salaries) / ARC / Other National Competitive Grant funding / Other external government funding / Industry / Overseas / Private (e.g. endowments, charitable trusts) / Other (please outline)

   b. Do you believe that overall funding for your research activities is:

      Inadequate / Adequate / More than adequate

   c. Over the next 2–3 years do you expect your funds for research to:

      Increase a lot / Increase a little / Stay the same / Decrease a little / Decrease a lot

d. How well are your research infrastructure needs met (e.g. computing, technical support, laboratories)

   Inadequate / Adequate / More than adequate

5. **Collaborations**

   a. To what extent do international collaborations inform your space science research?

      A lot / A little / Not at all

   b. To what extent do collaborations with industry inform your research?
      A lot / A little / Not at all

6. **Future prospects [open-ended written responses]**

   a. What are the main barriers to growing your group's research activities?

   b. What single action could most significantly improve your opportunities for collaboration with industry?

   c. Are there other discipline areas with whom opportunities for joint collaborative projects should be explored (e.g. in-orbit astronomy, in-orbit manufacturing)?

   d. What are Australia's one or two most important advantages in the context of international space science activities?

For the following questions assume no resource constraints.

   a. What one or two key developments or discoveries would provide Australia with international leadership in space science and significantly benefit society?

   b. What are the most important pieces of science infrastructure in which Australia should invest in order to realise (e) above.

   c. Please provide any other comments.

Communication technologies

November 2020

WORKING GROUP MEMBERS

Chair: Adjunct Professor Bill Cowley

Members:

- Dr Francis Bennet
- Dr Gerald Bolding
- Dr Bradley Clare
- Professor Christophe Fumeaux
- Professor Gottfried Lechner
- Adjunct Professor Neil Weste

DISCLOSURES OF INTEREST

- Professor Weste: VP Engineering, Morse Micro Pty Ltd, NSW
- Professor Lechner: Advanced communications, connectivity & IoT technologies Program Director, SmartSat CRC

VISION STATEMENT

The year is 2030 and the rapid growth in telecommunications has continued, both in space and on the Earth. The number of Internet-of-Things (IoT) devices on Earth has passed hundreds of billions, with a significant fraction connected from space. Mega constellations of small Low Earth Orbit (LEO) satellites have become commonplace, supplying broadband services in areas with poor terrestrial coverage. Optical communication links have been deployed for many backbone global networks. SATCOM is increasingly used for emergency service restoration after climate-related disasters. From the perspective of end-users, terrestrial networks and satellite networks have merged completely with no noticeable handover effects between them. Communications latency is at a minimum as most traffic worldwide is routed over redundant LEO satellite links. Many optical links already utilize quantum key distribution (QKD) to generate common keys, which can then be used for encryption. Further microelectronics progress in system-on-chip technology has allowed more robust and adaptive networks, able to exploit higher frequency bands.

The proliferation of satellites has resulted in an increasingly congested Radio Frequency (RF) environment. Space is more accessible but possibly less regulated, exacerbating the RF interference issues associated with the congestion. Government, Military and Commercial agencies increasingly deal with interference that impacts the reliability of services.

With the complexity of multiple orbits, diverse satellite technologies, co-operative and non-cooperative legal jurisdictions and 'non-regulated' users, the search for resilience and quality of service has turned toward exploiting diverse resources. Ground and airborne terminals are often equipped with hybrid RF/optical systems, generally with at least two RF bands available. The use of higher frequency bands (70-90GHz) for SATCOM has been enabled by technology developments. Cognitive radio concepts have been extrapolated to 'cognitive space' where terminals and satellites work autonomously to maximise communications availability across the resources they can access, both private and public.

BACKGROUND

Satellite communications have traditionally been provided using RF spectrum. Unfortunately this limited resource has become very congested. Spectrum allocation is a lengthy and expensive progress, requiring extensive international coordination. Efficient use of spectrum has been difficult due to the constraints of space-segment electronics, inflexible licensing and the need to avoid interference.

Recognition of the change in paradigm from a 'noise limited' SATCOM channel to one that is interference limited is emerging in literature [1]. This paper focuses on single High Throughput Satellites (HTS) and Very HTS, but is an indicator of the future where the issue could further extend across multiple satellites, increasingly relevant due to the small size of antennas on 'User Terminals' causing interference into other satellite systems. The key to operating in such an environment will be advanced signal processing (interference mitigation techniques) where channel estimation, beamforming and multiple input, multiple output (MIMO) techniques, plus commensurate waveform standards (such as DVB-S2X) combine to provide a way forward. Whilst the scenario is highly complex and exacerbated by signal propagation delays associated with geostationary satellites, it is likely tractable with ongoing technology development. Techniques to efficiently deal with the processing complexity, and indeed to extend the scenario to resource 'sharing' across multiple satellite systems combined with terrestrial spectrum co-use, are of interest in making the best use of limited spectrum resources in a bandwidth hungry world. Australia, originally through the University sector and more recently via a small number of startup companies, has a rich history and extant capability in signal processing as applied to SATCOM, and is in a position to contribute to and capitalise on developments in this area.

Satellite on-board electronics are becoming more capable through increased flexibility (reconfigurable or reprogrammable electronics) plus the ability to operate in higher frequency bands. These advances allow higher-throughput communication payloads to operate in small satellites. Advances in microelectronics clearly underpin much of the progress in telecommunications. Through 20 years of WiFi CMOS System on Chip design, Australia has key expertise in this area. System on Chip (SOC) refers to the ability of a (largely) digital technology to include key analog and RF systems on a single monolithic technology (i.e. single chip). This leads to power, size and cost points that cannot be approached by any other technology. This is difficult technology to design and fabricate with acceptable performance and yield, yet crucial for future progress. Similar expertise is required for the Reduced Instruction Set Computers (RISC) that control satellite payloads and provide DSP capability. CMOS System on Chip technology, combined with Gallium Nitride (GaN) DC and RF power technologies, will dominate space borne electronics for the foreseeable future. A case study on GaN is included below (case study 1).

One estimate [2] indicates there are 2,062 active artificial satellites orbiting the Earth (March 2019). The UCS Satellite Database [3] identifies 846 of these as directly (and actively) providing communications (and this excludes a large number, 283, principally Low Earth Orbit, associated with 'technology development/demonstration', which would include a proportion of communications functions, conservatively 25%). In 2015, similar data estimates 2000 of the 4077 satellites in orbit (not all active) were communications satellites. This data indicates that ~45–50% of all satellites are communications satellites! From 2020 we anticipate the emergence of satellite networks comprising very large numbers of small satellites, for example, Starlink [4] from SpaceX is reportedly based on ~12,000 satellites. Traditional communications satellites in geostationary orbits will remain important, but their relatively large communications latency renders them sub-optimal for voice and IoT communications. Enabled by optical satellite-to-satellite links, mega-constellations of satellites in LEO orbits will carry large amounts of data with latencies even lower than terrestrial options. The LEO constellations have the ability to serve almost all of the globe, providing high-speed connectivity for remote areas – this will have a massive impact on traditional telecommunications operators. These new constellations will also prove valuable when terrestrial infrastructure is unavailable – such as in conflict regions and after natural disasters. Some of the LEO constellations will be augmented by geostationary high-altitude platforms (HAP).

Traditionally communication payloads have used simple wire or patch antennas on small satellites or deployable parabolic antennas on large communication satellites in GEO orbit. The advances in CAD techniques and computing hardware have revolutionised antenna engineering capabilities. Devices with increasing complexity and enhanced performance (gain, efficiency, and bandwidth) can be digitally modelled and optimised with a high level of fidelity in geometry and materials. The radiation characteristics of multiple antennas or arrays mounted on platforms, from cubesats to large satellites, can be accurately predicted, even in the higher frequency bands. Additional mechanical requirements such as stowage mass and volume, deployment methods and pointing capability are key characteristics that can be co-designed in dedicated CAD tools. Australia has some excellent antenna expertise, mainly located in the CSIRO, specialised enterprises and selected universities. Focussed activities include satellite-on-the-move, ground station and cubesat antennas, as well as fundamental research from low frequency bands to the terahertz regime. An example case study is presented below (case study 4).

Optical fiber carries the bulk of terrestrial communications but until recently the use of free-space optical (FSO) has been limited by atmospheric effects and size/mass constraints in space. The former can be addressed by error correction, adaptive optics and diversity techniques. Given the pressure on the RF spectrum, laser optical communications between satellites and from space to ground has become common for

Earth Observation (EO) telemetry data, with larger satellites. New opportunities are available given rapid progress in the last several years with miniaturised pointing assemblies and inertial reference stabilisers, providing opportunities for a great expansion in FSO SATCOM. Australia has developed significant expertise and international collaborations in FSO communications during the last decade and stands to benefit from these developments given suitable support. Case study three describes a DST small satellite mission hosting an experimental FSO communications payload.

Besides benefits of smaller, lower-power FSO terminals, the lower beam divergence gives more secure communication at the physical layer plus the ability to carry quantum information for 'un-hackable' security. Quantum communication techniques can be used to transmit encrypted information or encryption keys in a way which prevents anyone from decrypting or hacking the transmission. The laws of physics themselves are used to secure the communication channel to provide the only provably secure communication method. One future application of this will be to establish a global quantum network. Quantum communication satellites will be able to distribute information around the world and exchange encryption keys in an ultra-secure manner. This would enable the connection of continents with secure networks. Australia has excellent expertise in this area. An example case study is presented below (case study 2).

ISSUES TABLE

Insight	**Communication resources in space are becoming more prolific. This increases potential capacity but RF interference has a limiting effect. Signal processing techniques, free space optical communications and the use of higher frequency RF bands provide a way forward**
Aspiration	Maximise the use of resources for resilient, reliable, available communications despite the congested environment
Actions	Develop terminals with RF band/hybrid optical/RF diversity, capable of operating with more autonomy, independently or cooperatively, integrated with a broader more complex and aware Satellite resource control environment. Promote awareness of the standing capability in SATCOM signal processing in Australian Universities and the opportunity this represents for future STEM professionals for ongoing contributions.
Impacts	Investment in communications capacity in space can continue without the self-limiting effects of interference. Reliability and availability are maintained. Delivery of increased bandwidth from space is achieved with the broader societal economic, safety and security benefits
Metrics	Societal benefit. Communications Availability, Reliability and Bandwidth. Spectral efficiency (bit/sec/Hz) achieved relative to investment in capacity on orbit.

Insight	**Lack of students in specialized topics such as high end integrated circuit design, or advanced antenna modelling**
Aspiration	More students, especially women
Actions	Marketing to alert young people to opportunities. Professional scientists and engineers provide example problems and projects to motivate student 'missions'. Make this available at a web portal for teachers and students.
Impacts	Critical Mass of knowledgeable students
Metrics	Number of PhDs relevant to advanced SATCOM

Insight	**Lack of networking of people with key technology knowledge**
Aspiration	Knit people together – 'Team Australia'
Actions	Convene technology workshops and forums to educate people what expertise is available
Impacts	Enable people to propose and carry out keynote projects (e.g. complex SOC payload designs)
Metrics	Number of SATCOM payloads and ground stations

Insight	**Australia can offer site diversity for an FSO ground station network**
Aspiration	Ground station networks for improved remote area and regional communications
Actions	Development of rugged optical GS equipment, plus telescope technology, integrated GS networks and protocols
Impacts	Better connectivity of remote and regional areas via high rate FSO downlinks; more EO data with lower latency
Metrics	Size of GS network; availability, throughput

Insight	**Eavesdropping and decryption of intercepted communications signals**
Aspiration	Quantum encryption technology for global communication security
Actions	Trials of quantum technology such as QKD and quantum memory, ruggedisation of quantum components, demonstration of satellite quantum sources and receivers
Impacts	Ultimate security for global communications with a global quantum network (e.g. memory in space)
Metrics	Provable security between terminals e.g. between continents

RECOMMENDATIONS

The Academy of Science should promote both national and international collaboration between Australian organisations with interests in next-generation satellite communication techniques by:

- wherever possible, promoting the actions included in the Issues Table of this report
- approaching the SmartSat CRC Board and suggesting they devote one session of their regular CRC conference to an externally-promoted open-invitation show-and-tell session related to advanced SATCOM technologies. The ASA and the Australian Space Forum could also be consulted. Given the multidisciplinary nature of future satellite communications, this session would aim to inform and link local organisations with relevant specialist expertise.
- promulgating the supplementary information attached to this report, for example on its own web pages and by encouraging the Australian Space Agency to establish a web portal for information relating to local R&D directed at, or applicable to, new SATCOM techniques.

CASE STUDIES

CASE STUDY #1 HIGH FREQUENCY MICROELECTRONICS: CAPABILITY AND TRAINING

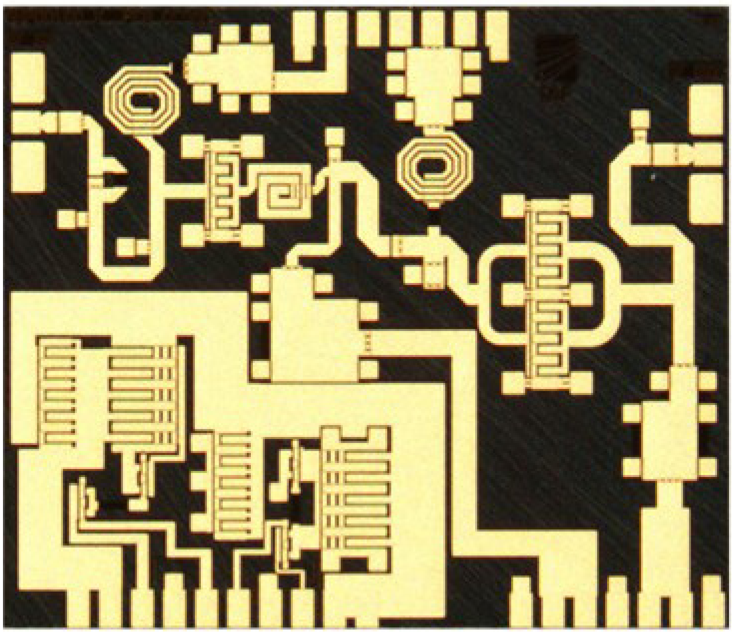
Gallium Nitride (GaN) is a high speed technology for very high frequency amplifiers and power conversion circuits. Australia has built some small beachheads in GaN design at the University of Adelaide under the leadership of Dr Aaron Periera and Altum RF in Sydney under Tony Fattorini. GaN fabrication is currently carried out in Taiwan, China, the US and Europe. GaN circuits (and their design) are a key platform for satellite systems both for radio systems and efficient power conversion. For example, DSN network transmitters are moving to GaN based power amps and NASA is currently investigating GaN-based orbital SARs. **Figure 1** shows a recent example from a collaboration between Adelaide University and the Fraunhofer Institute[5].

It would be desirable to consolidate our leading position under Dr Pereira by providing funds for prototype GaN chip fabrication and the training of new graduate students. Altum RF can be supported by perhaps support for development contracts for mm-wave satellite systems. This capability could also possibly be used by defence companies such as CEA in Canberra.

Millimetre wave (mm-wave) circuits are a key platform for satellite systems of the future. Currently Australia has a small but capable mm-wave circuit design capability. Two companies of note are Altum RF who specialise in the design of GaAs and GaN circuits and Movandi who design CMOS mm-wave circuits under the leadership of Dr. Michael Boers (their HQ is in the US). There is also mm-wave CMOS design experience in Melbourne (originally under Dr. Stan Skafidas – Nitero that was acquired by AMD).

Given the complexity of advanced microelectronics design and its underlying importance in future spaceborne communications, we recommend nurturing existing courses in this area and support for new programs. (See Issues Table).

Figure 1. Photograph of IC that integrates for the first time a modulator and 3W power amplifier for X Band aerospace applications, fabricated in 0.25um GaN.



CASE STUDY #2 AUSTRALIAN COLLABORATION WITH DLR IN OPTICAL COMMUNICATIONS

Australia has excellent expertise in satellite communications and photonics. While this hasn't been combined at large scale for optical satellite communications yet, there are a number of recent activities in this area, which are supported by international partnerships. The German Aerospace Center (DLR) has a well-established track record in this area with strong international collaborations. For more than 10 years the University of South Australia has collaborated with DLR in the area of high speed channel coding for optical channels affected by atmospheric scintillation. This work included staff exchanges, field trials and the development of hardware testbeds.

More recently, QUOLLSat, a quantum communications satellite mission by ANU and the German Aerospace Center DLR, is a potential civil space flagship mission for Australia using technology developed at ANU to demonstrate world-leading quantum communication capabilities. The satellite's advanced optical communications payload and telescope will generate and transmit quantum information from space, offering highly-secure communication. This mission will use ANU's innovations to change the way quantum communication networks can be used in space. Australia's point of difference is the ANU-developed 'quantum memory' and continuous-variable quantum source. These components enable quantum information to be transmitted, stored and routed across a global network.

CASE STUDY #3 BUCCANEER CUBESAT PROGRAMME

Australia's Defence Science and Technology Group plans to launch the Buccaneer Main Mission CubeSat in early 2022, with the primary mission to explore how a space-based High Frequency (HF) receiver can calibrate and optimise the performance of the Jindalee Operational Radar Network (JORN). This launch will follow from the successful launch and operation of the exploratory Buccaneer Risk Mitigation Mission in 2017 (see **Figure 2**). Buccaneer will also carry additional payloads. One of these is a laser terminal, provided by Aerospace Corp., which aims to demonstrate high speed space-to-ground optical communication. The Buccaneer programme will advance Australia's expertise in space experimentation and research and provide a stepping stone to significant sensing and communications capabilities for Defence.

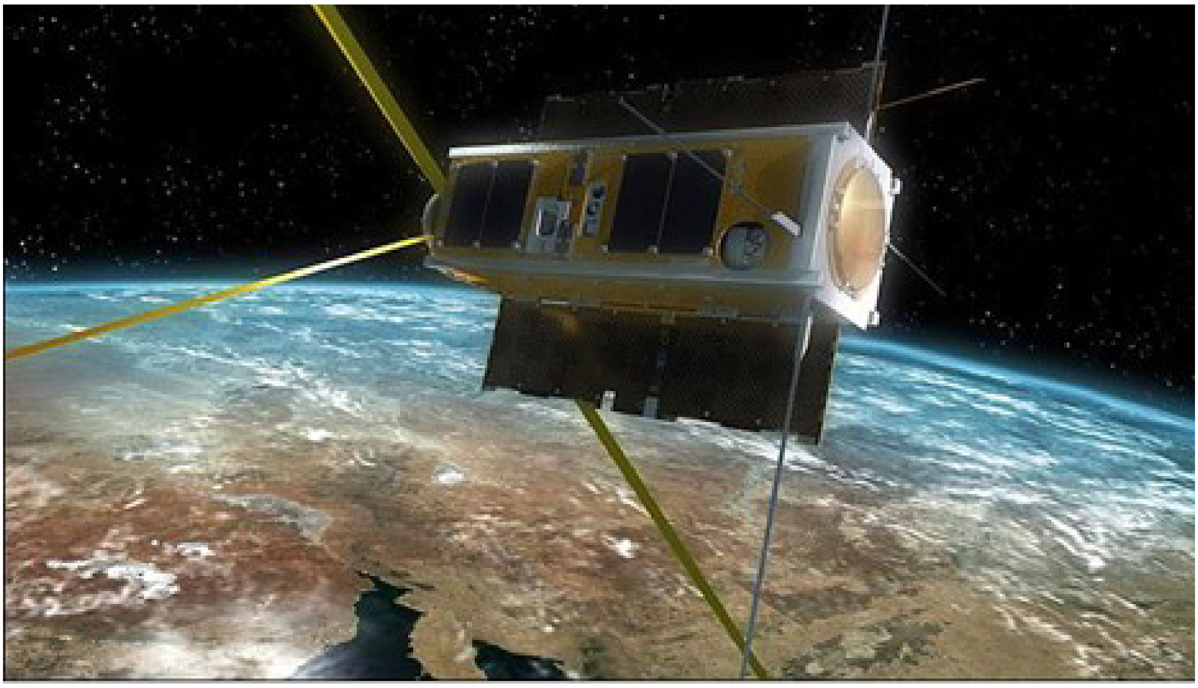
CASE STUDY #4 REFLECTARRAY ANTENNAS

A reflectarray antenna is a directive antenna composed of a free-space feed (such as a horn) illuminating a large planar surface patterned with periodically arranged sub-wavelength structures (such as metal patches of various shapes and sizes over a ground plane). As such, a reflectarray is often described as hybridisation of a reflector antenna and a phased array, where the individual elements are scatterers fed by a free-space wave. The main advantages for satellite applications are the reduced stowage requirements and low deployment complexity of planar panels, as well as a reduced weight compared to a conventional metallic reflector.

The general principle of reflectarray operation is based on the fine localised phase control of the reflected wave, offered by the individual scatterers on the planar surface. While reflectarrays intrinsically exhibit a narrower operation bandwidth than reflectors, their design offers additional design flexibility that can be harnessed for specific purposes. While a typical configuration can mimic a parabolic reflector profile from a planar surface, more advanced functionalities include directive beams with shaped contours for illumination of a particular Earth region, specific beams tailored to individual frequencies or polarisations, or diplexing abilities in multi-feed configurations. Related concepts include the so-called 'metasurfaces' made of deeply sub-wavelength resonators, and the array lenses or 'transmitarrays' operating in transmission mode.

Related research activities at the University of Adelaide are dedicated to reconfigurable reflectarrays, where the reflection phase profile of the planar surface can be dynamically tuned using varactor diodes or MEMS components. This opens promising perspectives in adaptive beam shaping. Further research activities concern the translation of reflectarray design principles into the terahertz range to support communications within a satellite constellation, or to create engineered quasi-optical components such as polarisers, wave-plates, polarisation beam-splitters or focusing mirrors.

Figure 2. Artist's impression of the initial Buccaneer mission, successfully launched in late 2017. This was the first sovereignly-developed defence-science CubeSat mission flown by Australia.



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Ref 2 https://www.statista.com/statistics/264472/number-of-satellites-in-orbit-by-operating-country/, accessed 09/03/20

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Ref 4 'Starlink: SpaceX's satellite internet project', Adam Mann, Space.com, January 17, 2020. https://www.space.com/spacex-starlink-satellites.html, accessed 09/03/20.

Ref 5 A. Pereira, S. Al-Sarawi, N. Weste, D. Abbott, J. Kuhn, V. Carrubba and R. Quay, 'X-band GaN HPA with integrated supply modulator for airborne applications,' IEEE Radar Conference 2018 (RadarConf18), Oklahoma City, OK, 2018, https://doi.org/10.1109/RADAR.2018.8378716

Ref 6 eoPortal Directory: Buccaneer CubeSat Mission: https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/buccane-1

Earth observation

October 2020

WORKING GROUP MEMBERS

Chair: Jointly run by Earth Observation Australia Inc., from initial work by Professor Simon Jones, RMIT University

Members:

- Dr Renée Bartolo
- Professor Simon Jones
- Professor Megan Lewis
- Sylvia Michael
- Professor Stuart Phinn

DISCLOSURES OF INTEREST

- Professor Stuart Phinn: President, Earth Observation Australia Inc.; Next generation Earth observation data services Program Director, SmartSat CRC.

VISION STATEMENT

By 2030, Australia will generate Earth observation (EO) products and services from Australian and global space and ground assets. Our sovereign EO collection, processing, analysis, and distribution infrastructure, industries and skilled workforce are world class, underpinning and stimulating the growth of the broader economy. Our science, industry, government and defence sectors driving EO development and applications are connected, coordinated, and scalable, allowing world class education to enable effective research to operational development of EO in all these areas. Our EO capability will support essential Australian industry, government, and community needs.

The statement above supports vision statements from:

> 'Australian Earth Observation Community Plan 2016–2026'.
>
> By 2026, the Australian Earth Observation sector will develop and deliver high-quality EO information, infrastructure, and services that are used widely by government, industry, research and the community in Australia and internationally.
>
> Australian Space Agency – National Civil Space Priority Roadmap 'Earth Observation' to be released in December 2020

BACKGROUND AND TOPIC AREA

Earth Observation (EO) encompasses a broad suite of activities that use remote sensing to gather observations and produce measurements and spatial data to monitor and examine our planet, its environments, human activities and infrastructure[1]. EO data are collected at a range of scales from centimetres to kilometres, throughout all our environments — built, natural, and managed. Some EO data have been collected regularly for decades through ongoing satellite programmes, while other data may be collected at specific times and places in response to particular needs such as natural disasters or emergency situations.

The EO supply chain starts with the collection of observations using a variety of platforms including satellites, aircraft, remotely operated vehicles (airborne or waterborne), and in situ sensors (Figure 1).

Figure 1. The EO 'supply chain' from the acquisition of observations using a variety of sensors and platforms, through to the processing and storage of data and data products, through to provision of information and services that can be used in a wide range of ap

These platforms may be fitted with any number of sensors capable of collecting different kinds of image data from the full electromagnetic spectrum, including visible, thermal, and micro-wavelengths as used by imaging radar. As a result, EO sensors can 'see' and measure more than the human observer can, over larger areas, on a repeated basis, and over any environment including harsh, dangerous, or difficult to access areas. These observations are collected at different spatial resolutions (pixel size and total area observed), different revisit periods from minutes to days to months, on specific dates, and in urgent response to emergency situations. The collected raw data are then processed with ground- or water-based calibration and validation data to deliver data products, information and services about our land, oceans, atmosphere, and built environments. This information can be used for a wide range of applications, including weather and oceanographic forecasting, preparedness and response to natural disasters like floods and bushfires, mineral exploration, precision agriculture, water resource management, urban planning, and environmental monitoring (Figure 2). Furthermore, EO information assists in decision-making across industry, government and defence, and informs development, implementation and assessment of government legislation at local, state-territory and national levels.

Figure 2. EO information and products are routinely applied across a wide range of industries for economic and societal benefit, some of which are shown here.

EO data are used for measuring and mapping:

1. Categories of features, such as land use and cover, mineral deposits, infrastructure, roof types, weeds, etc.
2. Biological or physical properties, such as vegetation heights, fuel loads, crop yields, soil exposure, water depth and velocity, building heights, cloud height and thickness, temperature, geomorphology, etc.
3. Changes in and over time, such as the detection of crop growth over time, or vegetation clearing, wind direction and strength, wave directions and strength, etc.

The diversity of spatial information products and services currently obtained from EO is very broad and continually expanding, with multiple Australian and overseas reports consistently demonstrating:

1. The significant and growing economic value of spatial information produced from EO data for our economy and governments, and
2. The essential nature of these data for supporting critical government and industry activities that ensure our food, water and energy supplies and security contribute to public health outcomes, and improve preparedness for and response to natural disasters.

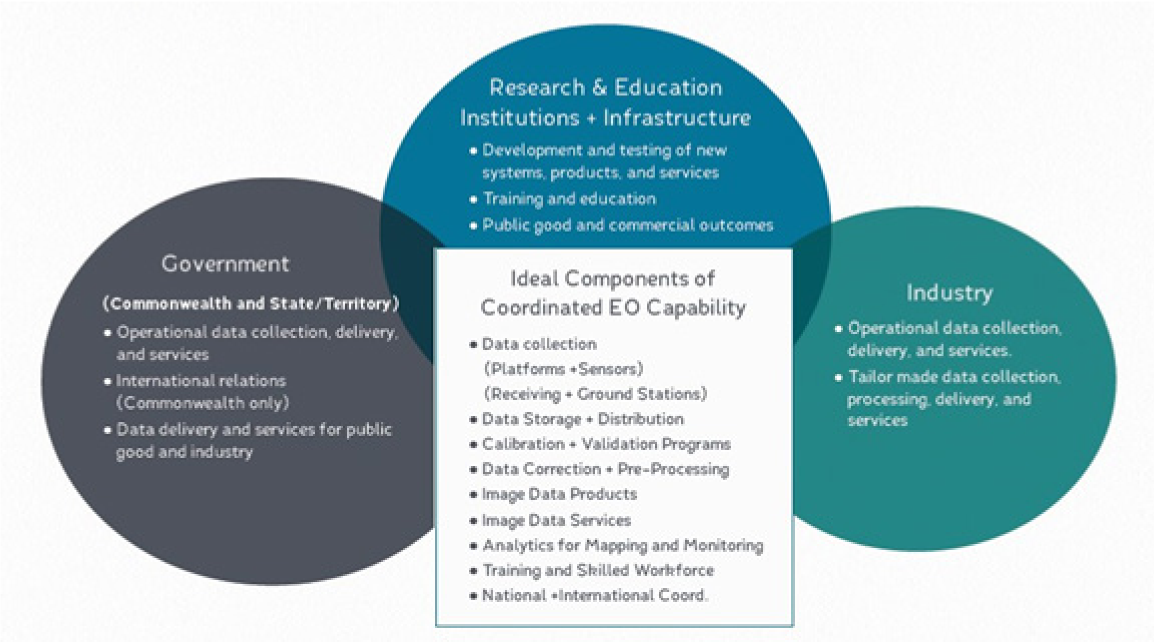
The potential growth in, and return from, EO-related applications derived from satellite and unoccupied aircraft systems (UAS) information products and services are immense[2].

Globally, the return on investment in EO is conservatively estimated to range from $2 to $10 for every $1 spent, depending on the specific application[3].

With ongoing development of EO data acquisition and processing platforms there are countless opportunities for EO to increase its value to society in coming years. To enhance Australia's economic and social well-being, Australia should invest strategically in our EO capability now, in order to create a vibrant, innovative and highly productive EO sector that effectively links industry, government, research and the public for widespread benefit.

Australia has an active Earth Observation community distributed geographically and across research and education, government, private industry and NGOs (Figure 3). Although Australia does not operate any EO satellites, we are active across the entire EO supply chain, from the initial stages of data collection and storage through to processing, distribution and application. We are also global contributors in the research and development of new EO sensors and processing algorithms. Our EO sector transforms EO data to value-added spatial information and services for government and industry and supports the end use of EO-based spatial information products and services by public and private sectors in everyday activities.

Figure 3. The ideal connected and coordinated EO capability for Australia, with all components of this sector — government, industry, and research and education — delivering complementary activities to ensure an effective and cohesive national EO capability. The central box represents the combined requirements of a national EO capability, with the individual circles representing the different contributions from government, industry, and research and education sectors. Collaborative research infrastructure provided by the Commonwealth is an essential shared resource across all groups.



EARTH OBSERVATION

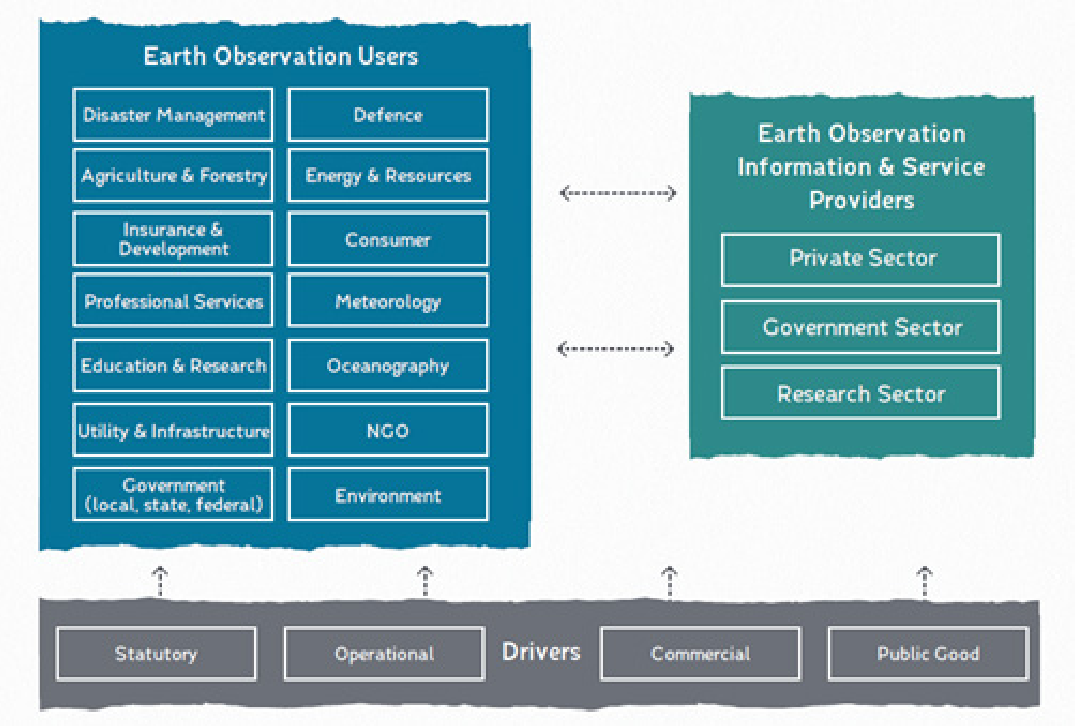
Australian government agencies at all levels have collected EO data over Australia since the 1940s, as evidenced by our extensive state-based aerial photo and image archives. Since the late 1970s we have moved to routine acquisition of satellite data, and since 2010 we have seen dramatic advances in:

- The ability to collect EO data across multiple satellite, airborne, and other platforms such as unoccupied aircraft systems (UAS) and the types of sensors these use; from digital photography to multispectral, hyperspectral and thermal sensors, LiDAR, radar and radiometry;
- Improved access to these data over areas of a few square metres to continental and global scales on a regular basis;
- Our ability to store, process, analyse, visualise and distribute very large and long-term EO data sets online, and to deliver derived spatial information and services to a wide range of users through mobile devices and websites; and
- End-user awareness of the level of expertise and time required to produce EO data, and the products and services derived from EO data, across diverse applications.

While Australia operates no EO satellites of its own, we access a wide range of satellite imagery, at moderate to low spatial resolution (20m – 1km pixels) through long-standing partnerships and arrangements with other countries. As part of these arrangements, Australia provides important ground station capability, highly skilled personnel, data access and distribution infrastructure, local environment and scientific knowledge, along with calibration and validation data to our international partners, and development of new algorithms and processing workflows. In combination, these activities add value to the available data for both our partners and ourselves. Access to higher spatial and spectral resolution data is through a range of private industry satellite, airborne, and UAS providers. The number and types of all these data sources are increasing continually.

EO services, delivered by both the public and private sector, are recognised as essential public-private infrastructure with numerous national reviews showing that Australian governments and industry are dependent on EO to maintain our economy and societal wellbeing[4, 5, 6, 7]. Data and information applications from EO are now commonly used across all levels of government, industry and society in a range of sectors (Figure 4). Over 140 Commonwealth, state and territory government programmes are dependent on EO from space, and the minimum economic benefit of these observations on the Australian economy is approximately $5.3 billion per annum. These services are also estimated to have created more than 9,000 jobs in 2015 and are projected to generate over 15,000 jobs by 2025. There are numerous examples of the economic and societal benefits generated from EO in Australia, across areas such as weather forecasting, onshore and offshore mining, mitigation and management of natural disasters like bushfires and floods, water resource management, design and assessment of conservation areas, insurance assessment, and land use planning (an excellent series of case studies showcasing the value of Earth Observation for different sectors is available in ACIL Allen (2015)[2]).

Figure 4. The users and providers of EO data products, information and services, and their drivers.



BARRIERS FOR GROWTH AND INNOVATION

While the existing impacts and level of dependence on EO in Australia are very significant in terms of diversity of activities and economic value, there is unrealised potential for the EO sector in Australia. Unless change occurs across the sector, this unrealised potential will grow, in effect translating to a net loss in essential capability for satellite, airborne and UAS data collection, processing and delivery. Some well-documented challenges will become significant barriers to growth if not addressed, including:

- Assuring coordination and a consistent vision within the EO community across research and education, government, and private industry, to ensure effective cooperation, collaboration, and use of resources within the sector, as well as improving advocacy by the sector at national and international levels. This vision needs to be backed by a clear strategy. When realised, this will bring together a far more effective critical mass of expertise, significantly increasing the value returned from Australia's investment in EO;
- Developing a clear, coordinated strategy to invest in and protect our international partnerships to ensure continued access to satellite data and international expertise, especially given our high dependency on foreign-owned satellite data;
- Providing clear pathways to develop, support and sustain the EO capacity required for Australia through skilled people, a growing knowledge base, and advanced data collection, storage, and analysis infrastructure;

- Effectively managing and enabling access to the very large and rapidly growing collections of EO data including historical archives and required new data streams, and taking advantage of new information systems and technologies for storage, processing, analysis, visualising and transfer, to overcome historical problems and future challenges with discoverability and access to the data, products and services; and
- Establishing connections between EO producers and users to enable the development of EO products and services suited to current and future user needs, and supporting the commercial development of EO products and services suited to current and future user needs, and supporting the commercial development of EO applications to deliver productivity gains across the economy, amongst other societal benefits.

RECOMMENDATIONS

The recommendations below support the priorities and actions from:

'Australian Earth Observation Community Plan 2016–2026'

By 2026, the Australian Earth Observation sector will develop and deliver high-quality EO information, infrastructure, and services that are used widely by government, industry, research and the community in Australia and internationally.

Australian Space Agency – National Civil Space Priority Roadmap 'Earth Observation' to be released in December 2020

1. CONNECTION, COORDINATION AND COMMUNICATION WITHIN AUSTRALIA'S EO COMMUNITIES

Undertake action and support programs that will enable Australia's EO science communities to be connected across education, government, industry and defence, for the development of a skilled and connected workforce and set of activities that understands how to work with and support each other to deliver essential national infrastructure.

2. CONNECTION, COORDINATION AND COMMUNICATION WITH INTERNATIONAL PARTNERS: SECURING AUSTRALIA'S ROLE IN THE INTERNATIONAL EO COMMUNITY

Through relevant national coordination bodies, Australia's EO communities develop consistent national positions on priority short (1–5 year) and longer term (5–10 year) requirements to communicate to the Australian Space Agency, to inform its EO Civil Space Priority work and international engagement.

It is essential this is across education, all levels of government, industry and defence, and is NOT solely based on views of Commonwealth agencies in Canberra alone.

3. RECOGNISE, CONNECT AND BUILD AUSTRALIA'S INFRASTRUCTURE, SKILLED PEOPLES AND ORGANISATIONS (PUBLIC AND PRIVATE)

Identify and link the sciences underpinning EO space sciences, from the development, build and operation of imaging satellites, to the development and delivery of products and services from satellite EO.

Link to the development of skilled workforce, public and private infrastructure and partnerships, and research to operations.

4. ESTABLISH AND MAINTAIN RESOURCES AND PEOPLE TO DEVELOP, BUILD AND DELIVER EO SENSORS, SATELLITES, PRODUCTS AND SERVICES

Enable all scales of industry, from single person start-ups to multi-national companies to partner with research groups, to develop, build, and deliver new capabilities, sensors, products and services for collecting and transforming Earth observation data into information.

Improve collaboration between and integration of contributing disciplines such as physics, engineering, signal processing, and machine learning, in education and research training programmes, to take advantage of innovation that is taking place at the interface of these disciplines.

5. LINK EDUCATION AND RESEARCH PATHS FROM SCIENCE TO GOVERNMENT, INDUSTRY AND DEFENCE

Improve collaboration between and integration of contributing disciplines such as physics, engineering, signal processing, and machine learning, in education and research training programmes, to take advantage of innovation that is taking place at the interface of these disciplines.

Promote and develop EO as an integral part of education in applications that would benefit from EO, such as agriculture, environmental sciences, geoscience, and mining, etc.

Increase linkages between undergraduate, postgraduate, and research training with government, industry, and defence applications and needs.

PRIMARY SOURCES

Australian Earth Observation Community Plan 2026 (AEOCP 2026)

VISION STATEMENT

By 2026, the Australian Earth Observation sector will develop and deliver high-quality EO information, infrastructure, and services that are used widely by government, industry, research and the community in Australia and internationally.

1. Connection and Coordination — establishing a consistent vision within the Australian EO community, and delivering processes for internal coordination to ensure effective collaboration, resource use, and advocacy for EO in Australia and internationally.

2. Securing Australia's Role in the International EO Community — Australia must be an essential component of the international EO capability, delivering benefits to the international community and securing our access to and involvement in international EO programmes.
3. Infrastructure and People — developing, supporting and sustaining a wealth of trained professionals and quality infrastructure to enable world-leading EO research, innovation and application development.
4. Access to EO Data and Services — ensuring all Australian EO producers and users can easily and reliably access the data and services they need.
5. Generating Value — strengthening end-user engagement to enable delivery of high quality EO products and services suited to user needs, and supporting commercial development of EO applications.

To initiate action in implementing this Plan, Earth Observation Australia Inc. (previously known as AEOCCG) commits to:

1. Engaging widely across the EO community to seek feedback on the actions set out in this Plan, and to determine what the community sees as the important areas for action in the short- (< 5 years) and long-term (5–10 years), in order to develop an implementation plan and the required financial, personnel and other resources to address this.
2. Linking Earth Observation Australia Inc. (EOA) to a suitable agency or programme able to work across a range of Government agencies to implement the actions required under the five priorities of the Plan, and to develop a linked EO Capability for Australia across government, industry, and research.
3. Establishing working groups or other groups with membership from across the EO community, who will take responsibility for progressing specific actions or priority areas of this Plan and work in close association with the coordinating programme established in (2).
4. Build the case for and obtain government and external investment for developing and implementing the Plan, and seek sources of funding to support implementation activities in the short- and long-term.
5. Promoting the Plan, its priority areas, and key actions to decision-makers and influencers in government and other sectors in order to build wider support for implementing the Plan.

Australian Space Agency Civil Space Strategy 2020–2030 and Earth Observation Roadmap

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SUMMARY TABLE

Insight 1	**Connection, Coordination and Communication within Australia's EO Communities**
Aspiration	A coordinated and consistent vision across research and education, government, industry, and defence
Actions	Undertake action and support programs that will enable Australia's EO science communities to be connected across research and education, government, industry and defence
Impacts	Collaboration and engagement across the EO community A skilled and connected workforce Delivery of essential national infrastructure
Metrics	Increase in efficient and effective use of our EO resources Coordinated and informed EO activities Coordinated and informed EO response to applications

Insight 2	**Connection, Coordination and Communication with International Partners: Securing Australia’s Role in the International EO Community**
Aspiration	A consistent, engaged, productive, and mutually beneficial relationship with international EO organisations and agencies
Actions	Develop and communicate consistent national positions on priority short and long term requirements to the Australian Space Agency to inform its EO Civil Space Priority Coordinate and build on existing relationships within the EO community
Impacts	Recognised and consistent communications with international EO organisations and agencies Continued access to data collected by international organisations and to international expertise Recognition of Australia’s contribution to the international EO community
Metrics	An engaged, productive, and mutually beneficial relationship with international EO organisations and agencies Recognition from and collaboration with the international EO community

Insight 3	**Recognise, Connect and Build Australia’s Infrastructure, Skilled Peoples and Organisations (Public and Private)**
Aspiration	A connected and collaborative Australian EO resource network combining a skilled workforce, public and private infrastructure and partnerships, and an effective and efficient transition from research to operation
Actions	Establish and develop public and private infrastructure and partnerships
Impacts	Clear pathways to develop, support and sustain Australia’s EO capacity
Metrics	Access to knowledgeable, efficient, and effective EO resources by all Australians and across all fields i.e. research and education, government, industry and defence

Insight 4	**Resources and People to Develop, Build and Deliver EO Sensors, Satellites, Products and Services**
Aspiration	An established, progressive, collaborative, and dynamic Australian EO capability that operates in all sections of the EO supply chain from upstream to downstream activities
Actions	Enable all scales of industry, from single person start-ups to multi-national companies to partner with research groups Develop, build, and deliver new capabilities, sensors, products and services for collecting and transforming EO data into usable and applicable information Improve collaboration between and integration of contributing disciplines in education and research training programmes Effectively manage and enable access to collections of EO Investigate and utilise new information systems and technologies for data and information storage, processing, analysis, visualisation, and transfer
Impacts	Effective and efficient access to EO data, products, and services across all sectors and applications A significant increase in Australia's EO capability and skilled workforce, in line with the Australian Space Agency's Civil Space Strategy 2019 – 2028
Metrics	Increased awareness, use, and application of Australia's EO data, products, and services across all sectors and applications Increased Australian EO capability to efficiently and effectively service this increase

Insight 5	**Government, Industry and Defence**
Aspiration	EO education programmes support a skilled and applicable workforce which contributes to both the EO community and all application sectors Research programme outcomes can be transitioned into operational EO products and services that benefit and support Australia's civil and defence needs
Actions	Improve collaboration between and integration of contributing disciplines such as physics, engineering, signal processing, and machine learning, in education and research training programmes Promote and develop EO as an integral part of education in applications that would benefit from EO, such as agriculture, environmental sciences, geoscience, and mining, etc. Increase linkages between undergraduate, postgraduate, and research training with government, industry, and defence applications and needs
Impacts	The Australian EO community will have a skilled and effective workforce and research cohort which benefits and contributes to all sectors and applications Education and research programmes will be relevant to and support real-world Australian applications
Metrics	Increased, efficient, and effective uptake of EO data, products, and services across all sectors and applications

Education, training and careers

July 2020

WORKING GROUP MEMBERS

Chair: Dr Sarah Baker

Members:

- Dr Brett Biddington
- Anntonette Dailey
- Damian Hockley
- Dr Robert Hollow
- Associate Professor Ady James
- Penny Johnston
- Darin Lovett
- Dr Paddy Neumann
- Karen Taylor-Brown
- Dr John West

DISCLOSURES OF INTEREST

- Dr Ady James: Education & Training Director, SmartSat CRC
- Anntonette Dailey: Executive Director, Operations and Communications, Australian Space Agency
- Dr Brett Biddington: Biddington Research Pty Ltd

VISION STATEMENT

It's 2030 and every school in Australia knows where students, parents and teachers can find information about current and future space careers and opportunities. The Australian Space Agency has been operating for over 10 years, met their goal to create 20,000 jobs in the Australian space industry, and the space economy continues growing past the $12 billion goal recently achieved. Key skills widely utilised across many space industries have been mapped and outlined within vocational, university and combination pathways for students of all ages including micro-credentialing for rapid and highly technical upskilling. Case studies and profiles of Australian 'Space Science Stars' linked to all educational disciplines are easily accessible and updated regularly as new industries and jobs are created and developed. Public events, research conferences and societal space activities are promoted both to the public and in regular updates to registered participants of a database managed, updated and compliant with cyber-security requirements and Australian Privacy Principles though a Commonwealth agency across all Australian states.

Space education links to the Australian curriculum and senior Science, Technology, Engineering and Mathematics (STEM) subjects across states are regularly reviewed by Early Childhood, Primary and Secondary Educators in collaboration with research & industry space experts to provide endorsed relevant and current teaching resources available through widely used and publicly funded platforms. These teaching resources are available for all Australian and international teachers to easily access, with associated professional development available face to face and online remotely for a range of levels of experience to maximise the impact of these classroom resources.

A position has been created within the Australian Space Agency to allow access to and develop opportunities that arise for students, schools and tertiary institutions to engage with 'real' space research and developing materials to be utilised for data collection or tested in space allowing access to 'Moonshot Missions' for students at all levels.

BACKGROUND

The mention of anything to do with space captures attention from students to science experts and across the general public. Space science and education has never been more important to society as space technology integrates into every part of our daily lives and becomes increasingly important in the future.

With the announcement of the formation of the Australian Space Agency in 2017 and the ongoing implementation of Agency nodes across Australia, students can now visualise a pathway to working in space industry and/or space research with a career in Australia rather than needing to travel and work overseas. Evidence from students who recently completed a placement through the South Australian Space Industry Centre/Advanced Technology Program with startup space industries at Lot 14 in Adelaide and in university research institutions shows they first became interested in space in primary school, between 8 and 10 years of age. Building on this early fascination with space and attracting more students into pathways enabling access to a future space career is the principal goal for the Space Education, Training and Careers Working Group. However, with enrolments declining in senior STEM subjects across Australia (Education Council, 2019), this situation needs to be rapidly reversed for the Australian Space Agency to reach a goal of 20,000 space industry jobs by 2030.

Many Australian schools across all educational sectors have a strong focus on literacy and numeracy skills. Given this, space provides a rich context for students to improve their skill levels to enable straightforward access and subsequent success in content-rich and technical senior STEM subjects, and presents an engaging context and great opportunity to develop student engagement with easy to access information and resources. To succeed in a future space-aligned career, students also need to develop competency in problem solving, data analysis, technology, communication, teamwork, tenacity and resilience.

The Victorian Space Science Education Centre (VSSEC) uses space as a vector to engage students in STEM education. It has had visits from over

120,000 students participating in one or more of their STEM programs since the Centre first accepted students in 2006. The programs teach students to solve problems via data acquisition, analysis techniques and by teamwork using effective communication between team members, which are all essential skills for current and future space careers (Pakakis, 2020). VSSEC's signature Mission to Mars program is now also being taught at Hamilton Secondary College in South Australia (Mike Roach Space Education Centre) where over 2,000 students have visited since the opening in September, 2017 (Kourbelis, 2020). Longitudinal studies published at the 68th International Astronautical Congress (IAC) from students attending the South Australian Space School camp over the last 20 years showed many of the Year 10 student attendees are now working in space industries. Furthermore, research across the world has found the shared experiences on camp produced strong friendships and ongoing supportive peer relationships, particularly for rural students (Clayfield, Samardzic, & Roach, 2017). The impact of these shared experiences demonstrate how important the development of networks for students, teachers and parents are for influencing and engaging students in a space career pathway.

When asking students about their interest in space, many immediately start talking about astronauts and rockets. While such aspirations are important for niche sectors of the space industry, there exists a great diversity of space science-related careers and professions. This breadth is evidenced through the Australian Space Agency's 7 national civil space priorities: position, navigation and timing; Earth observation; communications technologies and services; space situational awareness and debris monitoring; leapfrog R&D; robotics and automation, and access to space (Australian Space Agency, 2019). The SmartSat Cooperative Research Centre has over 100 partners from research and industry participating in a $245 million R& D program focused on technologies in advanced communications and IoT connectivity and intelligent satellite systems. In particular the Earth Observation next generation data services aims to 'spawn new businesses, create export economic value and generate new high-tech jobs for all Australians' (SmartSat CRC, 2020).

Australian states are also releasing their own space strategies aligned with the ASA priorities. For example, Queensland has a focus on launch activities, ground systems, Earth observation, niche manufacturing, robotics and automation for space (Department of State Development, Manufacturing, Infrastructure and Planning, 2020).

Mapping the skills gap in the space sector is currently being undertaken by a joint venture between the SmartSat CRC and the Australian Space Agency (Koronios, A.; James, A.; Sasanelli, N., 2020). This will be developed in the SmartSat CRC to identify the pathways needed for careers in the three SmartSat CRC areas. However, it is critical that this is extended for all of the ASA focus areas and that information be easily available for all students, teachers and parents.

These career vocational, university and combination pathway resources and links could be shared through the new Australian Space Discovery Centre. This will open in early-mid 2021 and be a public place to inspire, educate and engage anyone who aspires to a career in space

(Department of Industry, 2020). A public database linked to the Centre (compliant with Australian privacy principles) could provide regular updates on space education and career information, with feedback from database members informing this process. Longitudinal studies with volunteer surveys of members could also collate information about the most useful type of information, resources and events for influencing student and parental career choices in space.

As a result of the recent need to develop online school teaching during the 2020 Covid-19 pandemic, many Australian teachers have relied on space education resources from NASA and other international space agencies. This does not provide an Australian context. Although there are some excellent Australian resources available they are often aligned to one state or need updating due to curriculum changes. For example, the CSIRO Astrophysics for Senior Physics (Hollow, 2002) is currently out of date for the NSW Science senior science curriculum but contains useful information for students interested in astronomy, cosmology and nuclear physics.

Therefore it is proposed that funding for a panel composed both of teachers across all states and space industry/research experts is needed to regularly review and quality endorse curriculum aligned with the national Australian Curriculum and specialist senior subjects. This curriculum would then be easily accessible to teachers through national Commonwealth funded platforms under the 'Inspiring all Australians in Digital Literacy and STEM' measure of the National Innovation and Science Agenda (Commonwealth Department of Education, 2020).

Several recent decadal plans and science/technology strategies include individual Education and Outreach programs, e.g. the National STEM School Education Strategy (Education Council, 2015); the Women in STEM Decadal Plan (Academy of Science, 2019), A vision for Space Science and technology in Australia (Academy of Science, 2017). Recognising current gaps in STEM education, the Department of Defence developed its own strategic plan: 'Moving towards a high-tech future for defence: Workforce Strategic Vision underpinned by Science, Technology, Engineering and Mathematics' which has a key action to reinforce and harmonise objectives and goals from both their own strategic vision and broader strategies and plans (Australian Government, 2019).

It would be sensible to promote national education and career programs which coordinate information, recommendations and strategies identified in such various plans to reduce duplication of effort and resources, reinforce messages, and maximise government funding outcomes, for space related education, training, and the development of our future workforce

ISSUES TABLE

Insight	**Lack of understanding of wide range of skills and careers within space science research and industry**
Aspiration	Detailed mapping of workforce skills and vocational, university and combination career pathways needed for current and future space research and work
Actions	Align with current mapping by ASA and SmartSat to understand the current and future skills needed Provide skills and career mapping results on national website such as Australian Space Discovery Centre and Academy of Science Website
Impacts	Parents, teachers and students can easily find out and will have a greater understanding of what skills need to be developed and how school subjects/STEM programs/activities can also develop these skills
Metrics	Improvement in recognised space and STEM skills in students entering tertiary studies and workforce, especially space sector

Insight	**Difficult for students to visualise and understand current and future Space Careers outside of astronauts and rocket launching**
Aspiration	Real examples of Space careers, professions and relevant skills are easily accessible by students, parents and teachers
Actions	Videos, case studies, recorded panel webinars are available through national STEM Associations, Academy of Science and Space Discovery Centre career section and STEM media free to schools (such as 'Careers in STEM')
Impacts	Online and face to face resources are easily available for students to find role models for careers in Space Industry and Research
Metrics	Students, parents and teachers will have a greater understanding of the range of careers and diversity of people involved – feedback can be invited from students to understand which types of examples are most appreciated/understood by students and influence future choices

Insight	**Lack of easily accessible quality endorsed Space education resources for teachers linked to Australian curriculum, especially in Science, Mathematics and Technologies**
Aspiration	Expert panel of educators and Space Industry Personnel/ Researchers endorse quality Space aligned curriculum links and resources
Actions	A panel is funded with educators (across Early Childhood, Primary and Secondary) from all states and Space experts to meet every 3 years (Year 1, 4 and 7) over decadal plan to endorse Curriculum which is then linked to Commonwealth funded sites and through National Science/Maths Associations
Impacts	Teachers are able to easily access quality endorsed Australian based Curriculum and links to engage and inspire students to enrol in subjects enabling them to proceed along a Space career pathway
Metrics	Metrics are kept of how often educators are accessing sites, pre and post surveys are used to see how educators are utilising curriculum resources and feedback for improvements on the next cycle

Insight	**Many current STEM activities and competitions develop skills that are used in Space research and Industry but students/teachers participating are unaware of this**
Aspiration	Expert panel of educators and Space Industry Personnel/ Researchers endorse and showcase how skills developed in STEM competitions and activities (such as VEX robotics) are useful for a career in Space
Actions	A panel is funded with educators (across Early Childhood, Primary and Secondary) from all states and Space experts to meet every 3 years (Yr 1, 4 and 7) over decadal plan to endorse how skills developed through current and future STEM activities are utilised in Space research/work. These endorsements are added to promotion of the STEM competitions and activities through current promotions such as on the STARPortal
Impacts	STEM activities and programs that teachers are already involved in and are linking to current STEM curriculum will be easily able be linked to a career and pathway for Space for students
Metrics	Metrics are kept of how often educators are accessing links, volunteer pre and post surveys are used to see how students and teachers understanding of how skills developed link to Space careers

Insight	**Quality teacher PD is needed to be linked to endorsed Space Education resources and easily available (and credited) for all Australian teachers**
Aspiration	Professional development should be available at Beginner, Intermediate and Expert levels – easily accessible and provide accredited certificates across all states
Actions	Teacher PD is developed to run face to face or online individually or in groups based on quality endorsed curriculum and links and is able to be certified in all states by educational jurisdictions/sector bodies which includes the academic Space Education panel
Impacts	Teachers at all levels are able to access and increase their knowledge about linking Space Education to current Australian Curriculum (and some Senior courses which may differ from state to state)
Metrics	Pre and post surveys are used to see how PD has benefited teachers and changed pedagogy in the classroom as well as accessed metrics.

Insight	**Many Space related activities and events are happening all over Australia, difficult for students, teachers and parents to access unless they are members of particular groups**
Aspiration	Students, parents and teachers are able to find out about Space related activities and programs in all Australian states from joining one database
Actions	A position is created within the Australia Space Agency Discovery Centre to maintain a database (from students, parents and teachers who access the Discovery centre in person or online) and email out regularly (at least once per quarter) about activities
Impacts	More students, parents and teacher will be able to easily access public and paid events about Space Science research and careers which will lessen a current high volume of queries for Space Industry and Researchers
Metrics	Numbers are kept of those accessing events and a reduction is seen in queries for Space Industry and Researchers

Insight	**Space Conferences and Forums are not easily accessible by teachers to 'self-link' curriculum and Space research/industry**
Aspiration	Teachers, parents and students are able to access at least one 'open 'session of all conferences and forums in Australia to talk to researchers and industry directly
Actions	Similar to the IAC 2017 in Adelaide where the general exhibition hall was free to the general public and educators, free ticketed access is made available for part of all Conferences and forums with a relevant Space section
Impacts	This will enable 'open discussions' between teachers and Space Industry/researcher which can help provide 'real world context' to STEM subjects and curriculum already being taught
Metrics	Free ticketed access will allow documentation of numbers attending and post survey questions would allow information to be collected about the most popular links made which could feed back to the Space Expert Curriculum and Skills Panel

Insight	**Difficult for students and schools to access 'Space (Moonshot) Missions' and for these missions to be funded and run to completion with outcomes**
Aspiration	Students and schools may be able to engage more easily with 'real' space research and material development for data collection/Space testing
Actions	A position is funded for the Australian Space Agency that allows access to and development of opportunities that arise from Industry and Research to link directly with interested schools and teachers (an Education Space broker)
Impacts	Students and schools are able to be involved with real space Missions without huge costs and time impacts on teachers and industry for a major Australia/State wide 'Space Mission. Small groups of professional scientists and engineers provide motivation and expertise for students to continue on these long – often 3–5 yr missions
Metrics	Documentation of successful partnerships can be publicised and lead to more Industry/School partnerships and 'mini-missions' Students can be interviewed and followed to see the impact these missions have made on their study and career choices

RECOMMENDATIONS

The Academy of Science should call upon the government and government funded agencies to provide support for the Academy to conduct and/or help coordinate the following activities:

1. Work with other agencies for mapping of workforce skills and tertiary education career pathways (include a range of VET, Uni and combination courses) needed for current and future space-related jobs
    a. This should be aligned with related (ASA and SmartSat CRC) projects
    b. Mapping results to be available via a national website, e.g. ASA Space Discovery Centre or Academy of Science
2. Establish national responsibilities for provision of space-related careers information and opportunities
    a. The Australian Space Discovery Centre should have a position created to develop and maintain a database of space-related activities and programs in all states
    b. Careers information incorporating case studies, webinars, should be available to national STEM associations, STEM resources provided to schools, Academy of Science and the general public
    c. The Australian Space Agency should have a position created to develop linkages between students, teachers and relevant industry and R&D (including 'Moonshot') projects
3. Establish a national panel of stakeholders to support curriculum and careers development
    a. National panel of K–12 educators and space workers (industry and research) to endorse curriculum and STEM skills development in the space context.
    b. Curriculum information is linked to relevant Commonwealth-funded and teachers' association sites and regularly reviewed (every 3 years)
    c. STEM information linked to panel-endorsed relevant STEM activities including STARPortal
4. Establish a program for development of quality-endorsed space-related teacher PD (multi-level) material linked to relevant curricula
    a. Space conferences and forums in Australia have at least one ''no-cost' 'open session or stand' where educators and space workers can visit, network and share the latest space updates and curriculum/pedagogy advances

These recommendations should link with recommendations from other Decadal plans and long-term strategies to strengthen and consolidate government funding in order to improve space-related skills and jobs in Australia, space-related education, and participation of traditionally underrepresented groups where appropriate.

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Heliosphere science

(ENCOMPASSING THE SUN, SOLAR-TERRESTRIAL CONNECTIONS, PLANETARY MAGNETOSPHERES, AERONOMY)

June 2020

WORKING GROUP MEMBERS

Chair: Professor Colin Waters

Members:

- Dr Zahra Bouya
- Professor Iver Cairns
- Dr Brett Carter
- Dr Alina Donea
- Dr Trevor Harris
- Dr David Neudegg
- Associate Professor David Pontin
- Dr Ellie Sansom

DISCLOSURES OF INTEREST

None

CONTEXT

1. The development of the second decadal plan for Space Science in Australia was initiated by the National Committee for Space and Radio Science in 2019. A call for chairs of working groups (WG) to provide input into the Decadal Plan was made in October 2019. Invitations for WG member participation were emailed in Oct–Nov 2019, with Working Groups to report back to the National Committee by 15 June 2020.

2. The Heliosphere WG aimed for a broad representation of Australian research expertise in this area. The Australian Antarctic Division (AAD) were invited to participate. The response email was as follows: 'Space and radio science is not a part of AAD's core business. However, if there are other Antarctic matters that require advice from AAD, these can be directed to the AAD's Science Planning and Coordination section (planning@aad.gov.au).'

3. The AAD has supported Australian Space Science related research for over 50 years, providing valuable magnetic and ionospheric data from the southern hemisphere, high latitude regions. The shift in policy to exclude Space Science related research from the AAD Strategic Plan is very disappointing for national researchers and international collaborators in this field. Furthermore, this development threatens the integrity of long-term Antarctic data sets that are essential for the development, testing and refinement of realistic models of space weather and its impact on critical infrastructure.

4. Note that there is a separate WG addressing Space Weather, which overlaps with this Heliosphere WG.

All contributors to the following report are internationally recognised Australian space physics researchers.

PRESENT CAPABILITIES, GOALS AND IMPACTS IN HELIOSPHERE SCIENCE IN AUSTRALIA

SOLAR PHYSICS

CAPABILITIES

a. Theoretical and observational expertise in linear and nonlinear plasma instabilities of solar radio bursts from the solar corona to beyond 1 AU, including the evolution of electron distributions, generation of nonthermal radio emissions by single-charge and collective processes, wave-particle heating mechanisms and particle acceleration associated with charge-exchange, pickup ion rings, and magnetic reconnection regions.

b. Simulation codes and interpretation of the 3-D quasilinear evolution of Langmuir waves driven by electron beams in astrophysical plasmas.

c. World leaders in stochastic growth theory (SGT).

d. Experience with use of the University of Michigan BATS-R-US simulation code for novel predictive capability of solar wind shock arrival time at Earth. One additional application is the modelling of bow shocks associated with radio bolides and other large, fast, objects entering Earth's ionosphere.

e. World's best coupled quasilinear/nonlinear quasi-2D simulation code that models the development and evolution of the electron distribution, driven Langmuir waves, and nonlinearly produced radio emission for Type III solar radio bursts and electron beams.

f. Novel 3-D simulation code for quasilinear plasma wave physics.

g. Analytic solar-equatorial-plane theory that generalizes the Parker and Webber-Davis solar wind theories with traceback of 1 AU observations to the lower corona including non-radial flows and fields at the lower solar boundary.

h. Co-Investigator on NASA's SMEX PUNCH mission to study the transition from the strongly-structured coronal plasma to the turbulent solar wind, coupled with observations from the Parker Solar Probe, Solar Orbiter, future PUNCH data, and existing spacecraft near 1 AU.

i. Solar density model that produces excellent agreement with spectroscopic data, which indicates whether solar radio emissions are scattered by turbulence. Capability to model scattering of radio emission by plasma density irregularities.

j. Experts in plasma shock physics, simulations at small scales (spatial and temporal) and observations.

k. Simulations and observations of magnetic reconnection physics, associated electron and ion heating and wave-particle physics.

l. Simulations and observations of the solar corona heating problem; Reconnection, magnetic field topology and dynamics, turbulent heating and spectral lines, and energy conversion and transport.

m. World leaders in helioseismology techniques for probing the solar interior, using novel Solar Dynamics Observatory data analyses (magnetic field maps, Doppler data for seismic analyses, AI algorithms).

n. Use of helioseismology results for probing solar active regions and deducing the probability of CME/flare activity.

o. Solar flare prediction with 90% success for X-class flares and prediction of CME arrival times.

p. Various tools for extreme space weather forecasting at Bureau of Meteorology SWS.

GOALS

Overall Goals:

- To understand, at fundamental and quantitative levels, the plasma environment throughout the solar system.
- To develop capabilities to interpret observations and invert them to constrain and understand the physics of remote energy releases and transport and the interchange between plasma wave and charged particle phenomena.

Specific Goals:

- To develop a quantitative, data-tested theory/simulation capability to predict (with high probability) if and when a CME will reach Earth and what its properties will be.
- To develop high probability prediction capability of solar flares with lead times as long and short as possible.
- CMEs and DSFs with lead times as long and short as possible.
- Solar Energetic Particle (SEP) events.
- To develop a quantitative, data-tested theory/simulation capability to predict impacts of CME/flare events on near-Earth space, ionosphere and ground critical infrastructure. These predictions must be with sufficient lead-time to confidently produce relevant inputs to government and industry that will allow reliable warning and mitigation of space weather threats.
- To develop a data-tested, relativistic correct theory/understanding of Type II and III radio bursts and related charged particle dynamics in the solar corona and throughout the universe.
- To develop a comprehensive, full 3D theory for the origin and properties of the solar wind, including details of coronal heating, wind acceleration, transition mechanisms from structured coronal plasma dynamics to turbulent solar wind and the relative importance of different processes in explaining 1 AU observations and impacts.
- To improve simulations and understanding of kinetic-plasma wave shock physics, including particle acceleration at planetary bow shocks and solar energetic proton events, and objects (satellites) moving through the upper atmosphere.

- To improve simulations and understanding of particle acceleration and energy conversion in magnetic reconnection at small spatial and temporal scales.
- To develop novel experimental data collection and analysis methods for the discovery of space phenomena.
- To develop, launch and operate innovative satellites and sensors on small platforms for space exploration and discovery.
- To collaborate with international efforts (e.g. COSPAR Space Strategy)

IMPACTS

The majority of observations in space are remote sensed. Most space weather phenomena involve plasma waves over a broad frequency range that contain information about remote energy releases/activity. Understanding (observation supported models) these processes unlocks the specific agents that produce space weather.

- Understanding the complex plasma phenomena throughout the local solar system is key to exploring beyond and being able to determine if observed astrophysical phenomena require new physics (or not). Therefore, observation-truthed theory/models allow the extension of local solar fundamental plasma physics processes to astrophysical contexts and discoveries.
- Understanding the solar corona and solar wind are two high profile, ‘Holy Grail’ problems of solar physics and astrophysics. This leads to improved lead times and confidence in predictions of solar activity and conditions in the background corona which enables improved prediction and mitigation of major space weather events.
- Participation in, and playing major roles in the research of NASA’s PUNCH mission and other internationally coordinated efforts.
- High probability prediction of energetic solar processes (when and where of CMEs, flares, SEP etc.)
- High probability predictions of impacts on various forms of human infrastructure and technology.
- Allow for development of mitigation strategies for major space weather events with sufficient lead time to act effectively.
- Determination of space weather threat levels for specific infrastructure entities.
- Specific and effective guidelines and processes made available to critical infrastructure entities (space operations, AEMO, communications etc.) for space weather events of varying risk level
- Enhanced diagnostic capabilities of astrophysical phenomena through improved understanding of the fundamental physics. Unambiguous determination of which observed signatures are related to what physical quantity and its measurement uncertainty.
- Understanding of shock physics has impact in many areas of science and engineering that involve fluids, gases and plasmas; will benefit multiple research fields.
- Understanding wave and particle interactions and behaviours over a broad range of plasma parameters and energies has direct impact on fusion energy research with the increasing demand for low cost, low environmental impact mass energy (electricity) production

SUMMARY TABLE

Insight	**Why is the solar atmosphere so hot?** **What is the origin of the slow solar wind?** **What are the energy conversion pathways and time scales of the solar atmosphere?** **What quantities and what relationships are required for high probability prediction of CME/flare events?** **How do magnetised plasmas channel energy from large to small spatial and temporal scales and what are the signatures?** **Where can cross-disciplinary collaboration and applications be increased?**
Aspiration	Energy transport and conversion in the solar atmosphere is sufficiently well understood (models are consistent with observations) to allow a detailed understanding of the how, when, where and severity of solar eruptions Realistic models and understanding of plasma shocks, magnetic reconnection, plasma wave emissions and instabilities and their origins. Broaden fundamental plasma research base and expertise to astrophysical, fusion and industrial plasma research areas. Correct the present imbalance between research and industry applications so that fundamental research is positioned and resourced as the foundation of innovation and application development.
Actions	Develop improved computational tools for simulations that span multiple spatio-temporal scales. Ensure adequate high-performance computational resources are available for internationally competitive simulations to be undertaken. Provide training to higher degree research students and sufficient resourcing of early- and mid-career researchers in experimental data analyses, numerical methods, high performance computing and cutting edge theory. Create and adequately resource a multi-disciplinary centre for plasma phenomena research and applications with relevant academic, industrial, international and government involvement.
Impacts	Fundamental plasma physics research findings and discoveries will advance astrophysical, industrial and fusion applications. These will improve our understanding of processes and phenomena throughout the universe and in laboratory plasma devices (e.g. magnetically-confined fusion devices). Allow development and use of predictive models of solar eruptions and threat levels with adequate lead-times to inform space weather predictions. A cost-effective and coordinated cross-disciplinary plasma phenomena research focus that efficiently advances knowledge to enable innovative technology development with the proper resourcing and interaction between fundamental research and industry/application development.

Metrics	Australia is a recognised, leading nation in space science/solar physics Predictions of solar eruptions have improved, making space-weather forecasts more accurate. Discoveries in solar/space physics phenomena are transferred to industrial, astrophysical and fusion plasma research and applications and vice versa. An adequately resourced, best-practice, coordinated approach to plasma phenomena research and applications is developed within a stable policy environment involving academic, industrial, energy sectors and government support and international expert interaction.

Insight	**What sensor technologies and data processing methods can be used to probe the Sun, particularly the far-side?** **What useful information on the structure and evolution of active regions can be gleaned from solar acoustic waves?**
Aspiration	Advanced sensor technologies, ground and space platforms and data analysis techniques (e.g. AI) are accessible and provide long-term data streams. The fundamental processes that control the characteristics of the solar wind are sufficiently well understood to allow predictive modelling.
Actions	Develop pathways for the translation of fundamental science results into space weather modelling/forecasting services. Access to solar experimental data including vector magnetic field and Doppler time series maps. Development of new remote sensing methods and pathways to develop these.
Impacts	Improved understanding of solar wind formation mechanisms are key to building improvements in space weather modelling efforts and predictions of extreme space weather events. Improved understanding of stellar winds allows
Metrics	Novel sensors are developed and flown on Australian manufactured systems. Australian developed and manufactured sensors are the product of choice for international space missions. Accurate assessments of the habitability of planets beyond our solar system.

MAGNETOSPHERE AND IONOSPHERIC PHYSICS

CAPABILITIES

a. Computer simulation and observational expertise of ultra low frequency (ULF) plasma waves for remote sensing near-Earth space (plasmasphere plasma mass density, electric field magnitudes for electron and ion energisation that disrupts spacecraft functionality).
b. Instrumentation for probing properties of the ionosphere: HF radars, ionosondes, TEC from GPS and associated tomography tools.

c. Ionospheric HF wave propagation and radar/ionosonde data analyses and interpretation.
d. Coupled troposphere-stratosphere-mesosphere-thermosphere-ionosphere modelling and data assimilation.
e. Data analyses and modelling of ionosphere coupling and forcing from the thermosphere and magnetosphere.
f. Real-time regional (mid and low latitude) ionosphere modelling; response to geomagnetic disturbances and effects on HF signal propagation.
g. Observations and interpretation of relationships between layer heights, spread-F, sporadic-E, delays between geomagnetic and ionospheric disturbances.
h. HF communications propagation prediction and advice services.
i. Modelling of geomagnetic induced currents (GICs) from ionospheric current to ground magnetic signature and spatial/temporal details of the GIC electric field. The Bureau of Meteorology (SWS) have also developed an electricity supply network model (with AEMO), with simulation capability of GIC impact on the Australian east coast electricity grid.
j. Equatorial plasma bubble observations, modelling and prediction capability.
k. Earth's ionosphere, cusps and auroral zones accessed via rocket experiments and CubeSats.
l. Theory and observations of thermal Langmuir waves detected by CubeSats in Earth's ionosphere, allowing reliable extraction of the cold plasma density and temperature.
m. Theory and data of the electrical signatures of dust impacts on CubeSats in Earth's ionosphere, allowing extraction of the dust particle sizes and numbers and in-situ assessment of space debris near Earth.
n. Capability to determine 3-D GNSS propagation and/or distortion through the ionosphere

GOALS

- To determine how different observational techniques and data represent the complex, magnetosphere-ionosphere-atmosphere system.
- To develop an integrated, multi-sensor observational network and platform (ground and space based) for viewing and understanding the atmosphere/ionosphere/magnetosphere system.
- To predict and monitor the radiation types and levels at LEO, MEO and GEO and their effects on spacecraft operations and biology in space.
- To understand (observation-consistent model) energy deposition, transport and coupling to the regional ionosphere from below (troposphere and thermosphere) and from above (magnetosphere/thermosphere) and how these are related to ionospheric variability, particularly density variations at LEO (<1000 km).
- To unravel the mix of direct solar driven and internal magnetosphere processes that drive space weather related effects.

- To understand the formation and effects of ionospheric sporadic-E layers; dynamics of descending layers, relation to meteors and thermospheric winds and airglow.
- To determine the sources of daily variability in equatorial plasma bubble formation and other equatorial ionosphere gradients; particularly the relative impact of 'seed' variables and conditions compared with background conditions and electrodynamics.
- To understand the source mechanisms and propagation properties of travelling ionospheric disturbances (TIDs including MSTID, AGW, LSTID from polar latitudes), including time of arrival at all latitudes.
- To develop an indigenous, surface to exopause atmospheric modelling and data assimilation capability that utilises data from a comprehensive space sensor network in order to accurately describe the complete physical state of the ionosphere-thermosphere system on regional and global scales, targeted to related research areas and operational space weather prediction.
- High probability prediction capability of the following:
  - Thermosphere-ionosphere particle densities at LEO to inform orbital dynamics and Space Situational Awareness.
  - Radiation environment impacting satellite operations in LEO, MEO, HEO and GEO.
  - Cosmic radiation conditions impacting aviation operations in the stratosphere and mesosphere.
  - Geomagnetic and ionospheric storms at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
  - Global ionospheric plasma densities at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
  - Scintillation-producing ionospheric irregularities at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
  - Aurora Australis occurrence at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
  - Geomagnetically Induced Currents (GICs) in the Australian electricity grid and industrial pipelines.
  - Quantification and distribution of relevant space weather effects and impacts at operationally useful lead times

In order to achieve the necessary understanding of complex solar-terrestrial responses and interactions, significant investment in developing an Australian whole atmosphere modelling and data assimilation capability is required. As part of these efforts, existing complementary areas of expertise within Australia (e.g., meteorology, high-performance computing, machine learning and big data science) should be effectively leveraged. Possible coordinated, multi-disciplinary structures include: Centre of Excellence, CSIRO sub-division, a funded entity of the Australian Space Agency or other agency (BoM, Geoscience Australia, AAD).

IMPACTS

- Ability to provide accurate predictions of the trajectories of descending space debris with applications to improved stability and control of LEO satellites.

- Understanding of energy deposition and transport from space into Earth's climate system with impacts on climate modelling, and prediction and mitigation strategies for future effects of climate variability.
- Enhance Australia's strong international reputation in space science as a capable and reliable provider of space environment data and knowledge.
- Improvements in the accuracy (cm level) and operation and applications of GPS services with associated economic and societal benefits.
- Improvements to the operation of JORN and other over-the-horizon radars, thereby significantly improving Australia's surveillance capability and national security.
- Adequate training and retention of knowledge of space and ionosphere processes in the Australian workforce to support space and ionosphere related operations.
- Ability to develop and sustain a 'critical mass' and national capability in space systems and missions, to grow and sustain a space economy and export stream.
- Provide essential components and indigenous expertise for a *sustainable* space industry and economy. This requires a coordinated, cooperative and adequately resourced combination from academia (research and training), industry (applications and exports), and government (stable policy framework), all suitably supported, encouraged, and impacted by progress.

SUMMARY TABLE

Insight	**What experimental data are necessary to identify the various mechanisms in atmosphere/ionosphere coupling?** **What are the energy exchange mechanisms between the various atmospheric and ionospheric layers?** **How can we improve measurements of the dynamics of the thermosphere?** **What data and analysis tools are required to provide high probability prediction of near-Earth space conditions and threat assessments?** **What tools and data are best for conveying research outputs and relevant warnings to critical infrastructure customers?** **What measurement of the ionosphere and near-Earth space provides information on which physical parameter?** **How do we combine multi-instrument data into a coherent, real-time view of the solar-terrestrial environment and its impact on space and ground based assets?** **How do we ensure the supply of qualified personnel to space related industries and defence?** **What is the set of physical drivers that cause ionospheric disturbances?**

Aspiration	Understand the physical mechanisms of energy coupling from above and below, and their signatures between different atmosphere and ionosphere heights Understand the relationships between small and large spatial and time scale dynamics in near-Earth space and the ionosphere. Build real-time multi-sensor data input and visualisation tools. High probabilistic prediction of adverse conditions for various customers. Develop accurate relationships between magnetic data and electricity grid and industrial pipeline impacts. Be able to identify and exploit the different responses of observational techniques to the system.
Actions	Develop improved computational tools for multi-data ingestion and prediction purposes Identify and develop remote sensing tools for ingesting additional experimental data into prediction tools. Ensure access to experimental data sources and expand observing network. Identify and develop remote sensing methods for expanding relevant data sources. Deploy high spatial resolution observing network, with a focus on low and equatorial latitudes. Develop a cheap and energy efficient method for monitoring thermosphere dynamics 24x7. Develop a coordinated approach to space technology and research training.
Impacts	Real-time operation of over-the-horizon radar detection and defence infrastructure. Improved understanding of space weather and cross-disciplinary impacts on effects on the atmosphere and Earth climate. Real-time, relevant data access to drive high quality prediction models for space weather impacted infrastructure. Allow development of targeted warnings and threat mitigation strategies for specific industries (e.g. energy supply, communications, GPS etc.). Improved prediction lead-times and accuracy of warnings of severe space weather events. Improved prediction of trajectories of space debris and space situational awareness. Improved predictions for stability and control of LEO satellites. A sustainable and qualified workforce to drive research and innovation in space technologies.

Metrics	Model predictions agree with the observational data Sufficient observational data are available to develop realistic models (long-term data sets) and to drive predictive algorithms (e.g. GIC predictions for AEMO, GPS services etc.). The specific warnings and mitigation strategies for each of the diverse infrastructure service operators are effective in protecting critical assets. The lead-times for warnings are expanded with high prediction accuracy The locations of space objects are known 24x7 The identification of space object at smaller sizes is improved Sufficient numbers of qualified personnel are available for the demands of the Australian space industry

INSTRUMENTATION AND DATA

CAPABILITIES

a. Capability to design, build, and test CubeSats and to operate them in space from Australia. Examples include CUAVA-1, M2, Buccaneer and CSIROSat. Several missions are being investigated without funding (at present), mostly focused on low Earth orbit projects but some are for Moon-Mars, planetary missions, and beyond.
b. Capability to design, test and fly sensors for space applications, such as GPS instruments, imagers, plasma wave receivers, plasma and gas thrusters, and radiation counters. Design and fabrication for electrical components of an instrument to detect thermal Langmuir waves (plasma noise spectroscopy) from a CubeSat platform and extraction of the electron temperature and density along satellite orbits in Earth's ionosphere and inner magnetosphere.
c. World Data Centre for Space Weather data service
d. Software and data products for AMPERE (Iridium constellation magnetic field data) and for SuperMAG, the global ground magnetic field initiative.
e. Ground magnetometer assets are declining at (Bureau of Meteorology) SWS, Australian Antarctic Division (AAD), Latrobe University and the University of Newcastle.

GOALS

- To halt the present reduction in, and preserve existing, instrumentation assets across Australia, the southern ocean, Antarctica and equatorial regions.
- To develop, test and use Australian relevant sensors from space-based platforms.

- To improve near-Earth space monitoring capabilities by expanding the Australian network of ground-based instruments, including ionosondes, magnetometers and HF radars, and expanding the sensor network to include Australian space-based instruments with both remote sensing (e.g., GNSS Radio Occultation and topside sounding, combined electron temperature and density data from the ionosphere) and in-situ sensing (e.g., Langmuir probes and mass spectrometers) capabilities.
- To obtain long-term observational data at small spatial and temporal scales over large regions.
- To develop techniques (with reasonable cost) to monitor the dynamics of the thermosphere, providing 24x7 measurements on a regional basis.
- To develop a comprehensive and coordinated platform for presenting space and Earth-based data from a diversity of instrumentation in a coherent manner.
- To foster and develop indigenous skills and industry for space-worthy sensors, deployment systems, command and control and necessary ground-based infrastructure to maintain and expand Australian spaced-based sensing.

IMPACTS

- Long-term data bases are essential for distilling and testing relationships on solar cycle time scales. These are critical for developing and using high confidence prediction theory/models.
- Ability to develop and export satellite hardware systems and sensors that enable major scientific progress, creation of significant economic benefit, and provide sovereign capability in high profile and impactful ways.
- Provide adequate observational data to test and refine scientific models of space weather impacts and their effects on a diverse range of infrastructure. This impacts the development and implementation of mitigation procedures and adequate lead-time guidelines for specific applications.
- Provide adequate input data to be able to run and effectively use prediction models of space weather (e.g. sufficient magnetometer data for the GIC prediction model)
- Coordinated multi-source data presentation platform in real-time is critical for timely and accurate monitoring and advisory services, in addition to the essential role in research and development of algorithms and applications.

METEORITE TRAJECTORY AND ORBIT ANALYSES

- Meteorite detection and recovery, with applications to identification and dynamics of objects in near-Earth space (space situational awareness).

RECOMMENDATIONS

RECOMMENDATION 1. VALUE RESEARCH

The importance of basic space science research should be recognised, valued and supported for its key role in Australia's space sector activity, application development and industries.

RECOMMENDATION 2. WORKFORCE PLANNING

There is presently an active internationally regarded space science research sector in Australia which leverages significant international IP through collaborations. However, the Australian community is small and comprises mostly senior rather than middle or early career workers. There is an urgent need for succession planning in order to ensure a sustainable space science capability able to meet national requirements.

RECOMMENDATION 3. COORDINATED MULTISECTOR R&D ENVIRONMENT

In order to create Australian jobs in the space sector and provide an efficient and cost-effective path from innovation to industrial applications, the diverse Australian research activity in space physics and dynamics, laboratory plasma, gas and fluid physics, data science, prediction and computational modelling expertise, should be brought together within a coordinated, focused entity with a more stable funding structure, clearer government policy environment and clear objectives developed from the national interest (i.e. defence, infrastructure security and integrity, sustainable energy and resource production, environment management etc.).

The present mechanisms, processes and sources for supporting (including funding, collaboration barriers, policy framework) space science research which fuels innovation, product development and export income, is in need of an urgent review. The existing structures and approaches threaten sustainability and the national expertise capacity and encourage a 'silo' approach that inhibits cross-disciplinary innovation resulting in inefficient spending and effort.

A coordinated approach and structure should be developed that combines the diverse research expertise, education and training (for succession planning and sustainability) with strong industry collaboration and clear career opportunities. The present situation, where Australian educated talent disappears to long-term, international destinations should be reversed and this talent redirected to solving problems that are relevant to Australia's needs and problems (e.g. HF communications and surveillance, enhanced GPS, GICs in our national power grid and gas pipelines, space situational awareness, space access and other technologies etc.)

Warning: Research results that are critical for developing and running space weather prediction models cannot be simply pulled from international research groups and results. Critical data and prediction tools must be derived from the relevant hemisphere, latitude and local time sources, including the high latitude southern hemisphere

RECOMMENDATION 4. AUSTRALIA AS A SPACE SCIENCE DATA PLATFORM

Australian territorial interests span an eighth of the globe, providing critical coverage of the southern hemisphere and Asia-Pacific time zones. However, the number of Australian data collection platforms and assets is declining. A national approach to operation of a sustainable suite of data and sensor assets, with associated data processing and analysis capability, is necessary in order to support research activity, real-time critical information (e.g. GPS corrections for SBAS, space object tracking, surveillance accuracy), and space weather warnings and predictions.

The reduction of the number of data collection platforms within Australia has already approached a critical level in some areas. For example, geomagnetic induced currents (GICs) are internationally recognised as a threat to critical infrastructure, having caused disruptions to electrical energy supply infrastructure in Europe, Canada, USA, UK, New Zealand, South Africa and China. To monitor such GIC events in Australia, the Department of Home Affairs Trusted Information Sharing Network Energy Sector Group and the Australian Energy Marketing Operator (AEMO) Power System Security Working Group, have invested in transformer neutral line sensors and monitoring infrastructure. Data from these sensors are combined with magnetic field measurements to provide the essential backbone of the monitoring and warning capability for electricity supply in Australia. The warnings and prediction capability developed by Space Weather Services is world's best technology but is compromised by limited availability of observational data, especially magnetometers.

Both the long term (sustainable) and real-time data requirements would make sense within a coordinated, focussed structure outlined in Recommendation 3.

A pooling of the data collection, different data types and data processing expertise is more cost effective and provides the opportunity for multiple expert attention compared with the present ad-hoc and 'siloed' approach to data collection and sharing.

The United Nations General Assembly has recently approved the recommendations put forward by the UN Committee on the Peaceful Uses of Outer Space (UN COPUOS), https://www.unoosa.org/oosa/en/ourwork/copuos/current.html, to increase the number and distribution of space weather sensors such as magnetometers, and ionosondes

Planetary sciences

June 2020

WORKING GROUP MEMBERS

Chair: Professor Phil Bland

Members:

- Professor Gretchen Benedix
- Dr David Flannery
- Professor Penny Kin
- Dr Helen Maynard-Casely
- Professor Craig O'Neill
- Associate Professor Andrew Tomkins

DISCLOSURES OF INTEREST

None

VISION STATEMENT

Australia has a world-class planetary science community, with expertise across all areas of the field, from the early solar system, to astrobiology, to comparative planetology. Early researchers like Stuart Ross Taylor, John Lovering, John Jaeger, Alfred Ringwood, Malcolm Walter and John de Laeter helped define the field internationally, and laid the foundation for Australia's recognised strength in sample analysis, synthesis and modelling. Our researchers are members of science teams on multiple missions currently led by other nations, evidencing the continued international standing of our community.

Planetary science is essential to solar system exploration, and missions are a key enabling capability for the field. Our vision for 2030 is to see Australia become an equal partner in the global community of space-faring nations by:

1. Leading our own planetary missions, with Australian-led science teams, and Australian-built payloads and spacecraft systems.
2. Contributing Australian hardware, software and scientific expertise to the most significant international space missions.
3. Creating a stronger foundation for Australian-led missions and contributions through education, innovative experimental work, sample analysis, field studies, and modelling relevant to planetary bodies.
4. Creating a world-class workforce of planetary scientists and spacecraft 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.

Adding a sovereign capability in solar system exploration to our world-leading research skill-set would allow Australian planetary researchers to expand their horizons in terms of the range of science questions that they can address. Our planetary scientists have built, over decades, relationships with partner agencies overseas. Working together on shared missions would deepen and strengthen those relationships. By contributing payloads in addition to intellectual expertise we would be partnering on an equal footing, participating in the definition of mission goals.

Australian research leadership will generate innovations that will improve the lives of Australians across the board. Blue sky planetary science has transformed our understanding of the Earth, with benefits in the management of scarce resources, mining, and knowledge of climate change. A strong research base will close the virtuous circle of science underpinning innovation and economic growth in the sector; growth that then feeds back into increased private sector funding for science. It will define for the first time an education program and career path for Australian science and engineering students, through university, working on projects with partner agencies, and then on to industry. But more than anything, a sovereign capability in solar system exploration would inspire Australians.

2030 will see a flourishing Australian planetary science community, with excellence in ground-based research, complemented and energised by a mature capability in planetary missions. Australian science teams will be exploring the solar system with Australian spacecraft and payload contributions.

We will leverage key strengths in sample analysis, astrobiology, Martian and Lunar geology, geophysical modelling, and solar system formation, to develop world-leading programs that combine ground-based and space-based scientific exploration. In addition to a planetary science research base, our geoscientists are recognised for world-leading expertise relevant to Moon and Mars exploration (e.g. geological analysis via seismic, magnetotellurics, field studies of rock analogues, as well as robotics and resource exploration/extraction in extreme environments), allowing participation across multiple research sectors. Australian expats, including scientists with leadership roles on key missions to the Moon and Mars, work for partner agencies. An Australian science program will leverage existing strengths to help partner agencies achieve their goals of robotic exploration, sample return, and a permanent human presence. Building on the success of our own exploration program, we will win preferred access to missions led by other agencies.

BACKGROUND ON TOPIC AREA

Planetary science involves the study of planets, asteroids, comets and moons, and entire planetary systems. Its particular focus is the origin and evolution of objects in the Solar System. It is highly interdisciplinary, encompassing dozens of other fields. Planetary science is intimately linked to space exploration. Research priorities for overseas space agencies are defined around knowledge gaps in the field. Planetary science is thus central to most space agencies exploration and research efforts.

There is ~AU$15 billion of hardware currently at Mars, or ready to fly. The combined cost of two of those missions – Curiosity and Perseverance (Mars 2020) – equals the US cancer research budget. Two thirds of NASA missions are defined around planetary science knowledge gaps. NASA's planetary science budget in FY 2019 was AU$4.2 billion. Outside of human exploration and operations, planetary science is NASA's single biggest budget item, accounting for 13% of the total budget in 2019. NASA spends more on planetary science than it does on Earth science and observation, or on the Space Launch System. Other agencies – both small and large – also prioritise planetary science. This level of investment speaks to a deeper motivation than simply a desire to explore the solar system. It is just that: an investment. NASA, and other space agencies, fund planetary science and missions that pursue planetary research goals because they create direction and motivation for their domestic space industry. The science goals create a framework around which engineering solutions need to be developed, acting as a crucible for innovation.

Internationally, agencies view planetary science as the driver of their domestic space industries, not as an optional extra. **NASA and ESA have calculated that every $1 invested in science brings a $4–6 return.** Planetary scientists generate the science cases that define inspirational missions. They work with overseas agency collaborators to build transnational science and engineering teams on the highest profile projects. These projects attract and engage the brightest students. The result is a pipeline of highly qualified graduating scientists and engineers, with experience that goes beyond their own disciplines, having built relationships with colleagues at partner agencies around the world. Planetary scientists build the hardware that flies on missions: IP that has translated into space industry applications, and the broader economy. Planetary science drives innovation at home, and brings innovations from overseas agencies to Australia.

Australian industry cannot work directly with NASA, but Australian researchers can and do. Australian planetary scientists have relationships throughout NASA, ESA, and many other agencies, built over decades. Planetary science connects industry to those agencies.

The intimate connection between planetary science and a thriving space sector was recognised during the development of the Australian Space Agency. The Review of Australia's Space Industry Capability recommended that Australia should 'participate in discovery science missions as part of international consortia and national space competition missions'. In July 2018, then Minister for Jobs and Innovation, Michaelia Cash, gave the keynote speech to the ASPI International Space Conference 'Building Australia's Strategy for Space.' As the Minister responsible for the new Australian Space Agency, she celebrated its imminent inauguration, outlined the strategic priorities that the agency would address, and identified Australian research strengths in five areas that the Agency would seek to build as a strategic priority. The Agency has moved forward on all but one of these. The outstanding element was the direction to build '…on Australia's research strengths in… planetary science'.

KEY SCIENCE QUESTIONS

The major goals of the Australian planetary science community align with international peers. Building on our existing research strengths, we see several key areas of investigation that Australian planetary scientists can progress or answer in the next decade:

1. **How did the Solar System form?**

   What were the initial processes of solar system formation and the nature of the interstellar matter that was incorporated? We understand much of how the Earth works. How the Earth and other terrestrial planets, as well as 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, and asteroids (from which meteorites come) as well as 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. Building on this key strength and analytical infrastructure in analysis of asteroid and comet samples, we see near-Earth objects as a logical target for Australian spacecraft to help answer the overarching question of how dust and gas came together to create our solar system, including at least one planet capable of supporting life.

2. **The formation and evolution of the Moon**

   Following the flurry of activity during the Apollo era, the Moon has been comparatively underexplored. Mars has been the target of a co-ordinated research program for decades, visited by 15 NASA spacecraft. In contrast, NASA has returned to the Moon only 6 times since Apollo. There is so much that we still do not know about Earth's nearest neighbour. When did it form? What is its internal structure? What can its ancient surface, and record of impacts, tell us about the impact history of the solar system? Going back to the Apollo era, Australian planetary scientists have led the way in understanding the geological and impact history of the Moon. With the Artemis program we are entering a new era for lunar science, and Australia is well positioned to participate. 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 a mature Artemis program, Australian science teams can operate hardware on the surface or in orbit to address key knowledge gaps.

3. **Enabling human exploration: in situ resource utilisation**

   Australia's track record in sample analysis means that we can be key partners with other agencies, 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 co-ordinated NASA program – the Solar System Exploration Research Virtual Institute (SSERVI) – which supports domestic US science teams, and connects and co-ordinates their research with overseas partners. SSERVI was created to supplement and extend existing Lunar science programs, with a particular focus on connecting science with human exploration. Australia became a NASA SSERVI partner in 2015. US teams have a singular focus on volatile distribution, ISRU, regolith properties, and impact on human health. Australia has risen to become a key partner in SSERVI at the national level. Australian scientists are also members of three domestic US NASA SSERVI teams. Relationships built within NASA SSERVI on projects to determine volatile content and distribution for ISRU, our track record in sample analysis, and Federal support for Artemis, potentially make us a preferred national partner with NASA in this area.

4. **The Origin of Life in the Solar System**

   How, why and where did life evolve in the solar system? Leveraging key Australian strengths in astrobiology and analogue site studies (Western Australia has some of the oldest rocks on Earth), there is an opportunity to develop Australian payloads around key science questions and knowledge gaps. 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.

   Australian science payloads could target a 2026 launch window for Mars, and a likely NASA lander, as well as other international missions. Although Mars is well explored from orbit, surface science packages can address key knowledge gaps. This contribution could take the form of instrument payloads on a lander or a rover, or novel platforms such as drones, or micro-landers. Payloads could deliver analytical capabilities to measure trace gases, rock and soil composition and/or map groundwater distribution, feeding into identification of astrobiology targets and resources for future missions. Such payloads for small platforms will have diverse uses, with applications on the Earth, Mars, Venus, Moon and small solar system bodies. Australia can be a leader in this technological space because the minerals industry has driven development of deployable, remote operated analytical technology, along with airborne and ground-based geophysics and analytical techniques.

5. **The Evolution of Planets: Pathways to Habitability**

   How have the chemical and physical processes that shaped the solar system operated, interacted, and evolved over time? The giant planets serve as laboratories to understand Earth, the solar system, and extrasolar planetary systems. Understanding the roles of physics, chemistry, geology, and dynamics in driving planetary atmospheres and climates will lead to a better understanding of climate change on Earth.

Mars today is dry, cold, and has little in the way of a magnetic field or atmosphere. In contrast, Venus is hot and shrouded in a thick greenhouse atmosphere. Observations of Mars' surface reveal features consistent with an active hydrosphere with rain, rivers and possibly a northern ocean early in the history of Mars. However, climate models have not yet been able to replicate such a warm and wet environment. Australian researchers are already working on this puzzle. We can provide the technological capability and theoretical know-how to conduct rapid, large-scale geochemical analysis of rocks, develop simulations of the surface climate and interior, determine the ages of various minerals, and characterize the isotopic variation of key elements. Importantly, understanding Mars will allow us to unravel other climate mysteries in the Solar System.

SUMMARY

Given the current focus on the Moon, with low cost ride-along opportunities for orbiters and landers in the next 2 years, it is logical for our domestic program to begin with the Moon. Missions to near-Earth objects will follow. Building on this success, as a trusted partner with space validated hardware, we can anticipate ride-along opportunities to more challenging and costly targets, such as Mars. We also wish to engage with the priorities of our international partners, translating demonstrated success with Australian science investigations to preferred access to their upcoming missions: lunar sample return with CNSA, Mars sample return with NASA/ESA/CNSA, JAXAs mission to the Martian moons, NASAs Dragonfly mission to Titan, ESA's mission to the Jovian satellites, and NASAs Europa Clipper.

RECOMMENDATIONS

Achieving our vision does not require NASA or ESA levels of funding. Existing programs such as ASAs Moon-to-Mars (M2M) could get us far along the path, for a small fraction of the total program budget. Academics are used to highly competitive funding environments. Competition drives excellence. But achieving our 2030 vision does require a structured funding environment. And it does require ASA to engage with the research sector. As in other nations, now that we have a space agency, the viability of our research sector is necessarily tied to agency funding policy and strategy. We feel strongly that a modified ASA policy that enables Australian scientists to leverage the deep and broad relationships with overseas agencies, acting as intermediaries between those agencies and Australian industry, would help Australian industry and boost the domestic R&D sector. If ASA-funded projects are mission-oriented, with science and capability cases that engage agencies overseas, and that deliver real outcomes for Australian industry, then everyone benefits.

RECOMMENDATION 1: OVERLAPPING REMITS IN A NEW FUNDING ECOSYSTEM

Background: The Australian space sector has benefited from significant federal investment: to ASA, with the Strategic Infrastructure Fund, International Space Investment initiative, Moon-to-Mars program, and to the SmartSat CRC. But currently blue-sky planetary science and engineering is in danger of falling between the cracks in the new Australian space research funding ecosystem. SmartSat IP provision means that universities cannot leverage their relationships with overseas agencies to fly their hardware on those agencies' missions. In the case of ASA, it is currently unclear whether planetary science projects are eligible within current and future funding schemes.

Risk: Previously, although funding was highly competitive, spacecraft engineering or Moon/Mars projects would be funded by ARC. Now, perception of a funding overlap with SmartSat and ASA will mean that a hard-pressed ARC will step back. The low level of ARC funding that has allowed an Australian planetary research community to survive will dry up. This is an existential issue for the field.

Recommendation: ASA should liaise and communicate with other Australian funding bodies to develop a space and planetary science funding strategy, and clearly identify remits. Our suggestion is to follow the UK model. The UK Science and Technology Facilities Council (equivalent to the Australian Research Council) funds non-mission science. The UK Space Agency funds mission science and engineering. ARC would continue to fund non-mission science. ASA would fund mission science and engineering.

RECOMMENDATION 2: ASA FUNDING POLICY

Background: The future of the Australian research sector is tied to agency funding policy. Current ASA policy appears to be excluding science. Initially, the announcement of a $150M initiative to partner with NASA on exploration of the Moon and Mars appeared to be a real opportunity for Australian planetary science. But the draft document and consultation clarified that M2M does not include funding for science. Will ASA take a similar approach with future programs?

Risk: Forging enduring relationships with overseas agencies that are focussed on science and missions requires a domestic capability in these areas. Ongoing engagement with an entity like NASA Science Mission Directorate will necessarily require us to have projects with science cases, developed around missions. Overseas agencies can demonstrate a clear return on investment based around funding models that include science projects and missions. A 'no science' funding model represents a unique experiment. In 10 years, with a model that does not involve funding for science, will ASA be able to demonstrate a similar return? At that point, with a substantially depleted research sector, there will be limited opportunity to pivot to a new policy, and our ability to engage with overseas agencies will be diminished.

Recommendation: ASA modify current and future programs to include university-led teams, allowing science cases that enable engagement with overseas agencies, while adhering to the ASA priority that there should be demonstrated benefits to industry. When considering missions, develop a program, rather than a delivery mechanism for a single project. Design all projects to be collaborative between industry and academia, with direct partner agency involvement. A package that includes science team involvement on missions for other agencies, and sample-return analysis, multiple Artemis-class CubeSat missions ($8–10M per mission), payloads for CLPS landers ($1–2M per project), and a PhD program for collaborative projects that would allow internships for students at partner agencies, would have minimal overall impact on existing programs in terms of direct funding for supply chain and industry, but it would pump-prime the research sector, encourage engagement with industry, and set us on course for achieving our 2030 vision. The result could be full Australian involvement in missions with partner agencies, 4 Artemis-class CubeSat missions, 6 payloads for CLPS landers, 1–2 tech packages on Mars rover missions, and 20 new graduate students in spacecraft engineering, with relationships across multiple overseas agencies. A single large mission is a high risk for a nation that is still building a capability. It benefits a small team, rather than a program that grows a research community and a sector. And the science benefit and inspirational value is not significantly increased over smaller missions. Multiple Artemis-class missions would spread the risk across more projects and teams, decrease cost and shorten the timeline for high visibility success, and minimise the project management overhead. Australia would get multiple inspirational projects, delivering regular high profile wins, and with multiple missions and projects, our relationships with overseas agencies would broaden and deepen across multiple areas and partners.

RECOMMENDATION 3: DEVELOP A MODULAR APPROACH TO MISSION DESIGN

Background: There are 13 6U CubeSats flying as secondary payloads on Artemis-1. Nine of these are science missions; 4 are technology demonstrators. Of the 9 science missions, 8 have buses developed by different, independent teams. This illustrates a standard approach in planetary mission design. Teams reinvent the same capabilities. R&D pathways are typically on a mission-by-mission basis.

Risk: Australia is a small nation. Our budget for R&D for missions will always be constrained. If we adopt a similar approach to other nations, with R&D focussed on a specific mission, rather than a program, our ability to deliver on our vision will be limited.

Recommendation: Australia should develop a space technology ‘toolkit’, and a modular approach to mission design. We should identify key enabling technologies, and develop and validate them on multiple missions. The result would be that new missions can be developed rapidly from validated systems, built for interoperability. This does not require a restrictive top down approach to R&D. Competitive funding drives excellence. It simply requires that we identify key technology enablers, and have teams interact to ensure interoperability.

Space-based PNT

August 2020

WORKING GROUP MEMBERS

Chair: Emeritus Professor Chris Rizos

Members:

- Professor Suelynn Choy
- Matt Higgins
- Dr Simon McClusky

DISCLOSURES OF INTEREST

- Chris Rizos: President Elect, International Union of Geodesy and Geophysics
- Matt Higgins: President, International GNSS Society

VISION

By 2030, Australia will be seen as a sophisticated user of space-based positioning, navigation and timing (PNT) technology. Our sovereign PNT infrastructure and skilled workforce are world class, underpinning and stimulating the growth of the broader economy. We have the ability to deliver and use superior PNT information to make intelligent decisions and make sense of the complexity of the world we inhabit, which are supported by resilient access to timely, reliable and accurate PNT information.

Space-based positioning, navigation and timing (PNT) technology is *critical infrastructure that* underpins many scientific, commercial and personal user applications (see https://www.gps.gov/applications/, https://www.ga.gov.au/scientific-topics/positioning-navigation/positioning-australia). Furthermore, it is expected that society's reliance on accurate, available and reliable PNT information will continue to expand rapidly over the coming decade. This increased *reliance* on PNT as critical infrastructure underpinning many economic-, social-, scientific- and security-related activities brings into sharp focus a number of issues related to *vulnerabilities*, and *shortcomings*, of space-based PNT technologies and services. This is of particular concern for Australia due to its unique characteristics – large area, important primary industry, location, small and concentrated population, PNT space technologies are operated by other countries. Hence Australia must invest in PNT systems that address Australia's diverse PNT requirements as well as building resilience in the event of space-based PNT capabilities are compromised.

The NCSRS has an interest in space-based PNT with respect to the *science priorities* for both the upstream and downstream components of the value chain in Australia. These include the development of satellite and augmentation systems, the user-end and system-level hardware and software components, the user-end signal and measurement processing algorithms and methods, the infrastructure and services for improving PNT capability, and specific user application scenarios both in the civilian space and defence that require input or investment by Australian space science researchers, industry and other organisations.

In this brief note it is not possible to mention (let alone detail) all of the PNT activities being undertaken in Australia, or to make a complete list of recommendations with regards to a PNT R&D agenda. What are listed are some of the science challenges that are associated with ensuring the delivery of a national space-based PNT capability that addresses today's, and future, requirements for accurate, reliable and resilient PNT information in the Australian region – its maritime areas as well as New Zealand and other neighbouring island states.

GNSS TODAY

Global Navigation Satellite Systems (GNSS) are at present the sole means of delivering a global PNT capability to users, with suitably equipped receiving equipment, to a *base-level* positioning accuracy of a few metres and timing accuracy of tens of nanoseconds.

The term GNSS refers to the various constellations of satellites that broadcast signals in predominantly the L-band frequency of the electromagnetic spectrum. When these signals are tracked by GNSS receivers, base-level PNT capabilities are available to all users 24/7 anywhere in the world. However with advances in receiver technology, operational procedures and measurement processing, GNSS positioning information can be *substantially improved* – to the sub-centimetre-level positioning accuracy, instantaneously, even when the user receiver is moving. Calculation of the Coordinated Universal Time (UTC) and time dissemination services using GNSS at better than the nanosecond-level is achievable. This *enhanced* PNT performance is extremely important for a number of user communities.

Today's GNSS receiver may track signals from most (if not all) of the following satellite constellations: the U.S.'s GPS, the Russian Federation's GLONASS, the E.U.'s Galileo GNSS, China's BeiDou GNSS, and region-based augmentation systems such as the Australian and New Zealand Space-based Augmentation System (SBAS), Japan's Quasi-Zenith Satellite System (QZSS), India's Regional Navigation Satellite System (NavIC). Over 140 satellites are broadcasting GNSS signals. With society's increasing reliance on GNSS-derived PNT, the myriad issues associated with the *accuracy*[8], *availability*[9], *continuity*[10] and *integrity*[11] of PNT information become paramount.

GNSS MARKET

The global GNSS downstream market continues to grow rapidly. Based on the report of the European Global Navigation Satellite Systems Agency (GSA) 2019 GNSS Market Report, the global installed base of GNSS devices in use is forecast to increase from 6.4 billion in 2019 to 9.6 billion in 2029, while global GNSS downstream market revenues from both devices and services are set to grow from €150 billion in 2019 to €325 billion in 2029. The GNSS market growth will be further stimulated by *global mega-trends* such as digitalisation, big data, the sharing economy and Artificial Intelligence applications that use GNSS for PNT. From the perspective of science, GNSS technology can also contribute towards tackling socio-economic challenges by supporting environmentally friendly transport solutions, natural hazards disaster risk mitigation and response, sustainable agriculture, meteorological and climate monitoring, as a tool of the geosciences, and others.

A recent economic study by Ernst and Young (EY) has found that *improved PNT capability* for Australia and New Zealand through an SBAS technology is expected to deliver more than $6.2 billion in benefits for Australia, and more than $1.4 billion in benefits for New Zealand, over the next 30 years. General benefits of an operational SBAS include wider coverage, enhanced accuracy, signal integrity and reduced commercial costs and infrastructure investment.

ASSURED GNSS-PNT

Assured GNSS-PNT is in many respects a form of augmented GNSS. *Augmentation* refers to improvements at the system or user level that enables suitably equipped users to derive PNT information at the level of accuracy, availability, continuity and integrity appropriate for their application, and in general at higher levels than GNSS base-level specifications. *Assured PNT* protects the users, ensuring that trustworthy PNT information is available to critical user applications. The science and research community has a significant role to play in the coming years in enhancing GNSS performance, e.g., by contributing to the development of assured and resilient PNT systems.

The quest for high accuracy (e.g., over long periods of time) GNSS has been a long-term emphasis of the GNSS R&D community for supporting science and user PNT applications. For example, Geoscience Australia is able to utilise GNSS data measured from the *Continuous Operating Reference Stations* (CORS), to estimate the relative locations of points up to several thousand kilometres apart with an accuracy of several millimetres. Today, enhanced GNSS performance is required by demanding *safety-of-life and mission-critical applications*, such as those relating to deployment of fully automated and connected land vehicles. For these applications, high availability, continuity and reliability of services, in addition to high accuracy, are critical to ensure *safe and reliable navigation*. Hostile cyber operations such as *jamming*[12] and *spoofing*[13] of GNSS signals are a growing concern due to the serious disruption to society that they may cause. Developing PNT technology able to address other GNSS shortcomings, such as its unsuitability for providing PNT information in *indoor environments*, is an additional challenge.

GNSS PRIORITIES AND CHALLENGES FOR AUSTRALIA

GEOSCIENCE AUSTRALIA

Geoscience Australia (GA) is primarily responsible for the (civil) *Australian National GNSS infrastructure* to deliver augmented GNSS services. It will do this via several strategic initiatives:

- Deliver a SBAS capability to enable accurate positioning to the decimetre-level across Australia and New Zealand, and surrounding maritime regions, as well as improving the integrity of GNSS for civil aviation applications.
- Develop a robust, open, real-time national GNSS tracking network. This state-of-the-art ground infrastructure to track, verify and optimise data for high accuracy positioning (3–5cm accuracy) across the Australasian region of operations.
- Develop an open source software toolkit for the real-time analysis of space geodetic observations to, e.g., estimate precise satellite orbit and clock behaviour as well as other bias parameters.
- Deliver augmented GNSS correction message streams to enable real-time precise positioning across the Australasian region of operations.
- Continue to develop and maintain the Australian Geospatial Reference System (AGRS) – Australia's 3D coordinate system that underpins all spatial and mapping data.
- Contribute to the maintenance of the International Terrestrial Reference Frame (ITRF), through GA's extensive geodetic infrastructure: Australia's GNSS tracking network, Australia's Satellite Laser Ranging (SLR) network, and (in partnership with the University of Tasmania) Australia's Very Long Baseline Interferometry (VLBI) network.

SCIENCE PRIORITIES

Science underpins all GNSS technologies and applications. These range from fundamental physics (time, relativity, quantum technologies, electromagnetic propagation, surface reflections, etc), Earth observation, geoscience and space weather applications, through to space engineering, signal processing, hardware and software development, robotics and automated systems, consumer devices, etc.

Several science priorities arising from space-based PNT are listed below:

- Operationalising continuous, real-time, high fidelity Earth and climate change monitoring, and for geoscience research and activities in general.
- Generating an accurate record of the absolute and relative sea level in Australia as well as countries throughout the Pacific.
- Facilitating the use of GNSS receivers aboard satellites, in all orbits, and even on missions beyond Earth orbit, for so-called space service volume navigation.

- Continued development of GNSS receivers for CubeSats, to support more applications of small satellites for communications, Earth observation and PNT.
- GNSS meteorology can measure moisture, temperature and pressure using ground receiver networks and/or space systems for real-time monitoring of the atmosphere.
- GNSS reflectometry uses reflected GNSS signals from land, ice and water surfaces, tracked by modified ground or spaceborne GNSS receivers to measure soil moisture, surface wind speed and direction, detect ships and oil spills, and more.

ANSWERING FUNDAMENTAL UNRESOLVED EARTH SCIENCE QUESTIONS

Improvements in GNSS precise positioning techniques will enable a shift in geodetic science focus from observing secular steady state processes to observing dynamic time-varying transient processes. Delivering this capability to monitor the Earth's ever-changing shape on a second by second basis with millimetre accuracy make tractable a range of important questions such as:

- How are ice sheets, oceans, and the solid Earth coupled in space and time?
- How is the terrestrial storage and the global water cycle changing with time?
- How do fault mechanics and Earth rheology interact to influence the occurrence of earthquakes and the earthquake cycle?
- How do solid Earth's material properties vary in space and time?
- What can observations of surface deformation reveal about magmatic processes and volcanic hazard?
- What is the connection between solid Earth processes and surface and landscape evolution?
- What do real-time approaches promise for geohazard forecasting, warning, and rapid response?

NATIONAL PRIORITIES, CHALLENGES AND OPPORTUNITIES

Additional priorities, challenges and opportunities can be identified:

- Exploring unique opportunities offered by Australia's early deployment of next generation SBAS capabilities, such as Dual-Frequency Multi-Constellation (DFMC) and Precise Point Positioning (PPP).
- Delivering GNSS products that contribute to our understanding of the atmosphere for weather forecasting, climatological studies, and the behaviour of the ionosphere and space weather.
- Encouraging the adoption of GNSS-PNT capabilities that contribute to the UN SDGs.

- Monitoring of satellite navigation system performance across the Australian region for all users.
- Augmenting the GNSS space segment, e.g. using low earth-orbiting satellites.
- Developing products and services essential for ensuring assured PNT information for mission-critical and safety-critical PNT applications such as automated industrial machines, driverless vehicles, etc.
- Design and implementation of sub-metre (and even decimetre-level) accuracy GNSS systems based on low-cost mass-market GNSS receivers, enhanced via 5G telecommunications infrastructure delivering augmentation information for enhanced accuracy and integrity.
- Collaborating on national and international GNSS interoperability and compatibility of all GNSS signals and services, as well as industry, spectrum and geodetic standards, including continued engagement with international forums such as the UN's GGIM and ICG, ISO, ITU, RTCM, RTCA, and others.
- Developing an industry strategy to facilitate development of high-tech GNSS-related products and services by local companies and organisations.
- Investing in training and education so that Australia will have the workforce able to take advantage of the opportunities of assured PNT.
- Supporting GNSS-related research in universities and other research organisations, including translation of research into products and services.
- Encouraging research, development, and commercialisation of PNT technologies that complement GNSS. These include new inertia sensors, terrestrial ranging systems, vision and imaging sensors, signals-of-opportunity, and others.
- Embracing digital transformation to fuel innovation in a data-driven society. This innovation will be underpinned by technological advances in the areas of Artificial Intelligence, the Internet of Things, digital connectivity (such as 5G), cloud computing, data analytics, and access to PNT and geospatial information.

CONCERNS AND THREATS

CYBERSECURITY

Interference (intentional or otherwise) and *spoofing* of GNSS signals is a topic of growing concern, globally as well as in Australia. The denial of PNT (or provision of falsified PNT) information is a significant concern. If unmitigated, these threats have the potential to undermine societal use of PNT technology and impact dependent science activities[14]. Cybersecurity is therefore one of the most critical threats to GNSS-PNT availability, integrity and resilience. A number of strategies will need to be implemented in order to detect and mitigate sources of denial of GNSS-PNT capabilities. Some will be organisational, though many will be technical. The need to develop and incorporate safeguards into GNSS-PNT reliant infrastructure and services requires significant work.

Considerable work is underway, e.g., GA is liaising with ACMA, the Department of Home Affairs, Department of Defence and relevant security agencies on appropriate regulatory and enforcement responses.

RESILIENT PNT

Ensuring the resilience of critical infrastructure such as PNT to respond to emerging challenges and threats is critical challenge. *Resilient* PNT is the convergence of traditional PNT technology with non-traditional and emerging technology to improve the reliability, performance and safety of critical applications. Resilience offers assured PNT information by protecting, authenticating and offering alternatives sources to the dominant GNSS-PNT technology. There are currently some investigations underway regarding risks to infrastructure and supply chains.

It is acknowledged that reliance on GNSS alone for many applications (especially those in urban environments where buildings block GNSS signals and therefore significantly reduce PNT availability) is not possible. PNT will have to be provided by multi-sensor systems, requiring ongoing R&D as well as investment in 'testbeds' for promising non-GNSS technologies, e.g. Locata positioning technology. Furthermore DST has established the Science, Technology and Research (STaR) Shots program to focus strategic research and proactively develop new leap-ahead Defence capabilities. One of the strategic priority is explore the use of quantum technologies and demonstrate a prototype quantum-assured PNT system independent of GNSS. It is intended to address assured PNT requirements in all domains.

SOVEREIGNTY

The issue of *sovereignty* when using unencrypted broadcast GNSS signals from foreign-owned and operated satellite constellations is intrinsically tied up with the two issues mentioned earlier: GNSS vulnerability to interference and spoofing, and limits to GNSS availability in indoor or urban environments. Sovereignty is therefore is related to PNT resilience. Resilience can be increased when the PNT infrastructure (signals, message broadcast channels, etc) are under state control. Non-GNSS PNT technologies are ground-based technologies that are better able to be 'protected' than satellite systems. Furthermore they are not just complementary to GNSS (able to be used when GNSS is unavailable), but may also be alternatives to GNSS for PNT under certain scenarios. Hence addressing the challenge of indoor positioning (which is not possible using GNSS) so as to ensure a *seamless* transition from outdoor positioning using GNSS to indoor PNT will also increase PNT resilience and the degree of sovereign control.

RESEARCH, EDUCATION AND TRAINING

An insufficiently skilled workforce is a clear and present threat to PNT research, development, commercialisation and systems operation. Australia's critical space-based PNT infrastructure and systems relies heavily on access to a highly skilled and trained workforce. Without an increase in resources allocated to STEM education and training of the next generation PNT scientists and engineers, Australia runs the risk of limiting its ability to take full advantage of emerging opportunities being afforded by the rapid growth in PNT technology and its many downstream applications. Hence addressing the workforce challenges will go some way to addressing both the resilience and sovereignty issues mentioned above.

RECOMMENDATIONS

The WG proposes three recommendations.

RECOMMENDATION 1: PNT RESILIENCE

Australia's increasing reliance on PNT for critical applications will require increased resilience in associated infrastructure and services. It is therefore necessary to implement measures that build PNT resilience. These include: monitoring the performance of GNSS systems; protecting PNT infrastructure against cyber attacks; understanding the impact of PNT service denial on different user communities; and encouraging the development, testing and implementation of back-up or alternative PNT technologies, including those not based on GNSS. In seeking solutions, the defence and security agencies should cooperate with the civilian industry sectors and universities.

Insight	**Australia's increasing reliance on PNT in critical applications will require increased resilience in associated infrastructure and services. The research community has a significant role to play in improving PNT resilience.**
Aspiration	Australia has improved the security and resilience of our space-based PNT infrastructure to protect and ensure continuity of services to businesses, governments and the community at large.
Actions	**1.** Build resilient GNSS-PNT infrastructure able to detect and mitigate vulnerabilities such as signal interference and spoofing and cybersecurity attacks. **2.** Promote the development of alternative (non-GNSS) PNT technology. **3.** Invest in R&D in academia, government and industry. **4.** Promote the development and commercialisation of resilient PNT products and services.
Impacts	**1.** PNT that can be relied upon for safety-critical and mission-critical user applications. **2.** Impact of denial of PNT service (either intentionally or unintentionally) is minimised. **3.** Australian science, industry, and society in general, benefits from access to fit-for-purpose PNT information
Metrics	**1.** Minimum disruption of critical science and societal activities due to denial of access to assured PNT. **2.** Increased sales of Australian-developed PNT products and services. **3.** Increased skilled PNT educated workforce.

RECOMMENDATION 2: SOVEREIGNTY

The sovereignty of PNT infrastructure is an increasingly critical issue. Little of the PNT infrastructure is under the control of Australian entities. Addressing this weakness requires a multi-faceted response. The Australian SBAS is one of the few examples of GNSS infrastructure that is an exception to the above. Australia should support the development of PNT products and services (based on GNSS and non-GNSS PNT technologies). This would require strategies for, e.g., industry development; increased R&D by universities and other research organisations; improved cooperation between different agencies and industry sectors; as well as addressing some of the issues raised by Recommendation 1.

Insight	**The sovereignty of PNT infrastructure is an increasingly critical issue. PNT that is accurate enough available where needed, and trustworthy requires that all aspects of PN technology and services are able to be monitored, and ideally be under the control of an Australian entity (or entities).**
Aspiration	Australia will have improved sovereign access to PNT infrastructure and services through: **1.** Improved understanding of the impacts of PNT capability denial on all user sectors. **2.** More development and implementation of the fundamental GNSS technology is developed and/or implemented by Australian agencies. **3.** Development and deployment non-GNSS PNT products and services be developed, tested and deployed in 'hotspot' mode to support safety- and mission-critical applications.
Actions	**1.** Scrutinise the degree of vulnerability of scientific, industrial and personal PNT applications to disruption. **2.** Engage with the R&D communities (academic, government, industry) to develop more local PNT infrastructure, products and services. **3.** Monitor overseas developments in this area. **4.** Coordinate implementation of GNSS and non-GNSS technologies, products and services across states and industry sectors to ensure interoperability of PNT systems.
Impacts	**1.** PNT information can support safety-critical and mission-critical user applications. **2.** Impact of denial of PNT service (either intentionally or unintentionally) is minimised. **3.** Australian science, industry, and society in general, benefits from access to fit-for-purpose PNT information. **4.** Affordable, trustworthy, PNT information of a suitable quality and assurance is also available indoors.
Metrics	**1.** Increased levels of R&D across all PNT systems including increased focus on non-GNSS PNT. **2.** Growth in the Australian PNT industry. **3.** Increased value of Australian-produced PNT products and services. **4.** Increased sophistication of PNT use in critical environments (that are not easily serviced by GNSS, such as urban and indoors) through use of appropriate non-GNSS PNT systems.

RECOMMENDATION 3: WORKFORCE CAPACITY

An insufficiently skilled and trained Australian workforce is a threat to PNT research, development, commercialisation and system operation. Such a threat will prevent Australian companies and agencies from taking advantage of the many emerging opportunities being afforded by the rapid growth in PNT technologies and the many downstream applications. Furthermore, in order to address Recommendations 1 and 2, an integrated national space science PNT innovation and education strategy with co-partnership with government, universities and industry sectors will be required.

Insight	**An insufficiently skilled and trained Australian workforce is a threat to PNT research, development, commercialis ation and system operation.**
Aspiration	Australia has a highly skilled workforce of PNT scientists and engineers. Australia is able to take full advantage of emerging opportunitie s being afforded by the rapid growth in PNT technology, and its many downstrea m applications.
Actions	**1.** Ensuring STEM education and training of a PNT-literate workforce with the knowledge, skills, and creative problem-solving capabilities and digital literacy to meet the demands of the industry, government and academic sectors. **2.** Engaging with peak bodies to identify skill and capability gaps. **3.** Fundamental R&D in geodesy, space science, and spatial skills, and others. **4.** Equipping science graduates with new skills, e.g. in business, entrepreneurship, finance, law, etc. **5.** Enhancing collaborative partnerships strategies between government, universities and industry sectors to stimulate broader socio-economic growth. **6.** Supporting and promoting diversity and inclusive STEM education.
Impacts	**1.** A knowledge-based economy – Australia is able to capitalise on scientific discoveries, basic and applied research. **2.** A vibrant space-based R&D and PNT industry in Australia. **3.** Leveraging Australia's unique position to create new innovations in PNT products and services. **4.** Knowledge and technology transfer – Australia to be known as a key sector leader in PNT and space science in the region.
Metrics	**1.** Skills needs and gaps in PNT and space science are understood by policy makers, peak bodies and education providers; and addressed through targeted strategies. **2.** There is a long-term stable pipeline of investment in PNT research and education. **3.** Australians working in PNT R&D are equipped with relevant skills, knowledge and training to drive and thrive in Australia's PNT industries. **4.** Recruitment of home grown highly skilled and trained STEM workforce. **5.** An integrated national space science PNT innovation and education strategy with co-partnership with government, universities and industry sectors.

Space health and life sciences

June 2020

WORKING GROUP MEMBERS

Chair: Associate Professor Gordon Cable

Members:

- Associate Professor Jeff Ayton
- Professor Siobhan Banks
- Professor Michael Davis
- Dr Jason Dowling
- Dr Rob Grenfell
- Professor Julie Hides
- Dr Gillian Hirth
- Professor Steven Moore
- Associate Professor Ewen McPhee
- Karl Rodrigues

DISCLOSURES OF INTEREST

- Assoc Prof Gordon Cable AM: Clinical Associate Professor, School of Medicine, University of Adelaide; Member, Space Life Sciences Committee, Australasian Society of Aerospace Medicine; Senior Lecturer Aerospace Medicine, University of Tasmania Director of Medical Operations, Human Aerospace Pty Ltd. Head of Training, RAAF Institute of Aviation Medicine, Dept of Defence
- Assoc Prof Jeff Ayton: Chief Medical Officer, Australian Antarctic Division, Department of Agriculture, Water and the Environment, Australian Government. Director Centre for Antarctic, Remote and Maritime Medicine (CARMM); Adjunct Associate Professor University of Tasmania – College of Health and Medicine; Adjunct Associate Professor James Cook University – School of Public Health and Tropical Medicine; Chair, Rural and Remote Digital Innovation Group Australian College of Rural and Remote Medicine
- Assoc Prof Jason Dowling: Principal Research Scientist and Team Leader, CSIRO Health and Biosecurity; Adjunct Associate Professor, Faculty of Medicine (UNSW) Adjunct Associate Professor, School of Information Technology and Electrical Engineering (University of Queensland); Honorary Principal Fellow, Centre for Medical Radiation Physics (Wollongong University); Affiliate, Institute of Medical Physics (University of Sydney) Conjoint Lecturer (Mathematical and Physical Sciences) (University of Newcastle)

- Prof Siobhan Banks: Research Professor and Co-Director, Behaviour-Brain-Body Research Centre, University of South Australia; Adjunct Assistant Professor of Sleep in Psychiatry, University of Pennsylvania
- Prof Julie Hides: Deputy Head, School of Allied Health Sciences, Griffith University; Clinical Director, Mater Health Services Back Research Clinic, Brisbane; Adjunct Professor, Menzies Institute for Medical Research, University of Tasmania
- Prof Michael Davis AO: Adjunct Professor, University of South Australia; Trustee and Faculty Member, International Space University Director, SmartSat CRC Limited
- Prof Steven Moore: Deputy Dean for Research, Central Queensland University; Adjunct Professor of Neurology, Icahn School of Medicine at Mount Sinai, New York City
- Dr Rob Grenfell: Director, Health and Biosecurity, CSIRO; Director, Grenfell Health Consulting Pty Ltd
- Associate Professor Ewen McPhee: Associate Professor, University of Queensland; Board of Directors, Australian College of Rural and Remote Medicine; Clinical Project Lead, Australian Digital Health Agency; Chair, Telehealth Governance Committee to Queensland Health; Quality Assurance Examiner, RACGP; Aviation Medical Examiner, Civil Aviation Safety Authority; Sentinel GP, Central Highlands Health
- Dr Gillian Hirth: Chief Radiation Health Scientist and Deputy Chief Executive Officer, Australian Radiation Protection & Nuclear Safety Agency (ARPANSA); Chair, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR); Member, Committee 4 of the International Commission on Radiological Protection (ICRP)
- Karl Rodrigues: Executive Director for Engagement and Industry Growth, Australian Space Agency; Director, Adentia Group Pty Ltd

VISION STATEMENT

It is the year 2030. The last decade has seen a spectacular reinvigoration of human space exploration by Government space agencies, the likes of which has not been seen since the Apollo era of the 1960s. A sustainable human presence has been established in lunar orbit on the Gateway, an international collaboration which has now been operational and expanding progressively since the mid-2020s. Although not crewed continually, it provides a natural waypoint for missions to the lunar surface and a research platform that has served its purpose well as a proving ground for technologies that will see missions succeed even further into the solar system. Australian expertise in remote medical care and telemedicine has provided the technology for the modular medical bay aboard the Gateway which stands ready to provide care in the event of any emergency, a proud and uniquely Australian contribution to space exploration.

Since the Artemis 3 mission 6 years ago, when the first woman set foot on the moon in 2024, yearly lunar missions have become almost routine allowing the establishment of a permanent beachhead at the lunar south pole from which surface exploration of the Moon has been answering many questions about the origins of the inner solar system. A collaboration of Australian Universities and Industry have flown many life sciences experiments, not only to Gateway but down to the lunar surface under the umbrella of the Australian Virtual Institute for Space Health and Life Sciences.

Now at the beginning of a new decade preparations are in place for the departure of the greatest and most momentous exploration mission in human history – to Mars. For Australia it is momentous too. Our world leading medical training programs, in particular in remote and extreme environment medicine, have been combined with space medicine training and moulded into the training pathway of choice for international physician astronauts destined for deep space missions. Graduates have already set foot on the lunar surface, but now Australia is proudly providing our very own crew medical officer on the first human mission to Mars. Artemis 8 will transport the crew to the Gateway to board their transit vehicle in preparation for departure, and then for the duration of the three year mission, Australian flight surgeons and biomedical engineers in Adelaide Mission Control will work side by side with colleagues in other centres around the globe and international agencies to provide 24 hour networked medical monitoring and care for the intrepid crew.

Alongside supporting the Moon mission, Australian Space Life Sciences and Health capability has also accelerated the emerging Space Tourism market. Facilities and centres established to support the growing Asian demand for Space Tourism have created new business opportunities, international collaboration and significant medical solutions in pre-flight, in-flight and post-flight monitoring and treatment with immediate commercial opportunities in the health sector.

In 2030, the success of Australia in the field of space health and life sciences has been achieved only through the decade-old plan to establish Australia as a global leader in space life sciences by stimulating research, establishing infrastructure, fostering local and international collaboration and generating spin-off products and services. The vision to provide a uniquely Australian niche biomedical capability to international human space exploration programs has been achieved. Those innovations and technologies have served to improve public health throughout the 2020s, and have generated considerable economic benefits for Australia, not only in the commercialisation of research developments, but also through reducing the economic burden of disease by improving health outcomes, particularly in elderly, underserved, remote and indigenous populations. Interest in STEAM subjects has never been higher in Australia and that has been largely thanks to the ability of space research and human space exploration by Aussies to inspire and engage Australia's healthcare and scientific workforce, and young people at all stages of their education.

BACKGROUND ON TOPIC AREA

The human and biomedical sciences can and should be a key element of the future Australian Space Industry. There are three domains in which biomedical science is an important contributor. First, it is an enabler of human space flight, supporting commercial space tourism and future exploration missions. Australia's Government has committed funds to stimulate our industry to assist NASA and other international agencies with the Artemis and Moon to Mars Program, the missions that will return humans sustainably to the Moon in 2024, as a prelude to exploring Mars. Second, the scientific spin-off benefits that arise from human spaceflight programs will provide substantial economic and public health benefits to Australia through improved health care, the development of novel technologies by private industry, and stimulation of the academic and research sector. The emerging Space Tourism market may stimulate awareness of the health of humans in space, contributing to a demand for similar health monitoring and treatment technologies on Earth – initially customised to a high-net-worth clientele but with great ability to expand into a global mass market. Third, space is a unique microgravity laboratory that, independent of exploration programs, can be used to develop novel biomedical technologies which can be commercialised purely for the benefit of human health.

The advent of an Australian Space Agency has provided a much-needed organised framework and point of liaison to allow greater contribution by Australia to international research efforts. Australian researchers and clinicians have already been working in this field for some time (both at home and as expats working overseas for Space Agencies) and collaborating internationally, but independently, often unaware of programs being undertaken in other institutions elsewhere in Australia. Work has been undertaken by professional bodies and colleagues in the areas of space medicine education and in world leading provision of rural and remote medical care. Government organisations such as the Australian Antarctic Division have a strong track record of polar and extreme environment medicine research and collaboration with NASA in space analogue work. Multiple academic and clinical institutions around the country 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.

Key science questions come from existing human spaceflight programs and have been well defined. For example, NASA's Human Research Roadmap Integrated Path to Risk Reduction (HRR iPRR) is a top-level summary of some 230 knowledge gaps yet to be closed, which identifies 28 overarching risks with the long-term view of Mars exploration in mind. Table 1 lists the high-level and mid-level risks identified, and risks for which there is insufficient data to allow stratification.

Table 1. Risks Identified by NASA's Human Research Roadmap	
RISK LEVEL (Likelihood vs Consequence)	
High Level Risk	• Space radiation exposure and its relationship to cancer and degenerative diseases of the cardiovascular and central nervous systems • Cognitive and behavioural effects of spaceflight • Inadequate food and nutrition • Team performance decrements • Spaceflight Associated Neuro-Ocular Syndrome (SANS) • Renal stone formation • Human system interaction design • Long term storage and stability of medications • Inflight medical conditions
Mid-Level Risk	• Injury from dynamic loads • Injury from EVA operations • Hypobaric hypoxia • Decompression sickness • Altered immune responses • Host-microorganism interaction • Sensorimotor alterations • Reduced muscle mass and strength • Reduced aerobic capacity • Sleep loss and circadian misalignment • Orthostatic intolerance • Bone fractures • Cardiac rhythm problems
Insufficient Risk Data	• Intervertebral disc problems • Celestial dust exposure • Effects of medications in space

Previous reports[15], and indeed the research conducted for this strategic plan, indicate that Australia is already working to answer questions in many of these key areas. Capabilities will need to be developed or enhanced so that this work can continue and flourish. Importantly, deliberate and organised networking to increase connections domestically between researchers, and between researchers and industry will be key to this, as well as the establishment of international agency collaborations for training people and fostering research. Domestic capabilities may include things such as 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 has the potential to supplement existing Antarctic analogue research to enhance understanding of psycho-social and human factors aspects of the risks identified.

The potential benefits to the Australian community and economy from a well-established space life science capability within the Australian Space Industry are enormous in revenue terms. The economic benefits come not only from commercialization of innovative technologies but from the application of those technologies to improve population health outcomes. The areas of greatest benefit for Earth-based medicine in the short term are likely to come from bone density research for osteoporosis[16], exercise development and reconditioning for people with musculoskeletal conditions[17], sleep and circadian physiology research[18], neuro-vestibular research for falls prevention[19], miniaturization of medical diagnostics, sensors and technologies[20], telehealth and remote medicine training and support, psychological care for isolated populations[21], antimicrobials to combat increasing antibiotic resistance[22], space-hardened pharmaceuticals and increased efficiencies in agriculture.

AIM

The aim of this report is to provide a snapshot of Australia's current capabilities and resources in space life sciences and identify new opportunities and potential innovations for the coming decade mapped against priorities and key questions that international space agencies must address to achieve success in the human exploration of space.

METHODOLOGY

Wide-ranging engagement with stakeholders from the space life sciences sector was sought by all members of the Space Health and Life Sciences Working Group. Using existing professional networks and snowball sampling techniques, respondents were invited by email to complete an online questionnaire. Face to face engagement was also employed during the Australian Space Research Conference in 2019 to provide information about the decadal planning process and invite participation in the survey. The survey requested demographic information regarding respondent's current professional positions. Previous, current and future planned work that may be relevant to space life sciences was explored together with any international space agency collaborations.

Respondents were asked to identify Australia's niche capabilities in the field, and what might lead to the greatest benefits for human health generally ('impacts'). Their opinions were sought on key issues/challenges/gaps ('insight'), what should be achieved in the next decade to address these ('aspiration'), actions required to obtain these achievements, and what metrics could be used to measure success. Finally, respondents were asked to indicate from a list of key knowledge gaps identified by NASA's HRR, where they felt their work might contribute to closing those gaps, checking as many as required.

Demographic information was summarised, and qualitative responses were assessed using thematic analysis and then tabulated using Microsoft Excel software.

RESULTS

N=50 respondents completed the online survey. Two respondents were excluded from the analysis: one who responded twice to the same survey, and the other who did not provide serious responses to the questions. This left a final sample of N=48 on which the analysis was conducted.

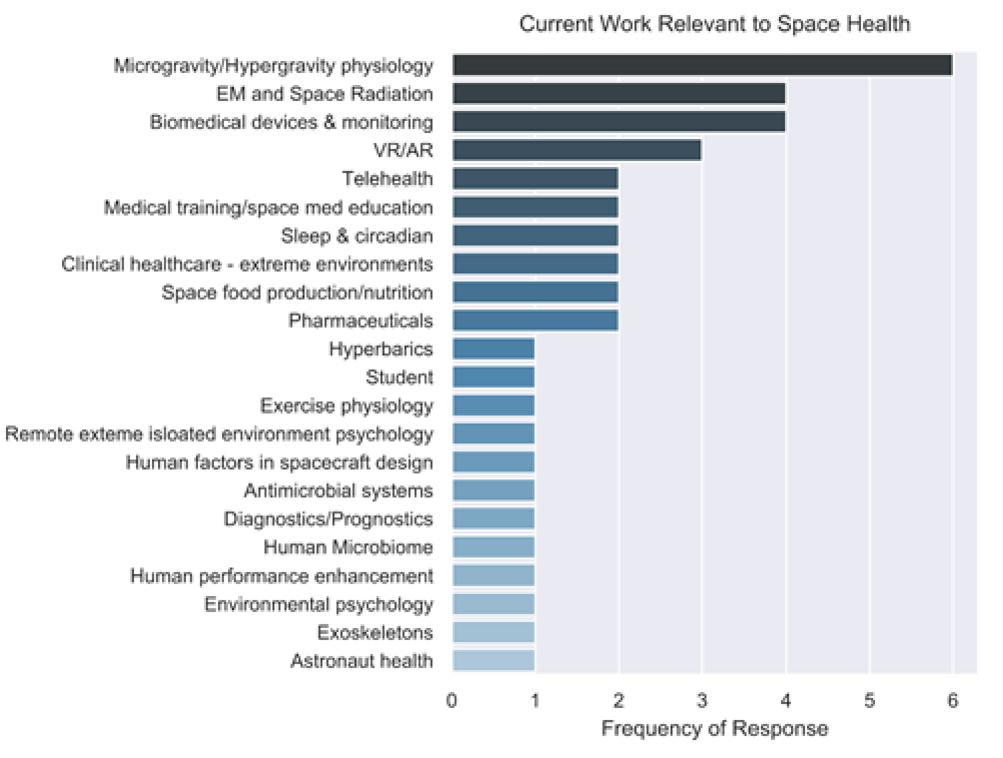
Respondents came from a broad range of scientific disciplines summarized in Table 2, with 51% working in academia, 17% in clinical roles, 12% in each of Government and professional organisations, and 8% from industry.

Table 2: Disciplines represented among respondents

Clinical Medicine	Sciences	Allied Health	Engineering
Aerospace medicine	Astrophysics	Psychology	Aerospace
Space medicine	Zoology	Physiotherapy	Engineering
Hyperbaric medicine	Flow chemistry	Nutrition Telehealth	Habitat design
Family medicine	Space biology	Technology	Biotechnology
Emergency medicine	Microbiology	Health education	
Rural /remote medicine	Physiology – exercise	Human factors	
Public Health	Physiology – vascular	Biomechanics	
Anaesthesia	Medical physics	Biosecurity	
Psychiatry	Archaeology		
Immunology	Physics		
Health and medicine	Physiology – comparative		
Radiation oncology	Biochemistry		
Bioastronautics	Neuroscience		
	Nuclear and radiation science		
	Computer science		
	Mathematics		
	Chemistry		

Work currently being undertaken by respondents relevant to space health, life sciences and human spaceflight was most commonly reported as gravitational physiology, electromagnetic and space radiation, biomedical devices and monitoring, and virtual/augmented reality devices. The range of current work is summarized in **Figure 1**. Seventy-seven percent of respondents reported current or previous collaborations with international space agencies, most commonly NASA (30%), ESA (21%) and DLR (12%). Only 23% of respondents reported previously commercializing SHLS research developments that could benefit the health of human populations, however 56% planned to do that in the future.

Figure 1. Current work being undertaken by respondents.



The responses to 5 key questions listed below, posed by the Australian Academy of Science, are summarized in Table 3. Summary of key issues/ challenges/gaps ('insight'), what should be achieved in the next decade to address these ('aspiration'), actions required to obtain these achievements, impacts, and measures of success.

- Can you provide **insights** into the current main issues, challenges and knowledge gaps in space medicine and life sciences?
- What capabilities and achievements should Australia **aspire** to develop in space health and life sciences over the next 10 years?
- What are the **actions** required to obtain these capabilities and achievements?
- In what area do you think developments in space life sciences and health could have beneficial **impact** on the health of the Australian population?
- What **metrics** could we use to quantify the success of space health and life sciences programs?

Table 3. Summary of key issues/challenges/gaps ('insight'), what should be achieved in the next decade to address these ('aspiration'), actions required to obtain these achievements, impacts, and measures of success	
Insight	**Radiation beyond the Earth's magnetosphere**
Aspiration	Increased research capacity into the effects of space radiation, with facilities and infrastructure to support research into biological effects, monitoring and countermeasures. Provides monitoring and countermeasures to future missions.
Actions	Australian radiation research laboratories conducting radiobiological research for space application. Foster collaboration between researchers and disciplines.
Impacts	Understanding radiation effects on cardiovascular and neurodegenerative diseases Improved nuclear medicine techniques Protection of radiation workers and protection of astronauts.
Metrics	Academic outputs Technologies and techniques translated to healthcare Research grants approved Experiments flown to space.
Insight	**Problems of altered gravity**
Aspiration	Microgravity & hypergravity research, and development of countermeasures
Actions	Collaboration with international researchers. Establish dedicated research facilities, programs and infrastructure to address these important priorities. Private industry to be encouraged to establish infrastructure in collaboration with Government and universities
Impacts	Microgravity mimics the process of ageing. Deeper understanding of diseases of the musculoskeletal system, cardiovascular system, and neuro-vestibular system in space will aid in the treatment of patients on Earth.
Metrics	Number of experiments flown. Reduced costs to the national economy
Insight	**On-board medical systems and telemedicine for Earth-independent operations.**
Aspiration	Operational capabilities derived from expertise in remote and extreme environment medicine and telehealth used to support Moon to Mars missions.

Table 3 (continued)	
Actions	Development of new medical devices, biomonitoring, robotics, AI, big data management, communications, and telehealth strategies. Miniaturization of diagnostics.
Impacts	Better management and improved healthcare of isolated and remote communities, and better healthcare delivery systems through the application of space technology, saving time, transfer to tertiary centres, support for isolated practitioners.
Metrics	Improved burden of disease statistics in rural and remote areas Reduced patient transfers to tertiary referral centres, transportation costs, patient-days in city hospitals. Australian technology chosen to fly operationally to space. Positive astronaut health outcomes.
Insight	**Collaboration between disciplines and the translation of research into useful applications**
Aspiration	Developing partnerships and opportunities, and integration with global experts, through an Australian Virtual Institute for Space Life Sciences as a national centre of excellence.
Actions	Establish an Australian centre of excellence in the form of a Virtual Institute to provide a focal point and leadership for interdisciplinary collaboration among Australian institutions
Impacts	A streamlined approach to facilitate access to international and domestic collaborators and funding sources specifically for the life sciences
Metrics	International investment and numbers of collaborations Successfully commercialized outputs
Insight	**The physiology and psychology of isolation and confinement, including circadian disruption and immune dysregulation**
Aspiration	Space analogue research capabilities and simulated environments – underwater, desert. Providing deeper understanding of immunology, microbiology and the microbiome, and behaviours/psychological impact of isolated/confined environments.
Actions	Link a consortium of Australian universities, Mars Society of Australia and Government agencies with international analogue programs to establish an enduring desert analogue research facility. Collaboration with NASA on NEEMO program. Promote expertise at AAD as world-leading in the field, increased outreach to international agencies for collaborative research in Antarctica.

Table 3 (continued)	
Impacts	Improved mental health outcomes for isolated populations. Novel treatments for autoimmune diseases, infectious diseases, sleep disorders, and circadian dysrhythmia. Improved performance of teams in the workplace, improved productivity and decreased healthcare costs.
Metrics	Number of experiments flown. Reduced costs to the national economy, disease prevalence, disease burden and numbers of patient-days in hospital over the next 10 years compared to current estimates.

Insight	**Funding for research and development**
Aspiration	Clear mandate for research
Actions	Ongoing Aust Space Agency support for research and industry, dedicated research funding streams/grants allocated for space life science research, space medicine star-ups
Impacts	An increase of Australian based research and translation
Metrics	Academic outputs Dollar amount of funding and grants secured for research Number of jobs created in the sector. Numbers of researchers in relevant fields.

Insight	**Suborbital flights for commercial tourism operations will become commonplace, yet there is limited experience with the physiological impacts of these flights on humans.**
Aspiration	Australia is likely to become a popular destination for suborbital launches due to favourable geography and geopolitical stability.
Actions	Collaboration with international agencies and commercial companies, Australian Space Agency support and facilitation infrastructure for micro- and hypergravity research, funding of dedicated research programs.
Impacts	Increased public interest in health technologies derived for high profile space operations. Appropriate regulatory approach and health/safety standards for commercial space passengers in Australia. Contribution to safety of operations internationally
Metrics	Growth in commercial space flight sector, flight safety, incident and accident statistics, and adverse in-flight medical episodes and injuries. Commercialised products spun off to the broader aerospace and health industry.

Table 3 (continued)	
Insight	**Life support systems and habitats to support long duration missions, including hypobaric environments, spacesuit design, and appropriate nutrition.**
Aspiration	IVA/EVA suit development leveraging off existing work. Using ag-tech and food science capabilities to develop sustainable nutrition and pharmaceutical sources suitable for space.
Actions	Newly established Civilian hypobaric/hyperbaric facility supported to establish research programs in collaboration with international agencies. CSIRO and UTAS/ADF nutrition laboratories establish research programs in space nutrition.
Impacts	Environmental engineering systems improving life on Earth, in particular for rural/remote communities, isolated populations through waste management, recycling, water purification and treatment bioregenerative systems, air filtration, toxin monitoring and biosecurity/infection risk. Agriculture and food production in austere/arid environments addressing global food shortages and hunger.
Metrics	Successful validation in terrestrial analogues, patents awarded and publications International partnerships Development of space nutrition laboratories Successful translation of technologies to long duration missions, lunar and Martian environments.
Insight	**Maintaining astronaut health and clinical management on long**
Aspiration	Development of space medicine expertise and space medicine
Actions	Foster international training opportunities and exchange programs
Impacts	Longer shelf life and more effective pharmaceuticals
Metrics	Number of graduates in STEM disciplines relevant to life sciences
Insight	**Australian citizens in space, while historically difficult to achieve and not prioritized, is becoming increasingly likely with commercial space and the democratization of space.**
Aspiration	Foster Australian astronaut contribution to international agency or commercial missions.
Actions	MoUs with international space agencies or commercial organizations. Sovereign space medicine capability for astronaut selection and training. Extreme and space medicine training program for physicians.

Table 3 (continued)	
Impacts	National pride inspiration for STEM study and research, sovereign capability. Australian research conducted by Australians. Niche expertise such as medical generalists provided to space programs as skilled astronaut physicians.
Metrics	Missions flown. Increased effective Australian remote and extreme generalist healthcare professionals.

Niche capabilities that respondents believed Australia could contribute to human spaceflight programs over the next decade are illustrated in **Figure 2**. Australia's expertise in rural and remote healthcare and telemedicine were commonly reported to be a niche strength.

Figure 2. Australia's niche capabilities.

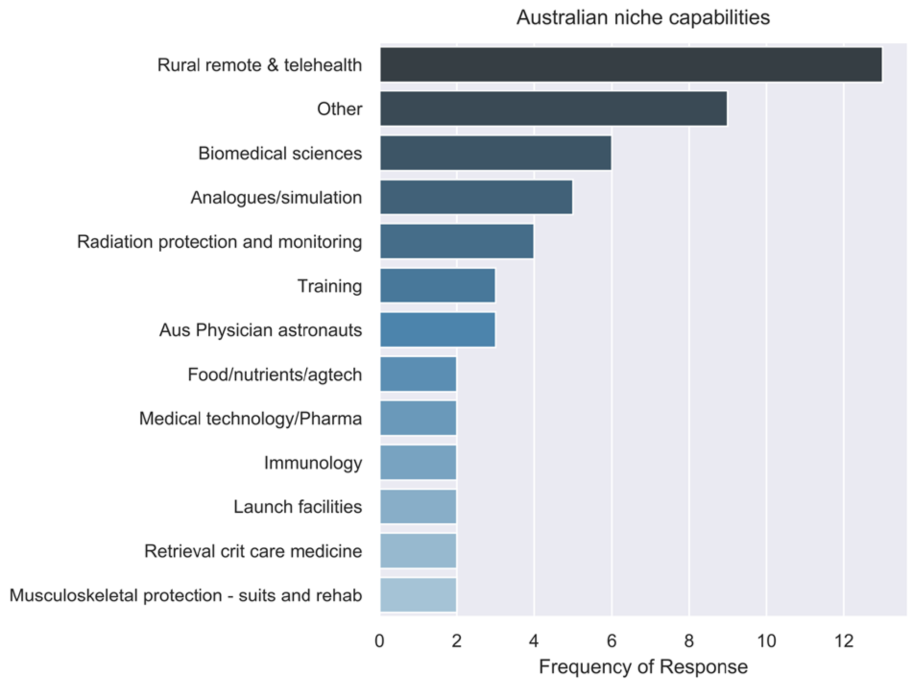
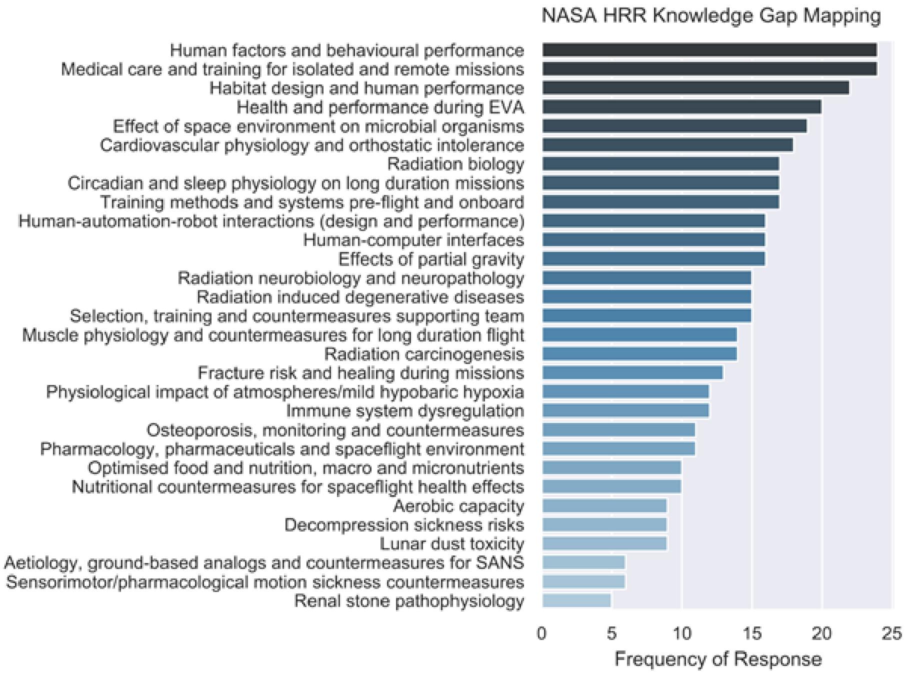


Figure 3 depicts graphically the number of respondents who identified that their current work may be relevant to key NASA Human Research Roadmap knowledge gaps. Respondents were asked to select as many as applicable. It is evident that Australian expertise covers the entire gamut of key research questions considered important for human space missions. In particular there seems to be an abundance of work that may contribute to knowledge of Human Factors and Behavioural Performance. Australia's unique experience with remote environments – from isolated communities in rural areas to isolated extreme environments in Antarctica – was also evident in the responses, with training of physicians and provision of medical care on exploration missions commonly identified.

Figure 3. Mapping of respondent expertise to NASA HRR knowledge gaps.



RECOMMENDATIONS

Prioritize funding for health and life sciences – a common theme and clear message from the survey, recognising that returns on this investment in terms of the jobs created and the reduced economic impact of disease in the population are likely to be substantial.

Establish a Virtual Institute of Space Health and Life Sciences fostering domestic and global multidisciplinary research collaboration, ensuring maximum effective translation of research from space for the benefit of the Australian community. Additional roles include developing human mission and astronaut health support through provision of clinical space medicine. Working side by side with the ASA, it provides a point of liaison and coordination with the biomedical community and international agencies.

Foster education and training, through the establishment of international exchange programs, tertiary and postgraduate courses, and astronaut physician training. The survey showed that an Australian astronaut with these niche skills contributing to human missions would inspire and galvanise the nation behind the space program.

Prioritize and grow research in the areas of:

- **Radiation**, where a significant body of expertise already exists. This capability should be leveraged 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**, 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.

Leverage existing expertise in delivery of healthcare and training for **remote/extreme environments** to provide medical systems and clinical support to exploration missions. Research and development to support these techniques for space will improve the lives of rural, remote and indigenous Australians.

Develop leapfrog telemedicine technologies, for imaging, patient monitoring and AI diagnostics, with capabilities for clear transmission and analysis of big data for space mission health care, and 21st century healthcare of isolated patients on Earth.

Establish a **desert analogue research facility,** leveraging an extensive body of work done to date, and capitalising on opportunities presented by international programs (such as AMADEE). Analogue environments exploring the physiology and psychology of isolation and confinement, human factors and psycho-social risks, are key NASA knowledge gap areas with many of our researchers already involved. It was identified by respondents as an important Australian contribution over the next decade and identified as a niche strength.

CASE STUDIES

CASE STUDY 1

Musculoskeletal conditions were the leading cause of non-fatal disease burden in Australia in 2015, representing 25% of cases[17] The following case study demonstrates how translation of research from space medicine can significantly improve the economic and social impact of such diseases.

Benefits of Space Medicine Research for Terrestrial Applications in Rehabilitation

Research on astronauts can benefit patients with conditions affecting the neuromusculoskeletal system and vice versa, as both face the challenge of managing the effects of disuse. Deconditioning in astronauts after spaceflight is a useful model for studying interventions for optimal recovery, as changes occur relatively rapidly and without the complication of underlying pathology seen in musculoskeletal and neurological disorders, where the effects of disuse are difficult to isolate. Physical inactivity is a major problem in the general population, despite the well-known benefits of exercise, causing public health and economic concerns in Australia and worldwide.

The effects of microgravity on the cardiovascular, musculoskeletal and neuro-vestibular systems are well documented. Changes in the neuro-musculoskeletal system include bone loss, muscle weakness (particularly postural muscles), reduced muscle mass, impaired motor control and balance and increased risk of lumbar disc pathology. As space missions will involve excursions on planetary surfaces, such as on Mars, challenges to the human body and requirements for effective postflight reconditioning need to be better understood by learning from existing knowledge and further research. For future exploration class missions to other planets, an additional phase of postflight reconditioning will be required following deep space cruise to the destination, to enable safe and effective exploration on a planet's surface. Effective and safe performance during surface planetary excursions on Mars following long duration flights at 0G will require preparation through specific functional exercise programmes on board prior to landing. Optimal reconditioning and preconditioning programmes for long duration missions have yet to be established.

There are three phases of mission cycles requiring the care of a multi-disciplinary medical team: preflight, inflight and postflight. The medical team includes specialists in medicine (flight surgeons), psychology, biomedical engineering, nutrition, physiotherapy and sports science. Implications for rehabilitation of the terrestrial population can be gained from these programs. Drawing on similarities with conditions seen in terrestrial populations may help inform postflight reconditioning, e.g. low back pain, where the distribution of trunk muscle atrophy is similar to that in microgravity.

Comparisons have been drawn between the effects of microgravity and ageing, but the greater challenges ahead resulting from longer missions and new environments may benefit from drawing on the challenges and rehabilitation strategies in other terrestrial clinical conditions involving deconditioning, such as neurological conditions and critically ill patients in intensive care. At the other end of the spectrum, reconditioning of astronauts may benefit from adopting physical and psychological strategies for achieving optimal performance in athletes in elite sports. Measures such as astronaut-specific performance testing and movement quality, and motor control strategies to improve these aspects of function, may be of value but require further research.

In summary, translation of knowledge from spaceflight research and practice has implications for several areas of rehabilitation. Insights into space medicine will have more direct relevance, and even become a necessity for some terrestrial clinicians, as space tourism is set to become a reality.

CASE STUDY 2

Antarctica as a Space Analogue

The Scientific Committee on Antarctic Research (SCAR) 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. The use of the Antarctic as a space analogue for human research has been of interest to the international polar medicine community for some time.

Australia's Antarctic Program uses 'Life in a Freezer' to offer a hi-fidelity space analogue for Operational Medicine, Training and Research for 'ICE' environments – Isolated, Confined and Extreme.

Isolated: It can be up to 9 months (March–November) without access to evacuation in the event of an emergency. In addition, there is limited sophistication of medical support.

Confined: small populations of 16–25 expeditioners live together in shared habitats over winter.

Extreme environment hazards: Antarctic cold and wind, psychological stressors, 24 hours of polar night, terrain. These hazards are just as life threatening as those found in space and on other celestial bodies.

This challenging environment provides an analogue platform that has enabled Australian research in physiology, epidemiology, behavioural Health and psychology, and photobiology. It has provided clinical and operational medicine and training for extreme environment, and advanced telehealth and other technologies for training and clinical support of isolated populations.

Space situational awareness and space weather

June 2020

WORKING GROUP MEMBERS

Chair: Dr Melrose Brown

Members:

- Travis Bessel
- Dr Brett Carter
- Joshua Fitzmaurice
- Dr Doris Grosse
- Samantha Lemay
- Dr Dave Neudegg
- Dr Murray Parkinson
- Dr Mark Rutten

DISCLOSURES OF INTEREST

- Dr Melrose Brown: funding from RAAF and AOARD
- Samantha Lemay and Brett Carter: RMIT
- Doris Grosse: Advanced Instrumentation and Technology Centre, ANU
- Mark Rutten: CEO Intrack Solutions
- Travis Bessel and Dave Neudegg: DST Group
- Murray Parkinson: Consultancy & development manager, BoM Space Weather Service
- Joshua Fitzmaurice: Surveillance of Space, RAAF

CONTEXT

By 2030 there will be at least ten times more satellites in orbit than in 2020. In order to ensure access to and use of a safe, secure, and sustainable space environment Australia requires a tightly integrated and sovereign Space Situational Awareness (SSA) and space weather capability across the defence, civil, and commercial space sectors. The burgeoning growth of commercial space-based activity, the emergence of on-orbit servicing and autonomous maneuvering of satellites, new capabilities for crewed space missions, and the emergence of new nation states into the space sector, mark step changes in how space is utilized, what it is utilized for, and who will be in control of space assets. While much of the emerging national space industry is based on the 'Space 2.0' paradigm using CubeSats, these have much lower resilience than larger more expensive spacecraft. Furthermore, the Space 2.0 paradigm has arisen in a very quiet space weather environment compared with the earlier space age. All spacecraft and space-reliant services are at risk from space debris and space weather, while critical infrastructure such as electricity distribution grids and long pipelines are also at risk from space weather effects. Australia is already an international leader in space weather science and prediction. By exploiting our geographical extent and growing our space science and SSA capability Australia can become a medium to major player in managing the global commons of space while securing strategic access to and use of space.

VISION STATEMENT

By 2030 a vibrant space situational awareness (SSA), Space Traffic Management (STM), Space Domain Awareness (SDA), and Space Weather community has been established to support the rapid increase in Australian space activity, fueled by a sustainable collaboration between academia, SMEs, primes, defence, and government organisations. At its core is a highly connected and collaborative community of researchers that comprise the vault of long term SSA and Space Weather knowledge and experience within Australia.

The community structure has succeeded in rapidly training students and researchers from adjacent fields to transition their skills into the SSA and Space Weather domain. Leveraging its geographic, geopolitical, scientific and technical advantages, Australia provides global leadership in SSA and Space Weather research, through:

1. Detection, tracking, correlation, and prediction of orbits for objects 1cm in size and larger as input to a new cooperative global space catalogue
2. Accurate characterization and change detection for objects in all Earth orbit regimes via a tightly integrated network of novel SSA sensors and algorithms
3. Fundamental and applied science on space environment interactions with ground and space assets to build resilience for communications, precision navigation and timing, satellite orbit uncertainty, over the horizon radar, and damage to critical satellite systems from Space Weather effects
4. Up to 72hr high fidelity predictions of key space weather events
5. A regular cadence of experimental SSA and Space Science spacecraft missions to generate benchmark quality truth data to verify and validate ground-based sensors, data processing, modeling and simulation tools. These missions will provide a low-risk pathway for the development of operational Space-Based Space Surveillance and Space Weather payloads, and will support international strategic alliances.

BACKGROUND

Currently around 2,700 active satellites are currently in operation around Earth. The small satellite (<500kg) market will grow this figure by approximately an order of magnitude, with over 16,000 small satellites expected to launch into Low Earth Orbit between 2020–2030 (Frost and Sullivan, 2017). Approximately 70% of those launched will be under 250kg and the majority of these satellites will belong to constellations owned by about 30 companies.

Commercially owned satellites in 2020 comprise 54% of all active satellites reported on orbit (UCS 2020), leading the US Department of Defense to actively devolve responsibility for space traffic management (STM) to a civilian/commercial role within the US Department of Commerce. Australia is identified as a crucial partner to contribute to both the commercial and military SSA/STM/SDA system owing to its geographical location, large landmass, clear skies, and growing sovereign SSA expertise.

Legacy SSA/STM/SDA approaches are unable to keep pace with emerging space technology and space utilisation. In addition to the vast increase in the number of objects to catalogue in the coming years, technology such as the Starlink constellation of 12,000 small satellites that feature continuous low-thrust electric propulsion will defeat traditional orbit determination algorithms. New ideas and systems are therefore required to permit safe and secure operations within the space domain of the future.

Knowledge of the space debris population will undergo significant evolution in the coming decade. New sensors offer the potential to detect a larger portion of the 500,000–750,000 pieces of space debris over 1cm in size that are estimated to already exist in orbit today (ESA). Extensive research and development is required to transform these raw detections into accurately catalogued Resident Space Objects (RSO) from which precise and actionable conjunction analyses can be derived.

Change detection in orbit, attitude, and communication behaviour is a key capability to predict on-orbit risk to civilian and defence space assets from space weather, debris, and/or intentional (cyber) attack.

Understanding, monitoring, and forecasting space weather is a central component to achieve this goal. The effect of thermospheric density, causing satellite drag, is well known as the biggest contributor to orbit uncertainty in LEO. Ionospheric disturbances can disrupt communications and passive RF sensor performance. High-energy particles and Electrostatic Discharge from lower energy particles in LEO can disrupt or destroy spacecraft subsystems. Interactions between the space environment have been cited as a potential cause for high area-to-mass ratio debris from the GEO graveyard orbit to re-enter the GEO belt.

The defence research community in the USA via DARPA is actively seeking to enhance the forecasting and monitoring capability of mid to small-scale travelling ionospheric disturbances in Earth's upper atmosphere to improve Space Domain Awareness in support of military operations. Australia hosts impressive ground based sensors and world-class expertise to enable the development of such capability. However, to date, there is no rigorous means to attribute spacecraft anomalies to space weather events.

Extensive capability exists within Australia, including: world-class monolithic and distributed sensors spanning optical, passive and active

RF, radar, infrared, and laser ranging; astrodynamics; space physics/ weather modelling and monitoring; AI and machine learning; and spectrum monitoring. Much of the excellence that exists today did not exist in 2010. We should expect and encourage new capability to emerge within the next decade. A finite window of opportunity is now open for Australia to emerge as a global leader in space domain awareness (of which space weather is a crucial part) and make a lasting contribution to a safe, secure, and sustainable space environment for the benefit of society.

Surveillance and intelligence data collection, analysis and dissemination, specifically involving over-the-horizon radar systems and space situational awareness systems, is a Sovereign Industrial Capability Priority identified in the 2018 Defence Industrial Capability Plan.

THE PATH AHEAD

Insight	**Community: Diverse pockets of excellence exist throughout Australia in key science, technology, and research areas that can fuel a tightly integrated SDA and Space Weather capability to support Australia's civilian, defence, and commercial space activities. Opportunities to exploit our human capital are lost due to a lack of coordination, common goals, and defined direction to focus effort and resources.**
Aspiration	A community of SDA and Space Weather professionals shall form to drive innovations in sensor development, analysis, forecasting, fundamental science, and long term scenario planning. Coordination and alignment of focus areas ensures that the pressing global SDA and Space Weather challenges are tackled holistically and that the systems required to integrate data, algorithms, and approaches are created.
Actions	• Connect and coordinate the community to attract significant funding for Australian SSA, STM, SDA and Space Weather research excellence • Up-skill the Australian SDA and Space Weather community through targeted training and education opportunities to fill key knowledge and skills gaps • Create new opportunities for SSA, STM, SDA and Space Weather careers in Australia within academia, industry, civilian, and defence
Impacts	• Improved funding opportunities for the Australian SSA and Space Weather community • Greater retention of knowledge and skills following the closeout of major SSA and Space Weather research projects • Support development of Defence workforce and sovereign capability priorities • International recognition for our knowledge, skills, and human capital • Better space policy, more commercial opportunities, and greater strategic benefit derived for Australia from space utilization • Contribution to global committees, technical working groups, and decision making bodies on SSA, STM, SDA, and Space Weather

Metrics	• Levels of funding • Number of PhD students graduated • Number of students enrolled in SSA/SDA related courses • Number of SSA/SDA/STM related jobs filled by Australians • Citations and the use of our research by others • Participation and exhibiting at national and international conferences • Hosting conferences, workshops, events and national challenges • Number and size of collaborative grants between academia, industry, government, and/or defence • Degree of international collaboration with key organisations (NASA, ESA, UK Space Agency, major research laboratories, leading industry players, and defence organistaions)

Insight	**Measuring, understanding and characterisng the space catalogue: Securing the safety of Australia's current and future activity in space requires monitoring of satellites and debris. Persistent, accurate, and timely monitoring of all objects >10cm in Earth's orbit with a revisit time of <1hr and the pursuit of technology that can reveal the population of objects between 1–10cm is critical to mitigating the risk of on-orbit collision.**
Aspiration	Australia shall develop a diverse and resilient network of sensors that exploit our geographical advantage in location, large landmass, and clear skies. Enhanced sensor persistence, accuracy, and coverage of the resident space object population shall provide input to advanced modelling and simulation tools that provide Australian SDA analysts with world leading expertise to understand, protect, and profit from the space domain for Australia's benefit.
Actions	• Support and grow our existing world class sensor capability to improve accuracy, persistence, custody and resilience for space surveillance activity • Create a curated pool of diverse and accessible sensor data and information to fuel R&D into new analysis, modelling, and simulation techniques to describe, characterise, and catalogue objects in orbit • Develop dedicated satellite missions to calibrate, benchmark, and accelerate Australian SSA/SDA and Space Weather capability
Impacts	• Australia becomes a trusted provider of high quality operational SSA data and analysis services • Australia makes a substantial and sustained contribution to the global effort to track all objects in orbit
Metrics	• High TRL sensors and systems • Number of objects maintained in the catalogue • Revisit/update rate on the catalogue • Number of new sensors and sensor networks created

Insight	**Monitoring and forecasting the impact from space weather: Space weather threatens the operation and performance of critical space and ground infrastructure. Distinguishing between space weather effects and intentional interference is severely restricted due to a lack of forecasting ability, resolution/ accuracy, and fundamental knowledge into how space weather physically interacts with our systems.**
Aspiration	A world leading space weather forecasting system is developed to mitigate and attribute impacts from space weather on space and ground systems, space object motion, and effects on humans up to 72hrs in advance.
Actions	• Accurately forecast particle densities and medium to small scale disturbances in the thermosphere/ionosphere/magnetosphere system up to 72hrs in advance • Accurately forecast the radiation environment impacting satellite operations in LEO, MEO, HEO, GEO, and cislunar regimes 72hrs in advance • Develop dedicated small satellite research missions to monitor the near-Earth space environment
Impacts	• Extended mission life of on-orbit satellites • Reduced uncertainty in orbital predictions • Increased resilience of ground and space-based infrastructure, including critical infrastructure, to deleterious space weather events • Greater awareness of the threats from space weather within government and the public sphere
Metrics	• Fewer disruptions to satellite services • More accurate forecasts of space weather • Higher spatial and temporal resolution for space environment monitoring • Increased number of space weather products used operationally

Insight	**Assessment and Attribution: SSA and Space Weather data only becomes valuable when it informs action. Understanding the underlying cause or predicting the future consequences arising from those data is central to the safe, secure, and sustainable use of space.**
Aspiration	Australia shall have the capability to perform its own high fidelity threat assessments to ensure safety of all its on-orbit assets on short, medium and long-term time frames.
Actions	• Fundamental research into the physical effects and impact of space weather on sensors, spacecraft, orbits, and ground infrastructure across all space weather scenarios • Develop systems that can discriminate and attribute changes in space object behaviour to natural or human sources in real time to enable actionable threat assessment • Provide long term modelling to assess the impact from changes in global space utilisation, technology, and policy

Impacts	• World leaders in spacecraft/space environment research • Improved safety and reliability for on-orbit, ground, and human space systems • Australian-led global space policy and guideline initiatives
Metrics	• Accuracy of predictions • Fewer false positive collision warnings in Low Earth Orbit • Number of Australian space norms and practices adopted globally • Improved compliance with national and international space policy

Insight	**SSA Market Opportunities: The US Department of Commerce has been charged with taking on the civilian Space Traffic Management mission. Global and commercial partnerships are central to their approach and Australia is in a prime position to offer services into the new commercial SSA, STM, and SDA system**
Aspiration	Australia will develop a range of products spanning sensors, data processing, fusion, and analytics to capitalize on the commercial opportunities arising from the DoC shift to a commercial space traffic management system.
Actions	• Demonstrate Australian SSA and Space Weather capability and utility in operationally challenging environments • Streamline transition from low TRL within research institutions to high TRL within industry and defence
Impacts	• A sustained and profitable SSA/SDA/Space Weather sector • New job opportunities in SSA products and services
Metrics	• Value of the Australian SSA commercial sector • Number and diversity of Australian SSA products and services

Insight	**Beyond Near-Earth Space: Australia has the expertise and emerging sensor capability to offer unique SDA and Space Weather support for the upcoming NASA Artemis program to the Moon and beyond**
Aspiration	Australia will apply its world-leading Near Earth Object (NEO) sensor research and space weather forecasting expertise to become world leaders in deep space and Lunar space domain awareness in 2020–2030 to support crewed and autonomous missions.
Actions	• Advance the state of the art for detecting, tracking, and predicting the behaviour of bodies in Lunar and cislunar orbits • Develop strong international partnerships to grow and apply our deep space and lunar SSA and space weather capability
Impacts	• Secures safe transit between Earth, the Moon and beyond • Preserves the unspoilt orbits of the Moon and other planets • Secures niche capability
Metrics	• Strong Australian participation in NASA Artemis • Number and persistence of monitoring of objects in lunar and cis-lunar orbits

RECOMMENDATIONS

1. CREATE AN AUSTRALIAN SPACE DOMAIN AWARENESS AND SPACE WEATHER INSTITUTE

The institute will align and coordinate a vibrant and tightly integrated community of SSA/STM/SDA and Space Weather professionals who are dedicated to safe, secure, and sustainable Australian space activity into the future. The membership is diverse in background, bringing together people from a broad range of science, engineering, technology, policy, and strategic backgrounds. Members cut across academia, industry, government, and defence. The institute should have a strong governance and leadership structure and foster an inclusive model for participation to capture niche skills and expertise that can provide Australia with the ability to exploit its advantage in the field. The institute should be funded to sustain its activities into the long term, however the institute itself is not a funding body. The institute's goal is to provide the strategic leadership and a united voice to allow its members to attract substantial external research funding that enables world-class research excellence in the field.

The institute should:

- 'Act like a cult, not a clique' – easy to join, hard to leave.
- Provide the momentum for world class Australian SSA, STM, and Space Weather R&D
- Facilitate training and skills growth – our real estate is being used by the world's leading experts to site their sensors, we should be seeking to exploit this connection to improve or collective knowledge and skills
- Build strong international collaborations to attract funding and enable secondments/exchanges to fast track knowledge and skills growth
- Have a strategic leadership team that is appointed by the Institute's membership

2. CREATE AN SDA AND SPACE WEATHER 'TECHNOLOGY SAND PIT' TO PROTOTYPE, TEST, AND INTEGRATE SDA AND SPACE WEATHER INNOVATIONS

The complete SDA and Space Weather picture only emerges when many diverse sources of data are intelligently combined, analysed, and acted upon. The technology sand pit shall support our SDA and Space Weather community by connecting their capabilities and enabling rapid developments that lead toward operational capability. The intent of the sand pit is to serve the community – not for the community to serve the technology. The sand pit should:

a. Be designed to fit the needs and constraints of individuals within the community

b. Be a **well-funded national facility** that removes the financial and technical barriers from individual groups and companies to participate in an operational-like environment

c. Provide a rich and diverse data set for the research community to use, test, and build upon.

d. Focus on understanding the quality, utility, and reliability of data (not just house a large volume of data)

e. Include all types of data: space weather, sensor data, open source data, spacecraft telemetry, simulation, experiment

f. Embrace new and emerging technology and solutions

g. Drive significant research outputs for the community to establish Australia as a world leader in the field

h. Enable transition of low TRL research to high TRL application within industry, government, and defence

3. DEVELOP AMBITIOUS SSA AND SPACE WEATHER SATELLITE MISSIONS/PAYLOADS TO INCREASE THE ACCURACY AND PERSISTENCE OF MONITORING THE SPACE DOMAIN

4. EXPLORE OPPORTUNITIES TO LEAD THE WORLD IN CISLUNAR, LUNAR, AND DEEP-SPACE SDA AND SPACE WEATHER

Australia is partnering with NASA for the Moon to Mars Artemis program. Securing safe and secure flight from Earth through cislunar and into Lunar orbit is essential for crewed flight. Blue-sky research built upon Australia's existing deep space surveillance expertise should be explored and exploited to secure Australia as the world leader in lunar and deep space SSA, STM, SDA and Space Weather.

Space technology

July 2020

WORKING GROUP MEMBERS

Chair: Nick Carter

Members:

- Simon Barraclough
- Katherine Bennell
- Professor Russell Boyce
- Dr Jason Held
- Julia Mitchell
- Chris Peck

DISCLOSURES OF INTEREST

None

VISION STATEMENT

It's 2030 and Australian space science comprises a consistent flow of space science missions that vary in field, size and complexity. The nation has the technology, knowledge and infrastructure to plan, design, build, launch and execute these space science missions that directly positively impact the lives of Australians.

BACKGROUND

Space technology developments typically arise in response to science mission drivers. The science working groups informing this report have highlighted a number of potential missions and capability developments required for positive and aspirational science outcomes. This section summarizes the technologies that map to these science drivers in order to identify opportunities for collaboration and investment.

Two key themes have been identified as primary space technology developments to enable these mission over the upcoming decade. First, strategic technology developments are required to enable a sustainable sovereign space sector and meet the requirements of the space science community. Currently in Australia these technologies may be lagging international players, however are recognized as prerequisites for a functional space ecosystem that can support Australian science, commercial and Defence space missions. Gaps exist within the Australian sector throughout the space mission lifecycle and identifying and filling these gaps is essential to be able to respond to science mission requirements.

Second, it is necessary to identify advanced technologies where Australia could play a key role in the international space sector, by examining space technology trends that align with Australian industry strengths. The drive toward low-cost satellites and space products and increasing requirements for flexibility and adaptability within the developing ‘Space 2.0’ industry will also present opportunities to compete internationally where emerging trends have yet to be fully capitalized on.

SCIENCE DRIVERS

EARTH OBSERVATION

Recent trends in EO data processing have looked to ‘democratize’ the downstream value-added chain by increasing accessibility and usability of EO data. For example, data from the LandSat and Copernicus missions can be processed through cloud based services. Australia has historical strength in data processing of such EO data and has previously excelled in breaking down these data for agriculture and other end users into an analysis-ready state using technologies such as the Open Data Cube.

Further democratization of this data chain will be available in the future, and a new market is becoming available targeting smaller and less sophisticated end-users that can benefit from satellite data. For Australia to lead in this sciences service field, specific processing algorithms and methods are required that can break information down into smaller and more dedicated chunks. The current data sets are in the petabytes and are growing constantly. Processing of this large volume of data may suit machine language sorting and processing algorithms.

On the upstream end, Earth observation payloads are advancing, however the trends for sovereign Australian satellites will be toward specific niche missions and payloads that suit the Australian community need or provide a unique capability to international partners. The proposed AquaWatch mission requires development of targeted SWIR/Optical imagers on a satellite constellation providing fast temporal resolution. Additionally, more complex on-board processing for data reduction is likely to become mandatory to ensure efficient use of the link budget and to support the calibration and validation of the satellite sensors.

PLANETARY SCIENCE

Planetary science missions in Australia are in their infancy, and the community have identified a desire to produce dedicated and niche nano- and small-satellite missions. This aims to demonstrate sovereign capability to enable and unlock potential collaboration with international partners. Significant international development over the next 10 years is expected in high value nano- and small satellites, and this can align with an Australia ambition to provide planetary science missions with this stepwise development approach. Launches for planetary science missions are highly likely to be provided by international partners in the near to medium future.

HELIOSPHERIC SCIENCE

Heliosphere science specifically requires development in, but also importantly access to, high-performance computational resources.

SSA & SPACE WEATHER

Current on-ground specific sensor technologies being developed in Australia covering adaptive optics, bi-static radar and lidar technologies, however the vast majority of SSA sensor technology is operating in a research mode rather than a dedicated operational mode. This results in a divide between the sensor data and the groups that produce the algorithms for orbit and trajectory predictions. The next steps for SSA focus on producing an integrated collaborative SSA system to support both commercial and military applications. Efficient utilization of cloud computing with a standardized 'data lake' could provide a clean link between sensor data and algorithm developers that is currently missing. A strong SSA ecosystem would then naturally support sensor technology development over the next decade.

The SSA & Space Weather working group identified a specific dedicated in-space SSA and Space Weather mission to map the thermosphere and ionosphere from space using a constellation of small satellites. There are many options for sensor and payload technology for such a mission that already exist at a relatively high TRL. Developing the technology in Australia for such a mission is an achievable goal in the 5–10 year timeline and would place Australia in a better position to look at larger Space Weather missions.

COMMUNICATIONS

Several specific technologies have been highlighted by the communications working group as key development opportunities for the next decade, including case studies in the areas of high frequency microelectronics, in-space optical communications, and reflect-array antennas and metasurfaces. These technologies are near the forefront of space communications and there is capability here in Australia to leverage. Providing these technologies to upcoming missions within Australia would provide opportunities to demonstrate and iterate. However, development of these technologies to the level required to impact the global space ecosystem over the next 10 years would greatly benefit from international collaboration. In particular, Australia has a natural geographic advantage in optical communications and this provides a pull for collaboration with international partners.

CROSS-CUTTING TECHNOLOGIES

Some specific technologies have been highlighted above. This section identifies technologies that cut across multiple sectors and complement the various space science drivers, and also identifies the step-change technologies that will position Australian space science into the future. Three key segments are highlighted.

ON GROUND PROCESSING

Significant cross-over exists in the on-ground processing domain. Over the next decade both the SSA and EO areas require developments in efficient cloud computing to provide an integrated and robust link between the data gathering and pre-processing community and the end-user. The focus for both communities is to combine inputs from a wide range of sensors and make the large volume of data highly accessible. This will allow researchers and commercial industry to interrogate data with exploratory data analysis and machine learning algorithms.

PAYLOAD ON-BOARD PROCESSING

Many of the science satellite missions and opportunities examined require a step-change in payload on-board processing for small and nano-satellite missions. Large volumes of EO data can be produced very quickly, however it is the efficient use of the data chain that can provide Australia with a competitive advantage. Similarly, planetary science missions are severely constrained by the link budget, requiring much smarter solutions to data collection. This is especially pertinent when an international partner is required for the ground segment.

Simple on-board processing such as feature detection can provide a rapid pass/fail criterion for data downlink, and further ahead developments in on-board processing for complex image cleaning, processing and calibration could significantly increase the efficiency of the satellite link budget. Additionally, utilizing intelligent imaging systems with sensors for anomaly detection and machine learning techniques such as feature extraction to pre-process and select data for downlink could significantly increase the satellite value and utilization.

This is an opportunity for Australia, and significant effort should be made to ensure that payload on-board processing hardware and software for all sovereign satellites is developed in Australia. Collaborative research in this way may lead to innovative solutions.

ACCESS TO SPACE

Access to space includes launch vehicles and complexes, however, also encompasses spacecraft technology and mission design techniques to reduce the complexity of executing space missions as well as increasing the confidence in them. The space missions highlighted in this report can be broken into two styles: constellation missions that require low cost and fast response; and high-value nano- and small satellite missions using dedicated niche science satellites and payloads that ultimately act as a stepping stone toward larger sovereign or internationally collaborative science missions.

CONSTELLATION NANOSATELLITES

A cost effective and responsive Australian development, launch and operations capability would greatly benefit the constellation missions examined here. This pressure on the whole mission chain, from concept design through to manufacture, test, launch and LEOP. A number of key drivers and opportunities are highlighted here.

- A well maintained and utilized concurrent design facility (CDF) can provide an efficient way to transition from an initial concept through to preliminary and detailed design. Additionally, digitization capability via such facilities can enable delta-developments using similar missions or product families for swifter early phase mission design and synergistic architectures.
- A highly responsive launch capability to send small and nano-satellites to LEO is required to provide fast response and constellation missions. This capability will ideally be available in Australia within a decade. The launch vehicle providers will develop technologies specifically to cater for this market, potentially primarily driven by the commercial and defense sectors. This knock-on opportunity for small science experiments to rapidly design, launch and iterate greatly increases the capability to push boundaries, since it creates the opportunity for spacecraft technology to rapidly transition from TRL5 to TRL9 with a prototype and iterate approach rather than a stepwise TRL approach.
- Ultimately, successfully developing and executing space science constellation missions will enable a Sovereign satellite prime(s) manufacturing capability for multiple satellite missions. This will encourage commercial IoT and defense operators to consider such missions in Australia
- Satellite operations and in particular LEOP need to be efficient and resource light. For short life satellites launched in batches there is a time critical aspect to commissioning each satellite and autonomous LEOP phases will be required, with advanced on-board processing required to accommodate this. Operational constellations will require far superior autonomous operations than currently exist and there is potential to exploit the Australian Space Agency Mission Control to ensure synergies are seen between science missions and their commissioning phases.

HIGH VALUE NANOSATELLITES AND SMALL SATELLITES

For satellites with significant payload development cost as well as satellites beyond low Earth orbit there is significantly more focus on reliability. There are still many advantages to using standardized nano- and small-satellite platforms for such a mission, but a different approach is required for the satellite design and verification phase. Development costs for dedicated sensors for Earth observation satellites could preclude the use of cheap, very low lifetime satellites, and launch opportunities for the planetary science community are infrequent and expensive compared to nanosatellite low Earth orbit missions.

The step toward such high value missions requires reliable processes to be able to produce a dedicated planetary class nanosatellite bus for high value and deep space missions and eventually a small satellite bus for satellites of around 100 kg for Australian missions in LEO. Both of these can be achieved within a 10-year timescale given sufficient investment.

Communications technologies for such missions have been highlighted above, while radiation tolerant electronics will become mandatory for these missions with significant research required in this field in Australia. Additionally, having a default scalable Australian propulsion module for Australian missions would potentially reduce flexibility in mission design but would greatly increase the variety of missions that are currently possible. The SSA working group also identified propulsion systems as a requirement for controlled de-orbit for small satellites. Guidance, navigation and control systems, and thermal control systems, require developments that will likely be mandatory in future missions.

RECOMMENDATIONS

There is genuine reason to believe that Australian space technology can answer the headline vision statement of this report. This can only happen by ensuring that science, defense and commercial

missions draw on the collective Australian space community to deliver them. Space missions are requirements led, and both Australian industry and research institutions can demonstrate the capability and flexibility to plan, design, build, launch and execute these space missions.

RECOMMENDATION 1.

Develop a true sovereign capability to design, launch and operate small satellite missions and constellation nanosatellites and microsatellites. Breaking this access to space barrier opens multiple opportunities for space science and technology.

A set of cornerstone Australian science missions with drivers to ensure development occurs in Australia is potentially the most feasible way for Australian industry to achieve this.

RECOMMENDATION 2.

The following advanced technologies present an opportunity for Australia to compete at the cutting edge of space technologies, adding value to the global industry.

- Optical communications, leveraging Australia’s geographical advantage
- The development of data processing facilities that aim to connect the data gathering and pre-processing community with the end-user while leveraging Australia’s historical strengths in EO data processing

Smart and adaptive on-board processing for small satellites and the associated technologies required. The target is to break ground in the still emerging fields of constellation and high value nanosatellites.

Workforce capability and capacity

July 2020

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DISCLOSURES OF INTEREST

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Led by the National Committee for Space and Radio Science, the decadal plan for space science (2020–2030) will identify key scientific challenges, changes and trends, and associated applications, which provide new opportunities in space science research and can support the development of Australia's scientific capability and contribute to national priorities.

The plan should:

- identify existing space science workforce capability and capacity
- provide a vision for the future
- set priorities and develop strategies on how that vision may be achieved.

VISION STATEMENT

It is 2030 and the Australian workforce has the capacity and capability to sustain and grow opportunity, discovery and applications in space science. This drives a vibrant space ecosystem, enhancing economic, social and national security. The space science workforce is enabled by access to education, training, and exciting, future-proof career paths which engage innovative young minds and others transitioning to the sector. Space science workplaces are respectful and inclusive, free of harassment and discrimination, value diversity and are structured to attract and retain diverse and professional employees.

CONTEXT: JOBS IN THE SPACE SECTOR

Australia's space sector has high ambitions and great potential.

The Australian Civil Space Strategy 2019–2028 (the Strategy) outlines Australian Government investment of around $600 million over next five years, and together with the establishment of the Australian Space Agency, provides a focus on growing Australia's space ecosystem. The space sector is considered key to diversifying the economy, connecting internationally, developing national capability in areas of competitive advantage, ensuring the safety and security of sovereign space infrastructure and activities, and inspiring and improving the lives of all Australians through high-value jobs. These investments seek to build on existing Australian skills and industries, exploit our geographical advantages, and harness historical support of and endeavour in space science.

Included as measures of success in the Strategy is achieving year-on-year growth of direct and indirect jobs that would meet a target of 20,000 additional jobs by 2030.

Other aims of the strategy include encouraging investment and growth in the space sector, and increasing public awareness of space activities. However, specific and targeted action is required to ensure the necessary workforce capacity and capability, that there are enough suitably qualified and skilled personnel available to meet the sector's requirements.

The Strategy commits to the following implementation activities to 'Inspire' and Build Future Workforce, although metrics for evaluating success and details of the specific strategies are unclear.

2018–19

Engage with the Australian community.

2019–20

Implement STEM initiatives and partnerships with industry to develop the future diverse and inclusive workforce.

Examine options for 'moonshot' missions to inspire the nation and stretch capability.

2021–28

Investigate training priorities and develop future workforce plan.

Continue to explore and develop opportunities with industry or international partnerships.

Partner with education, research and industry sectors for STEM initiatives.

Over the 5 years to 2018–19 the number of people employed in the Australian space sector grew by around 2,000 to 15,000 at an average annual rate of 11%. By extrapolation this is broadly in line with the Review of Australia's Space Industry Capability which found in March 2018 that between 10,000 and 20,000 jobs could be created by 2030. The Australian Space Agency's jobs mission could therefore be achievable if the annual compounding growth rate is maintained for the next decade. However, there are three important caveats.

First, growth predictions extrapolated over long timeframes are risky at best in the very uncertain post-COVID world. Second, it is more important to develop a space ecosystem which fosters new opportunities and initiatives and provides sustainable growth leading eventually to a sovereign space capability not reliant on government support packages. Third, around 60% of current industry revenue in the space sector comes from satellite communications and broadcasting services (e.g. Telstra and Foxtel), while space technology and manufacturing accounts for only around 15%. This is inadequate for stimulating a shift to innovation-driven growth in new cutting edge industries. Other stimuli are needed, for example through exploiting Australia's scientific, technical and geographic advantages with a sustainable national world-class space program.

To inform development of the next strategic plan for space science, the National Committee for Space and Radio Science undertook a survey of current and future space science research capacity. The survey was conducted in June 2020 and targeted heads of space science research groups in universities, government divisions, and SMEs. Thirty detailed responses were received, representing over 600 employees and around 120 higher degree students. Of these responses, 30% described one of their main barriers to research being the ability to find suitable staff. This demonstrates that workforce capacity is already a concern for Australia's nascent space sector. University groups also find difficulty in attracting suitable students to space science research projects.

A separate survey over January–March 2020 targeted space science researchers and attracted 210 responses spanning all age and seniority levels. Fifty-six percent of responses were from the university sector, but only 19% of all respondents were female. The view of job prospects in the space industry was generally strong; for example 60% of PhD students citing their job prospects as good to excellent. However, many expressed concerns regarding ongoing employment, including 'lack of funding' (38%), 'instability of employment' (22%), and 'poor career prospects' (13%). Only 15% reported no such impediments and were in high-level government or university positions, students, or retired. The negativity concerning employment related specifically to Australia, with many references to better prospects overseas. These results are also worrying when considering future workforce capacity.

Nationally, despite the rise of automation, ageing of the workforce may exacerbate a shortage of skilled workers. The COVID-19 pandemic may also have significant impacts on the availability of workers, with likely declines in skilled migration, higher education and research activity, career prospects, and possible redirection of investment from the space sector to other economic and social priorities.

However, because the space R&D sector focuses on new ideas and technologies and encourages STEM engagement, it presents an important post-COVID growth opportunity. Furthermore, apart from simply providing direct employment, the space sector is vital to Australia's social, economic and strategic security: think for example of Earth observation for resource and hazard monitoring; weather and climate prediction and forecasting; precise positioning and precision navigation; effective intelligence, surveillance and analytics for national security, and so on.

To harness these opportunities a national long-term workforce strategy will be required that:

- actively seeks to attract, retain and progress the space workforce;
- specifically supports diversity, inclusion and equity;
- engages all Australians in space science; and
- develops strategic partnerships with relevant domestic industries and businesses while leveraging international linkages.

This strategy must be appropriately supported at all levels of government, and be sufficiently adaptable to meet community expectations and changing circumstances.

The Australian defence sector faces similar challenges in attracting and retaining a skilled STEM workforce. Lessons can be learnt from the strategies being developed to address its workforce capacity and capability requirements.

The benefits of diverse research workforces and the risks of homogenous ones are well known, as are the economic and social benefits of including women and minority groups in current and future workplaces. The Australian government is committed to improving female workforce participation as a key to boosting productivity and innovation. National strategies have already been developed to ensure greater participation of women and girls in STEM, including the Women in STEM Decadal Plan and the 2020 Action Plan, together with equity action frameworks being established in STEM workplaces, including Science in Gender Equity. These all offer important learnings, solutions and opportunities for the space sector.

Broader diversity and inclusion initiatives across space science workplaces, such as Reconciliation Action Plans and support for people living with disability, should continue to be supported to engage a broader range of people to create diverse research workforces.

Women in STEM professions face specific impacts from the COVID-19 pandemic, including disproportionate job insecurity, increased caring responsibilities and disruptions and their capacity to carry out paid work. Hard-won gains by women in STEM are at risk. This risk will be even greater if STEM employers do not closely monitor and mitigate the gender impact of their decisions.

Insights (Problem we hope to address)
To meet the workforce needs of the space sector, we need to understand what skills, training and knowledge are required to meet current and growing demand within the sector, which will need to be developed at all levels of the education system.
Evidence (What we know now)
Jobs in the space sector include science, technology, engineering, and mathematics (STEM), and diverse areas such as digital apprenticeships and skilled trades, medicine, law, entrepreneurship, and finance.
More STEM and other graduates in other fields will be needed to meet this demand. There is specifically a shortage of flight-tested, mid-career engineers, and a depleted set of skills for making investment in the field.
The Australian space sector has strong experience in downstream services, such as satellite communication services, global positioning, and the use of satellite imagery. However, there is relatively limited experience in spaceflight services, such as manufacturing hardware and software for mission control, and on-orbit operations of space objects.
Similarly, the commercial and customer knowledge required by the changing and dynamic space market may be limited amongst pure space sector trained employees.
The types of jobs available, the skills needed to do them, and the length of employment is changing. Over 90% of future jobs will need digital skills, and more jobs will demand interpersonal skills, entrepreneurialism and hypothesis-based problem solving.
This is particularly relevant in the Australian space market where start-up companies comprise 87 per cent of it.
These businesses will require specific skills in finance and entrepreneurship but are unlikely to have capacity to invest in their skills needs over the long term.
People will also change jobs more frequently. An Australian student leaving school today is likely to have five careers and 17 jobs over their working life.
Strategies (Actions)
• A joined up national innovation and education strategy is critical to meet the skills demand of the space science sector.
• A national agency should be responsible for completing a skills and training gap assessment and ensuring that the relevant Government department policies and strategies address these in an appropriate timeframe.
• This skills map must be fluid and responsive to changing skills needs in the sector, while providing guidance on the long-term innovation and education investments. The Agency's strategy for education should focus on long-term growth and sustainability.
• The provision of spaceflight job opportunities for university graduates has also been highlighted as important – other specific opportunities are likely to emerge in the skills map. There is likely to be growing demand in data analytics, AI and related areas.
• Consideration should be given to equipping the burgeoning start-up sector with the skills they need to grow in the Australian space market, including tax incentives or other investments. A need for greater investment in R&D for this sector has also been identified by some business groups.

- The space sector also needs to consider its own workplaces and workplace development activities that reflect the changing world of work with the rise of automation in the post-COVID world and the demand for not only STEM-specific skills but interpersonal and other skills. The provision of graduate training that includes transferable skills will provide highly skilled graduates for roles across science research.
- The space industry must be willing to respond to this reality by acknowledging the transferability of skills and engage with an increasingly mobile workforce, as well adopting a culture of lifelong learning.
- The space sector should also consider, and be supported, to diversify its talent pool from activities such as exchanges with other industries and internships where traditional STEM skills can be complemented with customer and commercial know-how.
- National policies on education (in the early years, school, vocational and higher education) must consider the opportunities in the space sector and how it can equip students with the capabilities they need to thrive in the 2030 workforce. The next review of the Australian Curriculum is due this year. A Roadmap for VET reform is scheduled for endorsement in mid-2020. The HER sector is facing an uncertain future.
- Engagement of space scientists in teacher training and curriculum development should be part of this strategy. The Astronomy Decadal Plan 2016–2025 makes a similar recommendation, and anecdotally there has been an increased awareness of astronomy in schools, buoyed by public education and awareness campaigns.

Outcomes (Metrics)

Skills needs and gaps in space science are firmly understood by policy makers and education providers and addressed through targeted strategies, while Australian students and those working in space science R&D are equipped with key skills, knowledge and training to drive and thrive in Australia's space industries.

Insights (Problem we hope to address)

Space education and career paths need to be better understood in the community to attract people to the sector.

Evidence (What we know now)

Students and teachers lack the understanding of career paths in STEM. As identified by the Australian Space Agency, there is much more to a career in space than being an astronaut. Seeing what space science offers through public platforms will inspire younger generations.

As highlighted by Engineers Australia in 2018, we lack a national approach to STEM careers: 'increasing the awareness of STEM related careers, as well as other career opportunities that can be unlocked by those with STEM skills, will assist in overcoming the negative stereotypes of lab coats and hard hats that the term 'STEM career' evokes. Students can then consider which careers would contribute to solving real world problems, and the skills and knowledge they need, so they can make subject choices that will equip them with relevant skills for a changing work environment.'

Twenty Australian universities provide world-leading space-specific education, generating a pipeline of highly skilled workers for the sector, who have, until now, often sought work abroad.

The Canadian space sector has visibly grown to be increasingly prevalent in the everyday lives of Canadians, from ensuring their personal safety to improving their quality of life or being a source of inspiration. A 'hearts and minds' strategy could work here and encourage more people into space science careers.

Strategies (Actions)

- A national and multi-faceted approach to STEM careers should include a focus on the range of opportunities space science offers.
- A specific career strategy for space science would be warranted given the level of investment and potential growth – this would be linked to the 'Inspire' strategy, being led by the Space Agency.
- The responsible agency, logically the Australian Space Agency, has a focus on increasing understanding of career paths in space, including creating connections with 'real life' space scientists and professionals – this could be expanded, including working with enablers such as the Women in STEM Ambassador, STEM Australia, Science & Technology Australia (also developed the Superstars program) and the Australian Academy of Science communication and education programs.
- A 'Superstars of Space' initiative could be developed which, like the STA Superstars program, would equip space scientists with communication skills and provide opportunities to share their knowledge and experiences.
- Partnerships between universities and industry are critical to address the 'brain drain' in space science and harness existing and emerging opportunities.

Outcomes (Metrics)

Australian kids are inspired to be innovators and entrepreneurs and to tackle global challenges, spurred on by a national space program that entrenches a strong culture of ambition and innovation.

Australian space science graduates are supported to advance their careers in Australia with higher retention rates.

Insights (Problem we hope to address)

Those already working in space science may not be able to access, or do not understand, the opportunities for career progression and retention.

Evidence (What we know now)

While a number of space industry projects have been initiated in Australia in recent years (both government and commercially driven), they are often short-term and disconnected. This makes it challenging for companies to win capital funding, recruit skilled workforces and maintain scale, requiring them to either diversify income or scale down to be sustainable.

While there have been substantial increases in government funding to the sector, it's small by comparison to other OECD nations. This means funding will need to be complemented by innovative partnerships with local industry and foreign investment to achieve the Agency's growth ambitions.

This creates a situation where space sector employees may leave the industry between projects and contracts, losing critical skills and knowledge from space projects and locations.

In the post-COVID-19 world, companies who prioritise employee needs over shareholder needs could become talent destinations.

Strategies (Actions)

- Defining a long-term investment plan for space science, as has occurred in defence science. This would increase space organisations' ability to make longer term decisions that benefit employees and investment.
- This would be further enhanced by strategies to retain employees who may leave the sector between major projects and contracts. Partnerships within industry and HER could assist.
- While there is a peak group for the space industry, there is no professional body or similar for space scientists. Such a professional body should focus on the development of professional standards in space science, accreditation and training and membership with benefits such as mentoring, learning, and professional development support and networks. Ongoing membership of the professional body would support those who have career breaks to maintain connections with the sector.
- Acknowledgement of key advances in space science through awards and prizes. These may be industry sponsored.
- Targeted retention policies that offer lifelong learning and flexible work arrangements. Policies that address the needs of carers, parents, women and other groups are detailed below as part of diversity and inclusion strategies.

Outcomes (Metrics)

Those already working in space science may not be able to access, or do not understand, the opportunities for career progression and retention.

Insights (Problem we hope to address)

Increased awareness and efforts are needed to close the gender (and other) participation gaps in space science as a shared goal of the sector.

Evidence (What we know now)

The lack of gender equity in STEM in Australia is well known, with women comprising 16 per cent of the STEM skilled workforce, 20 per cent of researchers in the physical sciences, and 24% in a recent survey of space science researchers. Only 12% of academics at the professorial level are women.

In March 2020 the Australian Government released the STEM Equity monitor, a national data report on girls' and women's participation in STEM.

The gender balance in space science is worrying if we are to meet the future workforce needs of the space sector and to ensure all Australians can participate in the opportunities available in this sector. Many studies have shown that corporations demonstrate better performance when there is diversity in decision making positions.

We know less about the participation of other groups in STEM and space science, including Indigenous, culturally and linguistic diverse (CALD) Australians, people with disability, LGBTQIA+ Australians, but they are typically underrepresented in STEM fields.

As canvassed in the Women in STEM Decadal Plan, the STEM career pipeline for women is 'leaky' at every point from primary school through to senior levels – with specific barriers identified in each stage. Fewer women and girls choose STEM careers.

The Women in STEM Decadal Plan launched in April 2019 sets out six opportunity areas in leadership, evaluation, workplace culture, visibility, education and industry action, with key recommendations and actions to achieve gender equity across the STEM sector.

There are specific challenges impacting women's participation in STEM in view of the pandemic recently identified in a Rapid Response Information brief. Given the compounding effect of career breaks and gender-based discrimination on career progression, it is reasonable to assume the pandemic is likely to have more long-term negative implications for women in STEM than men.

The Decadal Plan for Astronomy has set a goal of achieving 33% of its workforce as female by 2025 (currently 20%).

Strategies (Actions)

- A better understanding of the gender and other gaps in space science is needed.
- Significant national efforts are underway that should underpin, inform and support the space science sector on its diversity and inclusion journey:
  - The Women in STEM Decadal Plan was launched in April 2019, authored by the Academies of Science and Engineering and Technology at the request of the Australian Government. It seeks to address barriers to STEM participation for women at every point of the STEM pipeline. The Australian Academy of Science continues to support the implementation of the Plan and all STEM organisations are encouraged to become Women in STEM Decadal Plan champions to align their gender equity journey with the Plan and to share gender equity actions. In 2019 ASTRO 3D became a champion and is a great example of how gender equity activities can be aligned with the Plan and publicly stated.
- The Science in Gender Equity (SAGE) initiative seeks to improve gender equity in STEMM (Science, Technology, Engineering, Mathematics, and Medicine) in the Australian HER sector by building a sustainable and adaptable Athena SWAN model for Australia.
  - All women in STEM can join STEM Women, a tool to access a range of career and other opportunities (launched by the Academy of Science in August 2019 and now host to over 2.5k profiles). This platform is continually updated.
  - Specific challenges pertaining to early and mid-career researchers are being addressed through the advocacy and support network of the EMCR Forum – support and new members are always welcome. The Forum is supported by the Australian Academy of Science secretariat.
  - Reconciliation Action Plans are an effective way to initiate and grow reconciliation journeys and should also be supported within institutions.
- Reconciliation actions can underpin greater participation by Indigenous people in STEM. This is also a very useful network for the promotion and use of Aboriginal Astronomy, now part of the curriculum.
  - In 2019, with the support of the Theo Murphy Initiative administered by the Academy of Science, QueersInScience was launched. This aims to build community and improve support for LGBTQIA+ people working in STEMM in Australia.

- Organsiations can consider becoming members of Diversity Council of Australia, an independent not-for-profit peak body leading diversity and inclusion in the workplace, providing unique research, inspiring events and programs, curated resources and expert advice across all diversity dimensions to a community of member organisations.
- All organisations can explore and assess how they are ensuring people with disability can participate – including an increased focus on virtual connectedness, flexible work, and accessibility.
- The Astronomy Society of Australia has created the Pleiades awards to recognise organisations in Australian astronomy that take active steps to advance the careers of women and strive for sustained improvement in providing opportunities for women to achieve positions of seniority, influence and recognition. A similar initiative could be explored for broader space science.

Outcomes (Metrics)

Increased awareness and efforts are needed to close the gender (and other) participation gaps in space science as a shared goal of the sector.

Insights (Problem we hope to address)

What role can the space sector play in economic recovery, economic transition, and structural adjustment, post COVID-19.

Evidence (What we know now)

While Australia's economy has recently retracted and entering recession due to the necessary COVID-19 restrictions, sluggish growth and persistent unemployment is typically location-based. A vibrant space sector offers growth and employment potential.

The development of Australia's space industry by establishment of the Australian Space Agency and through targeted space investment programs should create new opportunities for business and job growth across the economy, including the manufacturing, agriculture, communications, mining, and oil and gas industries.

However, the government programs, including the Space Agency itself, do not offer ongoing programmatic support measures. There is a danger that the sector will prove unsustainable if and when these measures cease.

By far the most significant investment in the space sector is from Defence requirements. For example, the ADF is seeking to acquire a next generation satellite communications system (JP 9102) at $2–3 billion, while the Australian Geospatial-Intelligence Organisation plans sovereign satellite imagery capability (DEF-799 Phase 2) costing around $3–4 billion.

Some recent changes in consumer demand such as in-home entertainment, work-from-home arrangements, online education and training offerings and increased internet usage may offer new opportunities for the space sector.

Strategies (Actions)

- The creation of physical and virtual precincts in locations experiencing economic transition have led to economic growth and renewal, often in high-value industries. The space sector must consider what partnerships, including through the Defence Innovation Hub, it can develop further to capitalise on these opportunities.

- Ensuring that the roles of the space R&D sector, industry and government agencies including defence, are considered in national and regional economic transition and recovery packages. A key aim should be strategic planning of civilian and strategic space programs to develop domestic capability and capacity able to secure sovereign capability in space over a realistic timeframe.

Outcomes (Metrics)
The economic opportunity of the space science R&D sector is understood by policymakers and investors and actively contributes to social, economic and national security.

RECOMMENDATIONS

1. AN INTEGRATED NATIONAL SPACE SCIENCE INNOVATION AND EDUCATION STRATEGY

In order to grow a sustainable space sector workforce it is necessary to first understand the gaps and needs then develop appropriate responses. A national agency should be responsible for completing a skills and training gap assessment and engaging with national education agencies spanning primary, secondary, tertiary and the VET sectors to consider how to space can be used a vector to engage and equip students and retraining workers with the capabilities they need to thrive in the 2030 workforce and beyond. A focus on increasing understanding of career paths in the space sector and embedding strategies encouraging engagement of underrepresented and disadvantaged groups, is essential. The strategy needs to form partnerships between the university, VET and industry sectors to harness existing and emerging opportunities. The Australian Space Agency has identified development of a future workforce plan in Phase 3 of its Strategic Plan but a suitably funded coordinated, multi-sector approach is required.

2. ARTICULATE A NATIONAL COMMITMENT TO A SUSTAINABLE SPACE PROGRAM

Australia's aspirations to develop its space economy rely on stimulating growth of a new innovation sector in a very difficult and competitive economic and international environment. To support such growth major organisations and the research and industry sectors need to be able to make longer term decisions, including around forming partnerships and recruiting, training and retaining their workforce. A clear commitment to an ongoing national engagement with civilian space is required. Defence science has already recognised that a long term commitment and investment plan is needed to ensure it is able to meet its workforce needs. This necessarily includes core commitments to equity and diversity. A long term national goal should be development of capability and capacity able to secure sustainable growth of the sector and sovereign capability in space over a realistic timeframe.

3. STIMULATING ECONOMIC GROWTH VIA THE SPACE SECTOR

The space R&D sector is at the forefront of new technologies and opportunities which are necessary not only because our economy and well-being are increasingly reliant on space-based products and services, but also to support structural transition to an innovation-led high tech future. Therefore space-based activities in universities, industry and government agencies including defence should be considered in national and regional economic transition and recovery packages. This could include the creation of physical and virtual precincts in locations experiencing economic transition. The space sector must consider what partnerships, including through the Defence Innovation Hub, it can develop further to capitalise on such opportunities. Presently various state governments are competing to establish space innovation and industry hubs, which risks duplication of effort and unhelpful competition for resources.

4. A PROFESSIONAL PEAK BODY REPRESENTING SPACE SCIENCE

While there is an effective peak group representing the space industry, there is no professional body or similar for space science. Such a professional body should focus on the development of professional standards in space science including the promotion of equity, diversity and inclusion; accreditation and training; promotion of career pathways; and supporting the growth of space science research and development through forming partnerships across government, university and industry sectors. These activities would support the goals and activities of the Australian Space Agency and other organisations including the SIAA.

Endnotes

EARTH OBSERVATION

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3 Henttu H, Izaret JM, Potere D (2012) 'Geospatial Services: A $1.6 Trillion Growth Engine for the U.S.Economy', The Boston Consulting Group

4 Senate Standing Committee on Economics (2008) 'Lost in Space? Setting a new direction for Australia's space science and industry sector', Canberra

5 Australian Academy of Science and Australian Academy of Technological Sciences and Engineering (2009) 'An Australian Strategic Plan for Earth Observations from Space', Canberra

6 Commonwealth of Australia (2013) 'Australia's Satellite Utilisation Policy', Canberra

7 Space Community of Interest (2015) 'A first pass analysis of risks associated with Australia's dependencies on space-based assets: Communications, Positioning, Navigation, Timing and Earth Observation.' Trusted Information Sharing Network for Critical Infrastructure Resilience, Attorney General's Department, Canberra, RESTRICTED ACCESS

SPACE-BASED PNT

8 Definition of Accuracy: The accuracy of an estimated or measured position at a given time is the degree of conformance of that position with the true position, velocity and time.

9 Definition of Availability: Availability is the percentage of time that the services of the system are usable by the user.

10 Definition of Continuity: The continuity of a system is the ability of the total system (comprising all elements necessary to maintain user position within the defined area) to perform its function without interruption during the intended operation.

11 Definition of Integrity: Integrity is the measure of trust that can be placed in the correctness of the information supplied by the system.

12 Jamming refers to the interruption of a receiver's receiving electromagnetic signals from a satellite by using a signal with the same frequency but with significantly higher power. The aim is to overpower the extremely weak GNSS signals so that the GNSS receiver cannot track them. Jamming is a synonym for intentional interference.

13 Spoofing refers to transmission of fake signals, i.e., mimicking of the characteristics of a true signal, so that the user receives the spoofed signal instead of the real one. The aim of spoofing is to mislead a GNSS receiver.

14 The impact on Timing (as it provides necessary synchronisation electrical power networks, mobile telecommunications, computer and financial systems, civilian time transfer, science applications, etc) is even more insidious than in the case of Positioning.

SPACE HEALTH AND LIFE SCIENCES

15 Cable G, Ayton J et al. Space Life Sciences: Australia's Future Space Industry Capability. Submission to the Australian Space Agency Expert Working Group, Nov 2017.

16 On current estimates by 2022, 6.2 million Australians over the age of 50 will suffer osteoporosis or osteopenia costing $3.84 billion. (Watts J, et al. Osteoporosis costing all Australians: A new burden of disease analysis – 2012 to 2022. Osteoporosis Australia, Deakin University, University of Melbourne, 2012)

17 Australian Institute of Health and Welfare 2019. Australian Burden of Disease Study: impact and causes of illness and death in Australia 2015. Australian Burden of Disease series no. 19. Cat. no. BOD 22. Canberra: AIHW.

18 The total cost of inadequate sleep in Australia was estimated to be $66.3 billion in 2016–17. (Asleep on the Job: Costs of Inadequate Sleep in Australia. Sleep Health Foundation and Deloitte Access Economics Report, August 2017)

19 In 2014–15, 1.4 million patient-days of hospital treatment were attributed to injurious falls. (Pointer S 2018. Trends in hospitalised injury due to falls in older people, 2002–03 to 2014–15. Injury research and statistics series no. 111. Cat. no. INJCAT 191. Canberra: AIHW)

20 For example: Moore ST, MacDougall HG, Ondo WG. Ambulatory monitoring of freezing of gait in Parkinson's disease. J Neurosci Methods. 2008 Jan 30;167(2):340-8.

21 The total disease burden rate in 'remote and very remote' areas of Australia was 1.4 times as high as that for major cities in 2015. (Australian Burden of Disease Study: impact and causes of illness and death in Australia 2015. Australian Burden of Disease series no. 19. Cat. no. BOD 22. Canberra: AIHW)

22 Antimicrobial resistance driven by the overuse and misuse of antibiotics shows little sign of abating in Australia and poses an ongoing risk to patient safety, with common pathogens becoming increasingly resistant to major drug classes. (Australian Commission on Safety and Quality in Health Care (ACSQHC). AURA 2019: third Australian report on antimicrobial use and resistance in human health. Sydney: ACSQHC; 2019)