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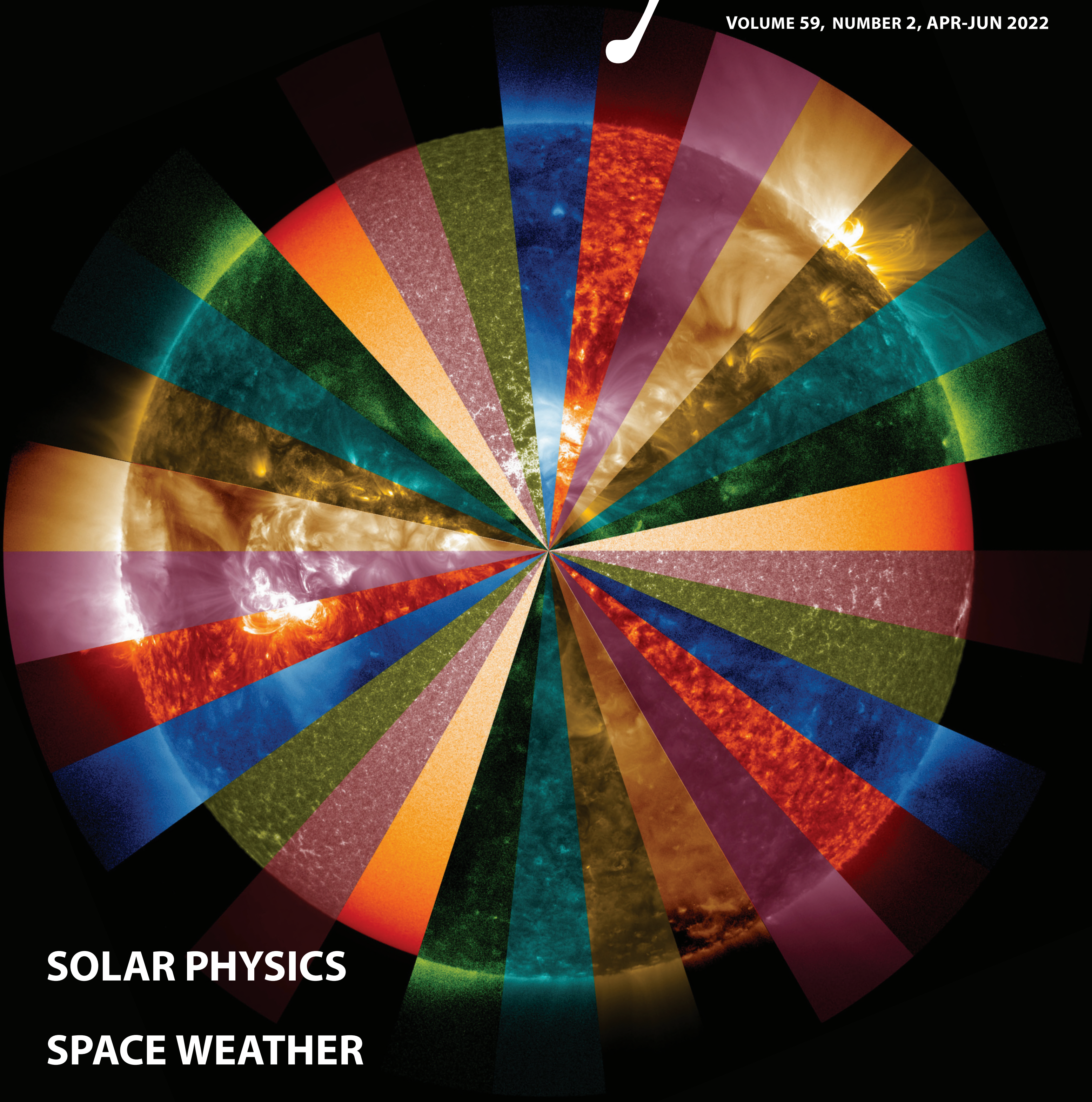


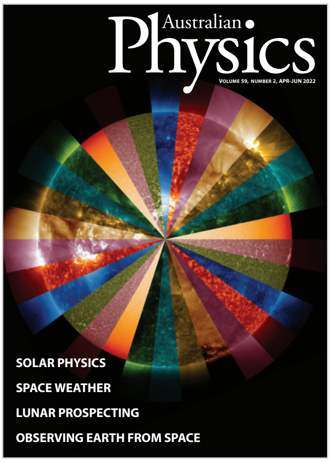
SOLAR PHYSICS

SPACE WEATHER

LUNAR PROSPECTING

OBSERVING EARTH FROM SPACE

CONTENTS



Composite image of the Sun showing the solar atmosphere at ten different wavelengths, ranging from visible (617.3nm) to EUV/Soft X-rays (9.4nm). Each colour segment represents one specific wavelength.

For details, see "Slices of the Sun" at https://solarsystem.nasa.gov/resources/698/slices-of-the-sun/. (image: NASA/GSFC Scientific Visualization Studio)

Australian Physics

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Editorial

Space

We are very pleased to present a special issue on Space Physics. This issue would not have come to life without a group of engaged people, brought together by guest editor Dr Alina Donea, who has co-ordinated, curated and shaped the articles and pieces that make up the heart of this iteration of Australian Physics.

As editors, we try to learn about the different physics that is 'out there' and help condense some of that into a magazine issue. This time, we had the luxury of taking one hand off the wheel and learning with a child's eye. We learnt that Space Physics in Australia is not about one thing only. It is colourful and multi-factorial. It's about looking at the Sun and looking down at Earth; space weather, geomagnetism, and satellites; flying things into orbit, new missions and reaching beyond so that we understand better how humankind could become an interplanetary species.

The space industry is growing rapidly worldwide and is forecast to be worth over $US1 trillion by 2040. In 2018, the Australian Government established the Australian Space Agency to support the growth and transformation of Australia's space sector, to ensure appropriate regulation, and foster our participation in projects with international partners. As these aims are achieved in the coming years, we hope we'll see many more articles on Australian Space Physics in this magazine. So, we invite you to have a fresh and curious look at space around us. We also hope you stay safe and help look after Earth.

Best wishes,
Alina Donea, David Hoxley, Clara Teniswood, and Peter Kappen.

From the Executive

I'm delighted to write about a number of aspects of my role as Registrar, which I have held since 2018.

Membership

The AIP was born in 1963, arising from the Australian Branch of the Institute of Physics (IOP). Earlier, in 1922, a request for an Australian branch was rejected as the IOP had only three members in Australia! Thus, like the IOP, Membership requires a degree in physics. Our membership grades have evolved over the years. Nowadays Members (including postgraduate and honours students) and Fellows have full rights to participate in the decisions and structures of the AIP. For those without a physics degree the Associate grade, including the Free Student option, is appropriate, plus we welcome other physics enthusiasts as "subscribers".

As the tertiary education system in Australia developed, the AIP Council developed processes for evaluating the syllabus of the physics programs offered by institutions. Generally, an institution would write to the AIP asking for its graduates to be welcomed by the AIP, which required evaluation by a small group of AIP members (usually Executive members).

Originally the Membership Committee met (in person) 6-8 times a year to consider all membership applications. Nowadays, it considers applications for Fellow and non-straightforward member applications.

Accreditation

In response to government initiatives to regulate the university sector in the 1990s, the AIP established an accreditation process to ensure that we were determining the requirements of a physics degree and therefore eligibility for being an AIP Member. AIP Registrars established panels to assist with the workload, with individual organisations being visited by an Accreditation Panel every five years. I wish to thank the many people who have contributed to this process; i.e., reading a detailed submission, a day-long visit, and writing a report. I have been a participant, including being Accreditation Manager for 2012-6 (as Accreditation activities had a high workload, this role was removed from that of the Registrar). It was a great privilege to see dedicated physics academics and the enthusiasm of their students for physics in many different parts of Australia.

Since 2020, the pandemic has significantly affected the delivery of university degrees especially laboratory programs. The AIP Executive is grateful for the efforts of the current Accreditation Manager, Deb Kane, in advocating for the vitality of a physics degree.

Operations

The AIP, as a small organisation, has employed various agencies to manage its operations, but sometimes with frustrations and concerns about the quality of services for our members and were "value for money". Thus, two years ago the AIP moved to a new arrangement, with our own Operations Manager, built on a "customer relationship management" system, Wild Apricot (also used by two AIP cognate societies). We hope that members are pleased with this and the updated AIP website, including provision of restricted "edit" privileges to branches and topical groups.

Archives

The AIP has amassed many materials (stored in Melbourne). During lockdowns, I had certain boxes of records, including minutes and membership data delivered to my home, for inspection and scanning, thereby beginning a digital online repository of these as a resource for the Executive. Interested in archival activity relating to AIP history? - please contact me.

Looking ahead

Our 60th anniversary next year is an opportunity to celebrate the many achievements of our organisation and our many thousands of members, past and present. The Executive seeks your ideas of how we can mark this milestone.

Stephen Collins, AIP Registrar

Space for Australia?

Frederick Menk
Chair, Australian Academy of Science National Committee for Space and Radio Science
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With the establishment of the Australian Space Agency on 1 July 2018, the Australian Government signalled its intention for Australia to 'grow a globally respected Australian space industry sector that lifts the broader economy and inspires and improves the lives of Australians' [1]. This article examines the context for Australia's space ambitions, and the significance of space science in achieving these.

The global space sector

Transformative change is revolutionising the space sector. The cost of launching a payload to low Earth orbit (LEO, typically 350-800 km altitude) will have decreased by two or more orders of magnitude by mid-decade [2,3]. This will stimulate enormous growth in the number of space objects.

Previously the purview of governments and large prime contractors, space is becoming accessible to almost anyone. As of 1 September 2021 there were 3,789 operational satellites in LEO [4]. Nearly half of these were Starlink internet service satellites operated by SpaceX, who have plans to launch altogether 42,000 satellites, grow of the global space economy by a factor of three or so by 2040 [5]. Space science will be stimulated by exploration programs such as NASA's Artemis, and European (ESA) and Chinese activities. Artemis will see human lunar exploration supported by over 70 missions to the Moon this decade. Over the next five years China's space station will become fully operational in LEO, as plans for its human lunar missions mature [6].

This vast growth in space activity will amplify hazard risks. The most important natural hazard is space weather (see M. Parkinson, this issue), which affects satellite systems, humans in space, communications networks, and space-derived applications. Currently around 22,000 objects are tracked in space, but it is estimated there are over 1 million objects larger than 1 cm, mostly fragmentation debris from satellite explosions and collisions [7,8].

Vastly increased data volumes will be collected in and transmitted from space. However, the radio spectrum is already overcrowded. The development of free-space optical communication would open up many new opportunities providing continuous, on-demand quantum entanglement distribution service to ground stations [9,10].

Technological advances mean that even small satellites can undertake sophisticated tasks, including interplanetary missions. The basic building-block size unit for a nanosatellite is 1 U (10 x 10 cm, or 1 litre volume), and such CubeSats are within the capability of university and school groups. Within the decade there will be very large numbers of small satellites in LEO, including mega-constellations interconnected to global communications, data and surveillance networks.

Space-derived activities and services are already critical to economic, social and national security. For example, jamming of GNSS (global navigation satellite system) signals such as GPS would impact not just logistics and positioning applications but all critical infrastructure which relies on precise timing and synchronisation. Space is a profoundly dual use domain, with military priorities alongside civil and commercial interests. Access to and awareness of the space domain is essential for national security. The mutual risk of debris proliferation is prompting state actors to embrace more sophisticated strategies than kinetic weapons, such as directed energy, electronic and cyber counter-space capabilities.

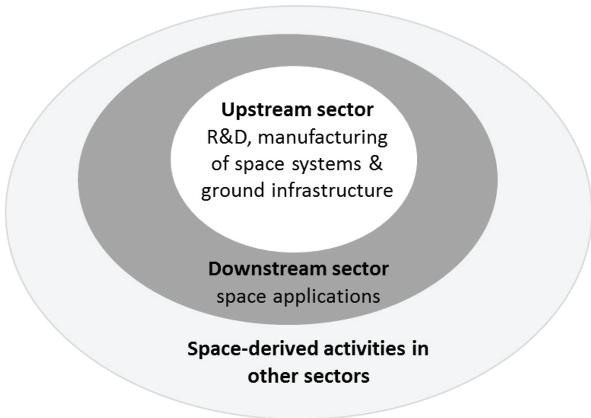

Fig 1. The space economy. The upstream sector provides the science, technology and systems necessary to deliver space-enabled applications such as Earth observation, positioning navigation and timing (PNT) and communications services to the downstream sector, with broader benefits to governments, commercial users and consumers in non-space sectors.

Space science and technology underpin all space activities and the space economy, as illustrated in Figure 1. Consequently these enablers are often regarded as strategic national assets.

Australia's space sector

The Australian Government has recently flagged the importance of the space sector for economic prosperity, national security, and social cohesion, through a number of measures. These include:

- Formation of the Australian Space Agency, with its remit to grow the space industry sector.
- Identification of 'space' and space-derived capabilities as Defence sovereign industry capability priorities [11], as national Manufacturing priorities [12], as critical technologies in the national interest [13], and in the proposed 'Australia's Economic Accelerator' program.
- Schemes such as the 3-year $15 million International Space Investment initiative, and the 5-year $150 million Moon to Mars initiative.
- Rollout of space-derived enhanced positioning capability by Geoscience Australia, to provide national positioning accuracy of 10 cm or better.
- Support for the SmartSat CRC, which brings together R&D and industry partners to advance capabilities in communications, Earth observation, and PNT applications.

Domestic civil space activities are coordinated by the Australian Space Agency. It released the Australian Civil Space Strategy in April 2019, which identifies seven national civil space priority areas in which Australia can capitalise on competitive advantage or opportunity to grow its space sector and the broader economy. The Agency is progressively rolling out technical roadmaps which provide vision, ambition and aspirational targets for each of these priority areas. These are important for flagging what could be achievable, but require funding sources and implementation strategies.

CSIRO released its space strategy in August 2018, and various state governments have since also developed their own space strategies; e.g. [14, 15]. As part of its coordination role the Australian Space Agency chairs the Space Coordination Committee, which comprises 14 government departments with space interests (e.g. CSIRO, Defence, Home Affairs), and also meetings with state representatives through the State and Territory Space Coordination Meeting. Many of these groups include Chief or Lead Scientists, but the Australian Space Agency currently has no such position or science-focused remit.

Federal government funding for civilian space research activities in 2020, including space-related ARC grants, was around $22 million in mostly short term one-off commitments. The Modern Manufacturing Initiative, announced in October 2020, provides $1.3 billion across all six priority areas (space is one of these) over 10 years but only through co-funding and only for trading corporations. The Defence budget identifies research funding across its priority areas of order $160 million annually plus $8.3–12.6 billion in space-related operational expenditure over the next decade.

The federal and state government initiatives are important and welcome, and along with activities of the Australian Space Agency and CSIRO are stimulating growth of the space industry sector. However, the space science research and innovation capabilities necessary to develop a sustainable national space ecosystem have not been similarly enabled.

Below we outline the challenges, opportunities and imperatives for Australian space science to contribute to national space needs and priorities.

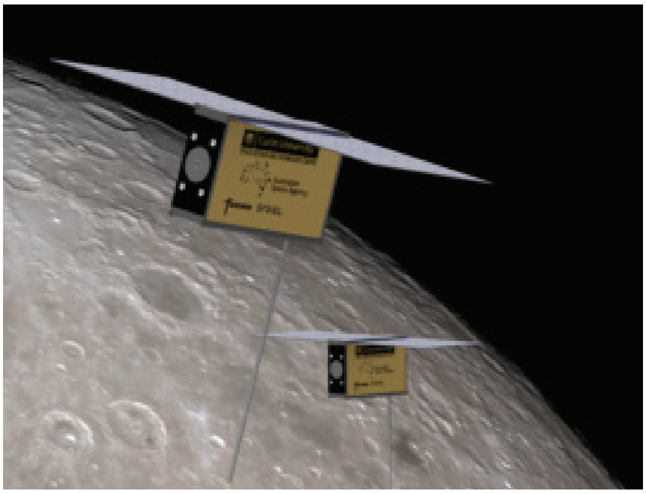

Fig. 2 Artist's representation of Binar Prospector nanosatellites orbiting the Moon. The Binar program at Curtin University is developing low cost, smart interplanetary class small satellite platforms that can be a workhorse for future Australian missions.

Australian space science

Space science is the science of and from space primarily for discovery and human benefit. It spans robotic and human space exploration; solar system planetary science; space weather science and mitigation of space weather events; remote sensing and Earth observation; space-based positioning, navigation and timing (PNT); satellite-enabled communication; and space life sciences.

In every case, basic space science discoveries and innovations underpin space technologies, industries and applications. Strengths, challenges, enablers and opportunities for Australian space science are outlined in the Academy of Science's Decadal Plan for Australian space science, released in January 2022 [16].

Australian space science research is world class in many areas. For example, Australian space and planetary science research is ranked 8th globally [16,17], above Japan and China. Australians have contributed to major international space missions since the Apollo era, and continue to work at, and collaborate with, international space agencies, research groups and multinational consortia across all the key space science disciplines. Australia's large and diverse territory spanning polar to equatorial regions, key time zones, extensive infrastructure and technical expertise, provide globally competitive advantages for space science.

The Decadal Plan identifies three objectives:

1. Advance excellence in space science research to drive new discoveries and generate knowledge, stimulate innovation and development of potentially transformative technologies.

2. Grow world-class fundamental and applied research to advance capabilities and applications which underpin the use of space to address national challenges and priorities, including growth of the space industry and sovereign capability in priority areas.

3. Grow the skilled workforce and its diversity.

Challenges, enablers and opportunities

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

In this regard the Decadal Plan identifies the following strategic priorities ('enabling platforms') necessary to deliver the objectives listed above.

- A national priority in space science to support civil and defence sovereign industry capability requirements, encourage discovery and innovation, and provide broader economic and societal benefits.

- A lead scientist role within the Australian Space Agency with responsibility for space policy settings.

- Commitment to an ongoing mission-oriented national space program to grow capability, stimulate innovation, address national priorities, and inspire citizens.

The Decadal Plan also identifies the following opportunities for Australian space science.

- A program of small satellite space missions harnessing opportunities provided through international partnerships including Australia's engagement in NASA's Artemis program.

- Ensuring sustainable use of space and protecting critical infrastructure by advancing space weather science and sovereign space situational awareness capability.

- Harnessing Australia's heritage in satellite tracking and telemetry, and expertise in radio science and optical astronomy, to develop a next generation hybrid radio and optical space communications network.

- A sovereign Earth observation satellite program to mitigate supply risk, and through ground truthing calibration and validation, establish international leadership in provision of decision-ready, quality assured remote sensing data.

- Development of next generation PNT capabilities, to provide resilient, reliable services with improved accuracy, such as real-time absolute navigation at sub-centimetre level in difficult environments.

- Supporting medical and nutrition requirements for long duration human space missions and off-Earth bases.

Training and growing the skilled workforce is essential for Australia's economic and social development, but there are significant capability gaps across STEM domains. Space exploration excites young people and can be used as a vector to STEM engagement, as exemplified by the Victorian Space Education Centre [18] and Hamilton College in South Australia. Women are greatly under-represented in the space workforce, pointing to programs: Women in STEM [19].

The Australian Space Agency aims to create 20,000 new jobs by 2030, a figure comparable to the entire Canadian space sector workforce [20]. Extrapolation against the Canadian example suggests that to meet targets Australia will need to train around 330 new scientists and engineers each year for a decade, in addition to meeting existing shortages across other sectors. Since other countries are experiencing similar workforce gaps, Australia's requirements would need to be met mostly from current school and tertiary enrolments, retraining and industry schemes.

A national space strategy

Australia has critical economic and strategic dependencies on space and seeks to grow the space sector and sovereign capability. The sector comprises many diverse elements across the defence, commercial, civil and academic arenas, with multiple existing and developing space-related strategies in various organisations. However, there is no long term plan to address knowledge and capability gaps, impacting growth of the innovation industry sector and downstream users. The entire ecosystem should be more focused in working together to progress national space interests.

Development of a sustainable Australian space sector requires an overarching strategic plan that embraces all stakeholders and provides a detailed picture of the architecture, components and capabilities to a clearly milestoned timeframe. This will encourage long-term decision-making by stakeholders, translation of basic research to commercial outcomes, development of sovereign capability and career pathways in the space workforce. Various reports including from the Parliamentary Inquiry into the space industry have identified this priority [21].

What might such a national strategy look like? The UK's National Space Strategy provides an example [22]. It brings together civil, defence and space weather strategies through an integrated goal-oriented approach supported by capacity development pillars (growing the space sector, advancing space science and technology, international collaborations, resilient space capabilities and services). Implementation of the strategy will be overseen by a National Space Cabinet chaired by the Prime Minister.

Any national strategy needs to first articulate its core principles, its goals, and the capabilities and measures needed to achieve these goals. The pillars upon which such a strategy may be built has been the subject of some discussion; e.g. [23-25]. As a starting point, a national space policy should embrace the following themes: (i) security and resilience; (ii) industry, both upstream and downstream; (iii) science and research; (iv) international collaboration; (v) workforce capability and capacity; (vi) public inspiration. There will be many interested parties sitting around the table, and much discussion and perhaps compromise. But this is an essential step if we are to achieve a sustainable industry and sovereign capability.

From the space science and technology perspective, this next decade provides unparalleled opportunities, and will be important in shaping future national and global development. Indeed, we live in interesting times.

Acknowledgements

This article is informed by the Australia decadal plan for space science, which was developed under the auspices of the Australian Academy of Science. Thanks are due to all those who contributed to the plan, although the opinions expressed here and in the plan do not necessarily represent the views of any individual or their employer. Financial support for development of the plan was provided by the Australian Space Agency, CSIRO and the SmartSat CRC, while the Academy of Science provided project management and operational support.

About the author

Frederick Menk is also Emeritus Professor of physics at the University of Newcastle and Fellow of the Australian Institute of Physics. He has conducted research in space physics for four solar cycles, in particular investigating properties of the ionosphere and magnetosphere with ground-based and in situ instruments, mentoring over 30 PhD students. He has convened numerous international symposia and national outreach events, and also served in various academic leadership roles. His research career started as a wintering physicist at Davis station in Antarctica.

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Space Weather: Why should users of satellite positioning care?

Suelynn Choy, Tam Dao, Brett Carter
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Satellite positioning technologies have revolutionised the way we locate ourselves on Earth and navigate to where we want to go. It has become an integral part of everyday life, from obtaining directions on our smartphones, providing navigation and guidance for emergency services and transportation, to delivering very accurate timing services for telecommunications, banking and finance.

An illustration of the Sun interacting with Earth's magnetosphere. Credits: NASA's Goddard Space Flight Center/Mary Pat Hrybyk-Keith

Global Navigation Satellite Systems (GNSS) is the generic term for constellations of Position, Navigation and Timing (PNT) satellites, which transmit signals from space enabling users to determine their position anywhere outdoors and at any time. The first GNSS system to be fully operational was the U.S. Global Positioning System or GPS. Since then, Russia, Europe and China launched their own global satellite navigation systems GLONASS, Galileo and BeiDou. India and Japan have also both launched their own regional augmentation satellite navigation systems NaVIC and QZSS.

In 2018, the Australian Government announced funding to the Positioning Australia program to provide highly accurate and reliable GNSS positioning to all Australians. The ambition of the program is to accelerate the adoption and development of GNSS positioning technology and applications in Australia. This will be achieved by having an Australian sovereign owned Satellite Based Augmentation System or SBAS, a coordinated and standardised national positioning infrastructure of ground based GNSS reference stations, and a GNSS analysis centre software toolkit delivering open, accessible and accurate positioning data and GNSS corrections [1].

While GNSS technology has become the primary source of PNT services for many applications, GNSS signals are extremely weak. GNSS is based entirely on radio signal transmissions from satellites that are well over 20,000 km from Earth and passing through the Earth's atmosphere before it reaches the receivers on Earth. Therefore, GNSS signals are highly vulnerable to interference, whether deliberate, unintentional, or caused by natural phenomena such as adverse space weather events. In fact, the effect of space weather is a major limiting factor for high performance PNT systems.

Effects of space weather on GNSS

Space weather effects on GNSS L-band signals include ionospheric perturbations and the direct effect of solar radio bursts, and these effects are exacerbated during the

~11 year solar cycle maxima. Of these two, the direct effect of solar radio bursts on the GNSS signals has been the least understood [2]. Solar radio bursts are intense radio emissions from the Sun, often associated with solar flares with durations from tens of seconds to a few hours. This is one of the extreme space weather events, which can affect acquisition and tracking of the GNSS signals at the receiver ends. This means that users would encounter intermittent loss of signal lock, which could lead to positioning error; and in worse cases, complete loss of GNSS measurements and PNT capabilities that can persist for a significant period [3]. The effect of solar radio bursts on GNSS was first seen on 5 December 2006 during a solar minimum. These solar radio bursts were measured at 1 million solar flux units (one solar flux unit = $10^{-22} Wm^{-2}Hz^{-1}$) with smaller events on 6, 13 and 14 December that year. These interfered with the operation of GNSS receivers for 10 to 20 minutes on each occasion. Positioning data from several semi-codeless (and therefore not robust) GNSS reference receivers around the world were completely lost [3, 4]

On the other hand, ionospheric perturbations affect GNSS signals in two ways: First, the ionosphere is dispersive, which means that the ionosphere introduces both signal delay and frequency dispersion errors. The magnitude of error is dependent on the frequency of the GNSS signal. This would impact the range measurements between GNSS satellites and user receivers, which subsequently affect the quality of the PNT data. During a low solar activity period, the ionosphere would typically cause vertical (zenith) range measurement delays between one metre at night to 5 to 10 m during the day. During peak periods of solar activity, the delay can vary between a metre at night to 100 m during the early afternoon [5].

Second, time-varying plasma density irregularities in the ionosphere cause amplitude and phase fluctuations in the received GNSS signals. This phenomenon is known as scintillation. Ionospheric scintillation can have profound impact on GNSS receiver tracking performance, which lead to positioning error and in extreme cases, complete loss of signal tracking [2]. In Australia, scintillation events are usually observed over the northern regions of Australia close to the geomagnetic equator where it is a serious and limiting problem for GNSS PNT services.

Methods to mitigate the effects of space weather on GNSS PNT

Most consumer market GNSS receiver users operate in a single L1 band frequency mode at 1575.42 MHz. To obtain accurate positioning, single frequency users rely on an ionospheric model (e.g. the Klobuchar model for GPS users) to estimate the signal delay due to the total electron content density in the ionosphere to compensate for the effect. On average, these models compensate for only around 50% of the ionospheric delay [5]. Single frequency GPS is specified to provide on average 95% horizontal and vertical positioning errors below approximately ≤ 9 m and ≤ 15 m, respectively [6]. During an extreme space weather event, position errors could reach hundreds of metres.

GNSS systems are designed with at least a second open signal to compensate for the ionospheric delay. The open signals, in addition to L1 band frequency, are L2 band frequency (1227.60 MHz) and a newer L5 frequency (1176.45 MHz). Dual-frequency GNSS receivers have been widely used in the professional market to obtain centimetre to decimetre level accurate PNT data; and in recent years, there have been an increasing number of dual-frequency (and multi-frequency) receivers becoming accessible for mass-market applications requiring high accuracy PNT solutions. Dual frequency receiver users are not spared from the effects of ionospheric scintillation. During a strong geomagnetic storm, dual-frequency positioning is expected to provide marginal improvement as compared to an ionospheric model.

Another method of mitigating the ionospheric delay errors is the use of augmentation approaches and systems such as Differential GNSS (DGNSS) and SBAS. Networks of ground based GNSS reference stations have been established and operated worldwide including Australia, providing real-time corrections to GNSS users in a local region (typically within 500 km range) [7]. Local and spatially correlated corrections such as for ionospheric delays, are applied at the user receivers to improve PNT performance. Similarly, SBAS offers corrections over a wider area spanning thousands of kilometres transmitted via a geostationary satellite. When fully operational, the Australian SBAS will provide ionospheric corrections for commercial aviation over Australia and other applications requiring high performance PNT data [1].

In addition to range delay measurement errors caused by ionospheric perturbations, ionospheric scintillation would affect the amplitude and phase coherence of the GNSS signals leading to loss of signal lock. Most often scintillation rarely occurs on all visible satellites simultaneously due to the nature of electron irregularities encountered along the radio propagation path, hence affecting only few satellites causing occasional outages and increase in signal noise of those affected satellites. Scintillation can be mitigated with the increased number of available satellites provided by the multi-constellation GNSS systems. In this case, if many well-distributed satellites hence signals are available to users, then the loss of one or two satellites will only have marginal impact on the overall PNT performance. The success of this approach is dependent on the overall number and the geometry of unaffected satellites.

Why should users of GNSS care about space weather?

Space weather can interfere with satellite electronics and communications including GNSS signals. Although the effects of ionospheric perturbations are generally mitigated using models, dual-frequency GNSS signals and differential techniques, they are less effective during severe space weather. The very large electron content variations and gradients at storm-enhanced density boundaries, though are rare, can even degrade differential GNSS positioning errors exceeding 30 m [7], thereby severely compromising the overall performance of the system making it inadequate to meet the requirements of many PNT applications. At low and high latitudes, ionospheric scintillations can degrade GNSS performance resulting in positioning errors at metres level, well beyond the accuracy threshold requirements for safety-critical applications (e.g. transport relying on GNSS PNT).

Increasingly, improved prediction of space weather and modelling is ever more important to the GNSS community as we strive to do more with the capability that GNSS provides. In addition to high accuracy precise positioning, emerging GNSS PNT applications, for instance autonomous and connected vehicles, would require high integrity PNT solutions to ensure safety and reliability. Close coordination and cooperation of the scientific communities with governments, GNSS system and service providers is therefore beneficial for identifying GNSS vulnerabilities and mitigating space weather threats.

About the author

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Complacency, preparedness and the not-so-great geomagnetic storm of 7 September 2017

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People suffer during natural disasters because of complacency. The worst impacts of space weather can be mitigated, as long as the threat is taken seriously. A 'monster' solar flare erupted from the surface of the Sun on 6 September 2017, sending a huge cloud of plasma (a Coronal Mass Ejection, or CME) toward Earth, which prompted a warning from solar storm watchers for a severe geomagnetic storm. The solar flare and storm blocked HF radio communication and interfered with navigational frequencies across the globe. The Australian Bureau of Meteorology (BOM) conducted a post event review analysis to identify opportunities for improving its forecast service in response to severe space weather. The Bureau has also been working with the Department of Home Affairs to improve national preparedness for when the 'big one' eventually hits Earth.

What is space weather? There is no universally accepted definition of space weather. According to the American Meteorological Society [1], "Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-borne and ground-based technological systems, as well as endanger life or health." This definition admits space weather occurring throughout the heliosphere. However, it does not admit the space weather of other stellar systems [2] impacting their extra-solar planets.

In the author's opinion, cosmic rays including gamma ray bursts from supernovae and other cataclysmic astrophysical systems can produce terrestrial impacts similar to solar impacts, and are therefore also part of space weather.

Some broader definitions of space weather admit the threat and terrestrial impacts of comets and asteroids (especially Near Earth Objects). Like cataclysmic astrophysical systems, NEOs are usually studied by astronomers, not space weather scientists. The latter tend to identify with the geophysics community. However, the overlap between the complementary efforts of astronomers and geophysicists is healthy.

The path to understanding space weather is not through formal definitions, but learning about space weather phenomenology and impacts.

Space climate and storms

Solar cycle 24 ended in December 2019 and was the least active cycle in more than one hundred years. New solar cycle 25 is predicted to reach maximum during 2025. Solar activity is currently increasing and major storms are likely to start occurring within the next 18 months. The consensus is for activity levels similar to solar cycle 24 (i.e., mild) [3]. At the time of writing, solar activity is trending well above the prediction and there is a possibility solar activity will exceed expectations. Predicting solar activity is reminiscent of predicting the behaviour of financial markets – some analysis based on incomplete science combined with the intuition that comes with experience. Basically, we are not very good at it, yet.

The Australian Space Weather Alert System (ASWAS) [4] was recently developed by the Australian Bureau of Meteorology to aid communication with government, industry and the public. The ASWAS is an adaption of the NOAA space weather scales, recast for the Australian context. The ASWAS uses impact-based scales defining the severity of space weather events.

A 'severe' geomagnetic storm occurs when the planetary geomagnetic index, Kp, is ≥ 7. The Kp index is a logarithmic activity index based on 3-hour measurements from a small network of ground-based magnetometers around the world. Severe geomagnetic storms are more likely to occur near solar maximum than solar minimum, but the most intense storms tend to occur during the declining phase. This happens because the polarities of magnetic fields embedded in the Coronal Mass Ejections (CMEs) of the declining phase are more favourable to extended intervals of magnetic southward conditions [5]. Magnetic fields pointing southward are important because this is opposite to Earth's internally generated field. The convergence of opposing magnetic fields triggers magnetic reconnection and increases the flow of solar wind energy into Earth's magnetic environment, the magnetosphere.

Extreme geomagnetic storms (Kp = 9) can occur during periods of weak solar activity and any phase of the solar cycle. The next 'big one' might prove to be a true 'black swan' event with little or no forewarning provided. There is a risk that experienced space weather forecasters could be caught off guard when a cluster of magnetically complex sunspots ruptures on the photosphere at short notice during a period of otherwise weak activity. A deeper understanding of interior solar physics would provide the tools required to avert this misfortune.

The geomagnetic storm of 2017

The severe storm of 7 September 2017 was, by various measures, the largest terrestrial space weather event for solar cycle 24. The storm was the largest in a decade, but it was mild compared to the extreme storms that occurred during previous solar cycles. The storm barely qualified as a severe space weather event, but it was one of the most comprehensively observed and studied storms in history. Importantly, it served as a training exercise for preparing society for when the 'big one' – an event with potentially catastrophic impacts – eventually hits Earth.

Solar cycle 24 activity reached a mild peak in April 2014, and activity had been relatively benign for many months before September 2017. There was sense that most of the space weather 'fun and games' were over until the next solar cycle. To our surprise, during 4-10 September 2017, the Active Region AR2673 produced 4 X-class solar flares, and at least 26 M-class solar flares. Solar flares are classified based on their peak emission in the 0.1–0.8 nm spectral band (i.e., X-ray) and are marked by letters "A," "B," "C," "M," and "X," identifying X-class flares as the most intensive ones with emission higher than 10^{-4} W m^{-2}. AR 2673 proved to one of the most active solar regions in a decade. It created some excitement (and stress) in the Bureau of Meteorology's space forecast centre (Fig. 1).

Figure 1: Dr Zahra Bouya issues a broad range of space weather products from within the Australian Space Forecast Centre located in the Sydney CBD. The various space weather forecast products are received and analysed by a broad range of clients working in government, defence and industry. Image courtesy of the Bureau of Meteorology.

AR 2673 generated the largest solar flare in a decade [6], a 'monster' X 9.3 class flare peaking at 12:02 UT on 6 September (Fig. 2). Eight minutes later, a long-lived burst of X-ray flux reached Earth and produced a strong enhancement of ionisation in the D layer, which is the lowest layer of the Earth's ionosphere. This is found between approximately 50 and 90 km, and is directly driven by solar FUV and X-ray radiation. Hence the D layer disappears beyond sunset.

Space weather effects and radio blackouts

The enhanced D region ionisation immediately caused a strong shortwave radio blackout over Europe, Africa and the Atlantic Ocean. The radio blackout lasted 2-4 hours, depending on the frequency channel. The availability of communication was further disrupted by the ionospheric depressions that occurred beyond the onset of subsequent geomagnetic storms.

Emergency services, aviation, military, and various commercial operators rely on the availability of HF radio communication to coordinate operations, especially in remote locations. Mobile and satellite telephony and cabled links are often lost during major natural disasters. The availability of HF radio becomes critical under these distressed situations.

Hurricane Irma was a powerful category 5 system [7] and devastated many communities throughout the Caribbean during early September 2017. High frequency radio communication was widely used to coordinate emergency response during the passage of Hurricane Irma. The shortwave fadeouts and ionospheric depressions disrupted the emergency response [8], having safety of life implications.

Solar Energetic Particle (SEP) event

Within tens of minutes of the X9.3 class solar flare of 6 September, the satellite energetic particle detectors on the GOES satellite at geostationary orbit observed

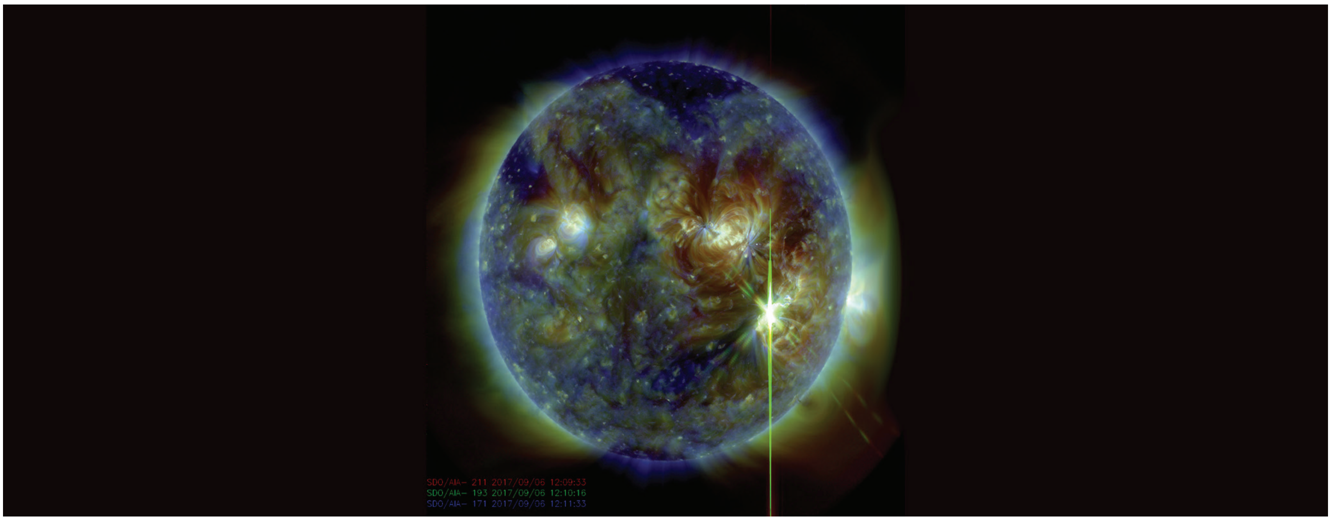

Figure 2: Solar active region 2673 generated the largest solar flare in a decade, an X 9.3 class solar flare peaking at 12:02 UT on 6 September 2017. This composite image was built from three separate images recorded by the Atmospheric Imaging Assembly on board the Solar Dynamic Observatory during 12:09 to 12:11 UT, near to the peak of the solar flare. Images recorded at wavelengths 211, 193 and 171 Angstroms were mapped to red, green, and blue respectively. Image provided courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

a Solar Energetic Particle (SEP) event. There was a large increase in the flux of >50 MeV and >100 MeV protons. Protons with energies >10 MeV were already enhanced near Earth because of an earlier M5.5 class flare occurring late on 4 September.

Relativistic radiation near Earth can have life-threatening impacts on astronauts and is well-known to increase the anomaly rate of satellites and their payloads, occasionally causing their complete, unrecoverable failure. There are growing concerns about the vulnerability of the new mega-constellations of Cube- and Small-Satellites, some of which may not be radiation hardened or adequately shielded. SEP events and CMEs do not occur in association with every X class solar flare [9], and SEP event prediction schemes exist, but their prediction skill is poor [10]. This deficiency in basic physics represents an outstanding gap in our capability and preparedness.

Tracking of the CME

On 6 September the Large Angle and Spectrometric Coronagraph Experiment (LASCO) on the Solar and Heliospheric Observatory (SOHO) – located at point Lagrange L_1 -- detected the launch of a full 'halo' CME [11]. A CME is a radially propagating region of increased plasma density and magnetic field strength embedded within the ambient solar wind, and will collide and slow if the solar wind ahead is slower. The magnetic fields of CME's often approximate to magnetic flux ropes [12].

'Halo' CMEs are a strong prognostic for a direct impact at Earth. A CME can be modelled simplistically as a cone pointed in a radial direction from the source location in the corona. White light from the Sun scatters faintly off the electrons in the CME. When observed from Earth, a perfectly symmetric halo of scattered light encircling the solar disk indicates a CME pointed directly at Earth.

The BoM's space weather forecasters used a GUI software tool to model a radially expanding cone to the SOHO coronagraph observations. The fitted CME parameters were used to inject a model CME into the ENLIL MHD model of the solar wind [13]. Based on an initial propagation speed of 1500 km/s, the model runs predicted a CME arrival time late in the UT day of 7 September. The coronagraph modelling suggested the CME would deliver a 'glancing blow' to the Earth. This means that the weaker edge of the CME was expected to pass over Earth, rather than the centre of the CME where the solar wind speed, plasma density and magnetic fields tend to peak.

The NASA Deep Space Climate Observatory spacecraft is located in a stable orbit around the L1 Lagrange point approximately 1.5 million km upstream of Earth. Depending on the speed of the CME, the solar wind monitor provides approximately 30-60 minutes warning for the onset of major geomagnetic disturbances at Earth. The solar wind monitor detected the arrival of the CME at 22:30 UT on 7 September. The solar wind speed jumped from approximately 400 km/s to more than 700 km/s and the magnitude of the Interplanetary Magnetic Field increased from its pre-arrival value <10 nT to more than 30 nT. Importantly, the direction of the magnetic field, Bz, pointed strongly southward. As explained before, this condition favours magnetic reconnection and energy transfer.

Kp index: The inter-planetary magnetic activity index, Kp, was discussed earlier in this article. It is an excellent indicator of disturbances in the Earth's magnetic field, and is widely used by scientists and aurora watchers to gauge the strength of high latitude electrical currents and the likely occurrence of auroras, the visual manifestations of those currents. Late on 7 September, the Kp index increased from a normal background values of 1-2 to 8. The Kp index is logarithmic, akin to the Richter scale of earthquake intensity. Like earthquakes, Kp values of 8 and 9 represent the most extreme and infrequent events, corresponding to unusually intense electric currents flowing up and down magnetic field lines and closing in the ionosphere.

Dst index : The disturbance storm time index, Dst, is another standard measure of geomagnetic activity. It provides a measure of the partial ring current encircling the Earth at geostationary distances. The ring current is a dynamic current system with its structure and intensity changing dramatically, depending on the level of disturbances induced by the solar wind:

During a geomagnetic storm the ring current increases in strength and has a net flow towards the west (clockwise looking down from above the North Magnetic Pole). The magnetic field perturbations curl around the volume of the current; hence the ground perturbations are negative (towards the south) inside the ring current. This is opposite to the direction of the Earth's main, internally generated magnetic field. A negative Dst value means the Earth's main field is weakened by the westward ring current in the magnetosphere. McPherron [14] gave a comprehensive lecture on the derivation of Dst index.

BOM and the Australian Energy Market Operator (AEMO) developed Standard Operating Procedures (SOPs) designed to mitigate the deleterious impacts of Geomagnetically Induced Currents (GICs). GICs are caused by the interaction of CME with the Earth's magnetosphere through a process called electromagnetic induction. The distorted magnetic field interacts with the ground conductivity resulting in ground potential differences, which generate flows of induced current through the neutral line of transformers.

The AEMO SOPs are activated when the BOM issues a severe space weather notification, triggered when the Australian region Dst index decreases below -250 nT. During the peak of the September 2017 storm, the Australian region Dst index decreased from near zero

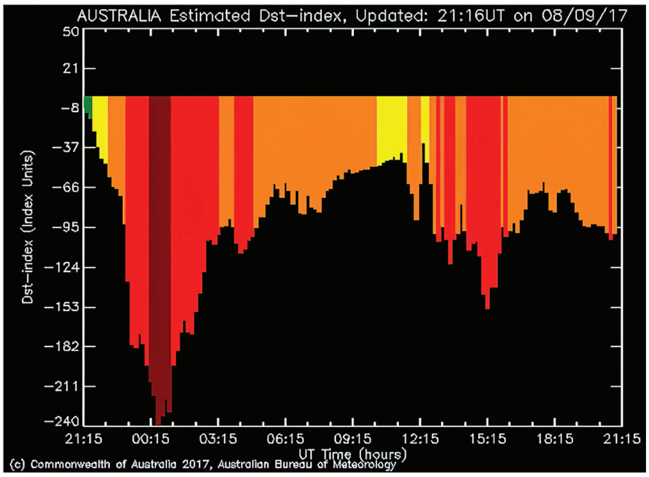

Figure 3: A bar graph of Australian region Disturbance storm time (Dst) index at 10-minute cadence for 24 hours commencing 21:15 UT on 6 September UT. More negative values correspond to stronger westward current circulation in the partial magnetospheric ring current, and provide a good representation of global geomagnetic storm progress in the Australian longitude sector. The index is a good proxy for possible impacts on the Australian electricity grid, as well as auroras visible from southern Australia. Image provided courtesy of the BOM.

to -240 nT (Fig. 3). The index is calculated using the BOM's magnetometer network, which is a critical asset helping to protect the Australian electricity grid. BOM also models GICs flowing throughout the Australian region in near real-time. For this event, the modelling showed the currents coupling into the electricity grid fell short of the thresholds expected to fatigue high voltage transformers. There were no reports of immediate disruptions to the Australian electricity grid throughout the storm.

Great geomagnetic storms

The Dst indices for truly great geomagnetic storms vary from -500 nT to -1500 nT, and possibly larger (more negative). The many diverse impacts to ground- and space-based technology will likely far exceed the minor disruptions occurring during the 7 September storm. For example, the electricity grids of nations located at high latitudes in the Northern Hemisphere will likely experience major failures. The electricity grid of New Zealand is more vulnerable than the Australian electricity grid, by virtue of New Zealand's closer proximity to auroral current systems and because also because of the linkage between generators in the South Island to users in the North Island.

Although the space weather events throughout this period were impressive, especially for the thousands of aurora chasers who watched the night time displays from

Tasmania and Victoria, it fell far short of what would be considered a great geomagnetic storm, the kind of storm that occurs once in a human generation.

During a great storm, the CME speed can be as fast as 3000 km/s, a speed that is off the scale for existing in situ solar wind monitors. Even if a new generation of monitors were redesigned to not saturate at these speeds, it is likely the spacecraft would be incapacitated by the SEP event preceding the arrival of the CME anyway. The solid-state imaging sensors such as the SOHO coronagraph or its follow-on would also be blinded by the SEP radiation blizzard.

Unfortunately, the full utility of space-based observatories could be compromised when they are needed the most during extreme space weather conditions. This is one of the reasons why the world must continue supporting a network of ground based solar patrol telescopes.

A list of space weather effects

Major but not truly great storms of this kind are a blessing because they provide an opportunity to evaluate the performance of space weather modelling and prediction, and for government and industry to exercise and hone an effective coordinated response, increasing the nation's preparedness for the inevitable 'big one'. The BOM's forecasters provided many telephone briefings to government and industry, and issued numerous warnings and alerts throughout the period:

- 31 flare alerts, all for AR 2673
- 4 shortwave fadeout warnings for 3-11 September
- 3 shortwave fadeouts in Australia, 5-7 September
- 3 Proton Event Alerts, 5-14 September
- 5 Geomagnetic Warnings, 6-15 September
- 4 Magnetic Alerts (Kp > 5), 7-15 September
- 2 Aurora alerts, 7-8 September
- 2 HF Communication Warnings, 7-10 September
- 1 Severe Event Watch, 7-8 September

The BOM conducted a post event review analysis to identify opportunities for improving its forecast service in response to severe space weather. The Bureau has been working with the Department of Home Affairs, the National Situation Room (previously named the Crisis Coordination Centre), and the aviation, defence, energy and space industries to increase whole-of-society preparedness.

Closing remarks

It can be argued that complacency, a failure to take a threat seriously and prepare and act appropriately, is a major killer during bushfires and other natural disasters. In principle, most life and property can be protected with sufficient foresight and preparation. In the case of space weather, many nations and sectors of society understand the threat and are developing risk mitigation treatments. Australia is making good progress at senior corporate and government levels. Our state and federal governments are preparing for the ever-increasing vulnerability of our technological civilisation to severe space weather events.

The potentially catastrophic impacts of a great geomagnetic storm can and will be ameliorated if we reengineer our systems and procedures to mitigate the worst impacts. However, there are still many unsolved scientific challenges in solar, heliospheric and magnetospheric physics [15] that must be addressed to seed the modelling and prediction tools required for this to be achieved at Earth and beyond.

About the author

Murray Parkinson obtained an MSc in applied astrophysics and a PhD in radar oceanography at the University of Queensland. Next he worked as an ARC funded research associate in Prof. Peter Dyson's space physics group at La Trobe University. Murray's research interests included the use of digital ionosondes and SuperDARN radars to study magnetosphere-ionosphere coupling. He has published approximately 60 refereed papers in scientific journals and presented at numerous conferences. Murray worked as the Consultancy & Development Manager in the BOM Space Weather Services for over 10 years, including during the September 2017 storms.

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Spaceflight Dynamics

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Mission operations are highly dependent on having accurate models for the satellite's position, velocity and attitude. Many factors contribute to a satellite trajectory in different orbital regimes. This article covers elements of spaceflight dynamics relevant for our understanding and discusses some of the relevant factors important for collision alert and warning systems.

In low earth orbit (LEO) regimes, the changes in aerodynamic drag effects due to space weather events can be large enough to cause calculations to be over a kilometre off after just a day [1]. From an operational viewpoint, this can be detrimental to avoiding collisions, docking or taking highly accurate astronomical measurements such as electro-optical measurements of distant stars. From a space domain awareness perspective, we are concerned with many satellites at once, so accurately calculating the positions becomes important as collision alert and warning systems require precise accuracy for at least a few days in the future for the alerts to be helpful.

A brief history

We are constantly observing and building new theories about our reality. With small incremental gains of knowledge, we build an accurate model of the universe. With his telescope, Galileo observed the phases on the moons of Jupiter and saw that they followed the same relationship with our moon; from this, he deduced that the Earth must orbit the Sun as Jupiter does [2]. To obtain the first laws of planetary motion, Kepler, using geometry as inspiration, observed the relationships from data and gave us his three laws of planetary motion [3]. Newton asked, "if the apple falls, does the moon also fall?" and gave us the calculus and the inverse square law for gravitational attraction:

$$\boldsymbol{r}'' = -\frac{GM}{\|\boldsymbol{r}\|^2}\left(\frac{\boldsymbol{r}}{\|\boldsymbol{r}\|}\right)$$

$$\boldsymbol{r}''_i = G\sum_{1\le j\le N} m_j \frac{1}{\|\boldsymbol{r}_j - \boldsymbol{r}_i\|^3}\left(\boldsymbol{r}_j - \boldsymbol{r}_i\right)$$

In the formula above, G is Newton's gravitational constant, **r** is the cartesian position of the body in an inertial reference frame, and |**r**| is the magnitude of the position vector. The two-body equation was sufficient for planets orbiting the sun, and we could make reliable predictions far into the future.

As Mercury orbits the Sun, it is affected by the curvature of gravity produced by the Sun's mass. Einstein wondered if this would cause the predicted position of Mercury under his new theory to be more accurate than if he used Newtonian mechanics. The prediction was more accurate than the previous, proving his famous theory of relativity [4].

As our tools and methods for taking measurements improved, we became more interested in the complex relationships we saw in our solar system. We simplified reality to two-body problems and noticed that our new theories did not align with the data - the moon's orbit, for example, is affected by both the Sun and Earth. We still required new models and extended our calculations to include the N-body perturbations:

As we introduced the third body, our analytic equations began to become inadequate. The three-body problem becomes problematic as we cannot solve it analytically, i.e. we can't write down a set of equations that the system follows. Some solutions do exist for special cases, but not for the general case - the same of course is true for the N-body problem. The three-body problem has motivated the invention of new mathematics.

For Earth-orbiting satellites, where third body forces became negligible, predicting a few orbits into the future we still saw discrepancies in our predictions and what we observed. The extra force that perturbed the orbit is because of the ellipsoid shape of the Earth caused by its rotation There is a centrifugal force causing the Earth to bulge out at the equator. The effects from the oblate shape of the Earth became apparent, and we began to model the Earth not as a point mass but as an ellipsoid.

Another force we have to consider are the effects of air resistance as the satellite moves through the atmosphere. Until we launched satellites, studying the upper atmosphere was impossible - early theories were built about the atmosphere by observing how satellites decayed and deorbited from slowly taking observations and making assumptions we built up these models.

As computational hardware and software were still in their early development while running early missions, the requirement for an efficient tool for calculating the positions and velocities for satellites was in demand. This requirement produced the simplified general perturbations (SGP4) algorithm [5]. This included the oblateness of the Earth and a static exponential model for atmospheric density, which we use for aerodynamic drag. We still rely heavily on this model for operations. The circulation of two-line element sets (TLE), the input of the SGP4 algorithm, is still the norm in the industry. This motivates conversations about accuracy and how reliable these models are for the safety of flight and space domain awareness. Figure 1 shows a screenshot of the TAROT software tool, written in Javascript & Python, which ingests space location data from various sources. The dots represent satellites. Orbits are resolved by standard physics models such as SGP4 or special perturbations.

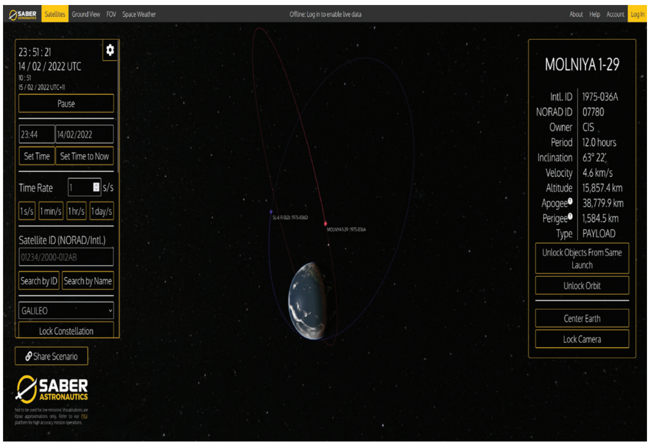

Figure 1: Screenshot of the TAROT software tool, showing the Molniya orbit (https://tarot.saberastro.com/).

TAROT is available for free to the public so anyone, from anywhere in the world, can see where their favourite spacecraft is flying.

High precision modelling

As technology continues to improve, we have many orders of magnitude more computing power than the scientists and engineers of the space race of the 1960s. We can run more precise algorithms for computing the future positions of satellites without the need for expensive computers only available to a handful of people.

The current gold standard of satellite trajectory calculations is the numerical integration of acceleration to find the position **r**, and velocity **r**′ of the satellite.

$$\boldsymbol{x}(t) = \begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{r}' \end{bmatrix} \quad \boldsymbol{x}'(t) = \begin{bmatrix} \boldsymbol{r}' \\ \boldsymbol{f}(t, \boldsymbol{r}, \boldsymbol{r}') \end{bmatrix}$$

$$\boldsymbol{x}(t+h) \approx \boldsymbol{x}(t) + h\boldsymbol{x}'(t)$$

Here, **x**(t) is a vector matrix with components of position and velocity vectors estimated at a time t. The function **f** accounts for every perturbation we wish to model, i.e. every force that affects the satellite's trajectory, **f** = **r**″. These forces include geopotential gravity, third body forces from other planets, the sun and the moon, atmospheric drag and solar radiation pressure.

The formula above shows that we can calculate a state in the future **x**(t+h), (where h is a small time step h >0) by knowing the current state **x**(t), and how the state is changing **x**′(t). If we repeatedly take small time steps, we can calculate the position and velocity far into the future. In practice, we use high dimensional Runge-Kutta methods [6] to integrate the equations forward through time.

The gravity geopotential is the strength of the gravitational field caused by Earth at any point in space. As Earth is not perfectly round or equally dense, we use spherical harmonics to represent the gravity potential and gravity vector in space. Finding the coefficients used in this model was done by taking many measurements by specialised satellites (see EGM96 [7] or JGM3, for example). The non-spherical Earth and the gravity anomalies can have varying effects on the trajectory of a satellite. If we look at the orbital elements of a satellite through time, we can see them oscillating and changing. The equatorial gravitational bulge produces an extra pulling force in the equatorial plane (the J_2 perturbation force). The additional force is the cause of apsidal rotation and nodal regression. The effect can also be used to produce unique orbits such as the Molniya orbit shown in Figure 1. For satellites in LEO, 400-800 km, the effect of the J_6 spherical harmonic perturbations can be as large as the force due to atmospheric drag, and as such, if we ignore them, our trajectory calculations can be off. A simple simulation experiment can show that ignoring terms J_6 and above results in an oscillating error between 0.1-1.0 km just after a single day.

Atmospheric drag is the most significant non-gravitational force that affects satellites in orbit. Calculating the force also requires having a model for the density of the upper atmosphere. Drag forces can also introduce significant uncertainties. For example, if a spacecraft has an organic shape and is tumbling, it creates a complicated aerodynamic relationship. The atmosphere's density also depends on space weather which introduces the need to be able to predict severe space weather events.

The drag force is calculated using the equation below,

$$\boldsymbol{r}'' = -\frac{1}{2}\rho(t, F_{10.7}, K_p, \boldsymbol{r})C_d\frac{A}{m}|\boldsymbol{r}'|\boldsymbol{r}'$$

Where **r''** is the acceleration due to drag, **r** and **r'** are the position and velocity respectively, ρ is the air density which is a function of space weather parameters (F10.7 and *Kp*), time and position, m is the mass of the satellite, *A* is the drag area, C_d is the drag coefficient.

The solar radio flux at 10.7 cm (2800 MHz) is an excellent indicator of solar activity. Often called the F10.7 index, it is one of the longest running records of solar activity. The F10.7 radio emissions (in "solar flux units", (s.f.u.)) originates high in the chromosphere and low in the corona of the solar atmosphere. The K-index, and by extension the Planetary K-index, are used to characterise the magnitude of geomagnetic storms [5].

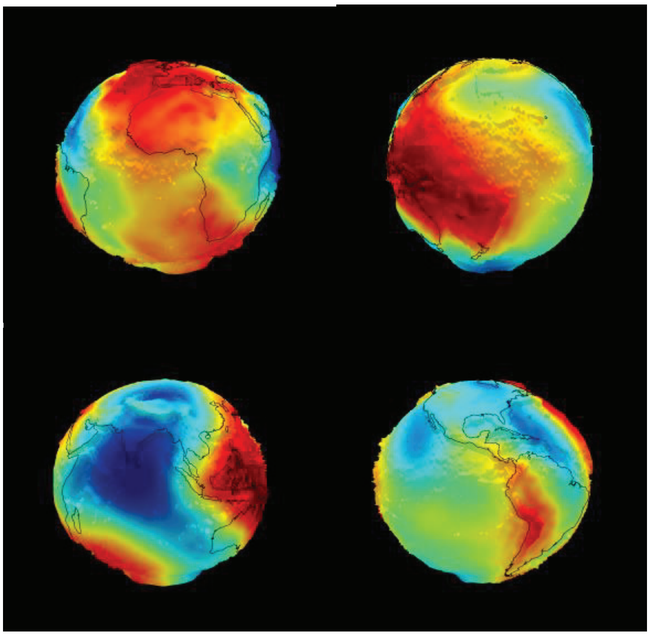

Figure 2: A 3D high-resolution model of the terrain on Earth (not to scale). The colour indicates the geopotential field strength of the geopotential anomalies. There are several points of interest: the low field strength below India and the high field strength of the Andes mountain range.

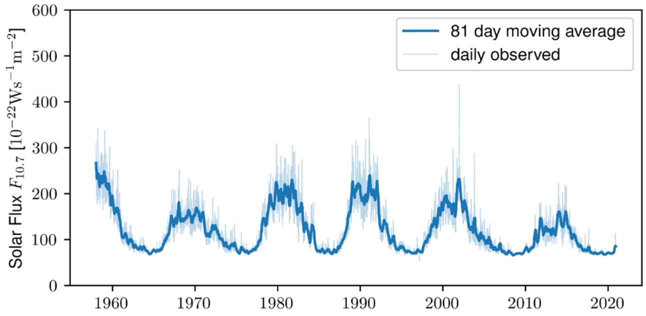

Figure 3: The figure above shows the exospheric temperature as a result of the Sun's activity as indicated by the F10.7 index. The seasonal relationship is caused by the magnetic pole on the Sun flipping. During periods of high exospheric temperature, satellites have shorter lifetimes as the aerodynamic drag is typically higher.

Extreme space weather events can cause large, volatile changes in atmospheric density, which is especially the case in LEO - these changes can cause the density to be 3-5 times higher than in nominal space weather conditions. This is because the exospheric temperature and geomagnetic flux index cause the atmosphere to expand. The temperature of the thermosphere at high altitudes is referred to as the exospheric temperature. As mentioned previously, failing to account for the large space weather events can cause your calculations to be over a kilometre off after just a single day [1]. Studying the upper atmosphere was impossible until satellites were being launched. Early models of the upper atmosphere were made by analysing how satellites decayed. Today there are many specialised satellites for building upper atmospheric models and geopotential models, such as the LAGEOS satellite [9].

Operations

For the safety of flight and space domain awareness, we want to minimise the risk of potential collisions or near misses in space. We define conjunction as when a satellite enters another satellite's spatial neighbourhood. To find conjunctions, we require accurate modelling of the satellite's position in time for at least a few days into the future. As we typically only know the position of a satellite to within a kilometre, and this uncertainty grows each day by several kilometres, we want to calculate conjunctions within a 5-25 km neighbourhood, depending on the use-case and size of the satellites.

Flight safety and space domain awareness will become more critical as space gets increasingly cluttered. There are now over 7900 satellites orbiting the Earth. 2800 of these have launched in the last two years. As the number of conjunctions depends on the number of unique pairs of satellites, the number of conjunction events increases

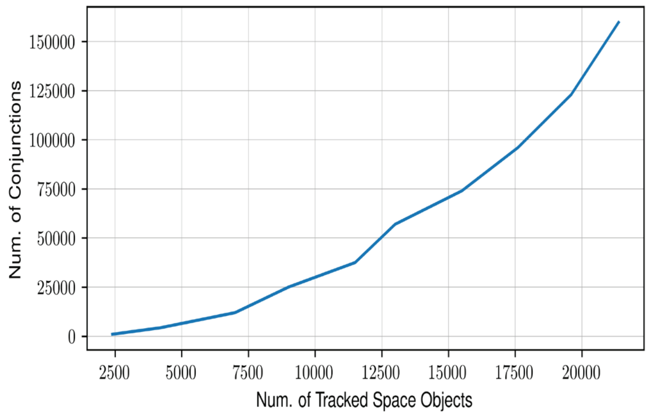

Figure 4: The number of conjunctions where the minimum distance is less than 5 km over seven days.

at a squared rate with the number of satellites, as shown in Figure 4.

As the space industry grows, operators spend more time planning manoeuvres to avoid potential near misses. If a collision occurs, it could cause millions of dollars worth of damage. In more serious events, satellites can break up into hundreds or possibly thousands of pieces of uncontrolled debris [10]. The debris could ignite a chain reaction of further collisions ending in a cloud of debris so large and dangerous that it will make impossible for humans to enter space safely or even launch an operational satellite.

Conclusion

As Australia's research and commercial space industry grows, we want the sovereign capability to command and control satellites safely. It will require having reliable and accurate tools to perform operations and collaborate safely in the international space industry.

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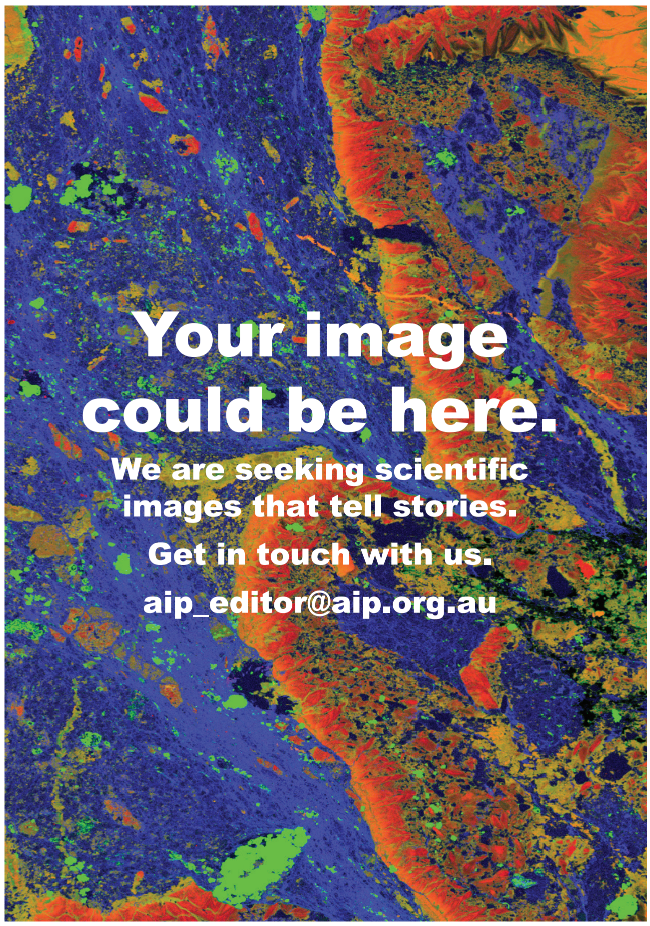
About the company

Saber Astronautics (SA) is a space operations and flight software company with 50 engineers skilled in mission operations, space traffic management and spacecraft systems. SA' mission is the democratisation of space, reducing barriers to space flight, and making space as easy as driving a car. SA provides flight operations, mission design services, and related software. The mission control service, the "Responsive Space Operations Centre" was selected by the Australian Space Agency's $6m Space Infrastructure Fund. SA is a trusted supplier to traditional space and government customers worldwide, for flights ranging from Cubesat class to 2-tonnes.



Behind the active Sun

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The Sun rotates rapidly, with an equatorial period of 27 days, and magnetic active regions can appear suddenly on the eastern solar limb as the Sun turns. These can generate huge solar flares or coronal mass ejections, triggering space weather events that can negatively affect the Earth. Many such events could be anticipated a week or more in advance if we could effectively view the far side of the Sun. Helioseismology can do this; it allows us to monitor the evolution of large active regions throughout their lifetimes and to forecast their arrival before they rotate onto the Sun's near side.

Solar activity

Solar activity exhibits several potentially destructive processes, including massive solar explosions that impact space weather, such as solar flares and coronal mass ejections (CME), erupting prominences, the fast and slow solar winds, energetic particles, and stream jets. Magnetic fields are the prime drivers of these events, and CMEs are their most dangerous feature when they impact the Earth.

In the interior of the Sun, the solar dynamo generates strong magnetic field from a combination of differential rotation and convection. When the motion of the hot plasma inside the Sun contorts the localised embedded strong magnetic fields, twisted turbulent magnetic structures emerge from active regions above the solar surface. These can explosively blast large amounts of magnetic energy into space leading to spectacular solar flares and coronal mass ejections, which sometimes occur at the same time, but act and emit different radiations, and produce different effects near the Earth. These impulsive events can impact the Sun itself, for example causing flare-generated solar quakes [1]. As the Sun becomes more active (as a result of its own 11-year magnetic cycle) it produces many eruptions with a maximum activity predicted for cycle 25 in the year 2025.

Helioseismology and data

Today, helioseismology [2] has major applications for space weather. It is a reliable monitor of large active regions on the far side of the Sun, making it part of routine space-weather forecasting [3,4]. Helioseismology as a branch of solar physics has done much to improve our understanding of the structure of the Sun and its internal rotation. It informs the physical inputs used to model stellar interiors, and is similar to geo-seismology: seismic waves travel through the Sun or Earth's interior and disclose what is below the surface.

We know that the Sun is in a state of permanent oscillation (the surface of the Sun, the photosphere, moves up and down with vertical velocity amplitudes of 3 cm/s, sometimes up to 1 km/s). The modes of oscillations are predominantly acoustic in nature. Acoustic oscillations are trapped inside the Sun by its radial temperature structure and are affected by and provide information on flows and near-surface magnetic fields. They are subject to strong refraction and travel along curved "ray paths".

With these insights, helioseismologists analyse the hot plasma through which the sound waves travel. Detailed long-time-series measurements of the properties of sound waves (energy, frequency, phase, amplitude) can be used as probes of the Sun's sub-photosphere, and in particular can image near-surface active regions and their impacts on the surrounding large-scale flows and magnetic evolution. These waves, called "*p*-modes" (pressure modes) are understood to be excited by turbulent convection in a thin layer beneath the Sun's surface. In fact, it was discovered in the 1960s [5] that patches of the Sun's surface were oscillating with a period of about five minutes, which led scientists to conclude that the observed motions are the superposition of thousands of global resonant modes of oscillation of the Sun (acoustic and gravity waves). These *p*-modes propagate freely throughout the solar interior, probing different depths depending on their frequencies and spherical degree ℓ, reverberating between the near and far hemispheres.

The most widely used local helioseismic techniques are time–distance helioseismology (TD) [6] and helioseismic holography (HH) [3,4]. TD detects changes in the travel time for acoustic waves traveling through a magnetised active region compared to those traveling only in the quiet Sun, while HH detects phase shifts in acoustic wave signals. Both methods map active regions on the near and far side of the Sun.

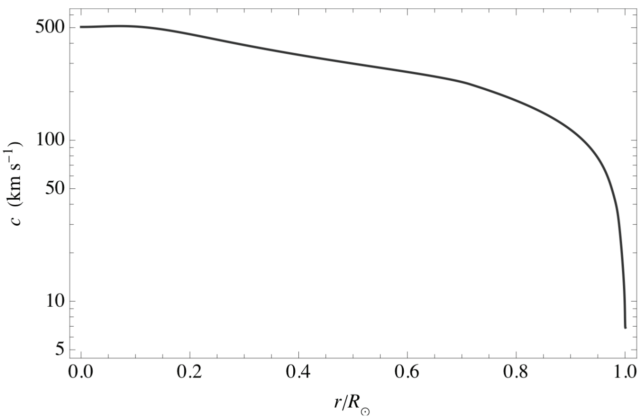

Figure 1: Speed of sound in a standard solar model as a function of radius. The sharp decrease in the sound speed near the surface of the sun largely traps p-waves in the interior, allowing them to skip multiple times over large distances.

Let us uncover some subtleties of helioseismology:

- Far-side imaging relies on multiple-skip waves, using waves that are reflected at the surface at least once on their paths from the focus point to observation point and vice versa [7,8].
- To understand wave propagation and interactions in a shallow surface layer and above we often employ elements of magnetoseismology and complex mathematical modelling.
- A sound wave propagates without hinderance along a magnetic field line not exciting any magnetic wave in the process? We identify this as total transmission [9].
- Active regions are strong scatterers of acoustic waves reflecting back into the solar interior from their photospheres, whether the incidence is normal or oblique.
- Two-skip seismology data and calculations [10] were used to measure travel times for waves of different frequencies, skipping from one side of the sunspot into the centre of spot, then again to an oppositely positioned observation point outside the sunspot. A quiet-sun reference for the travel times was derived by doing the same analysis. The travel delay was zero near 2 mHz and increases (in magnitude) to -100 s near 5 mHz. Interestingly, the umbra of sunspots proved to be shallow!
- Helioseismolog requires big data.

Big data

The validity of helioseismic far-side imaging was evaluated by comparing with the Sun's far-side observations of the Extreme UltraViolet Imager (EUVI) onboard the twin Solar TErrestrial RElations Observatory (STEREO) spacecraft. However, nowadays the surviving STEREO-A satellite has lost its view of the far side (angle<90° with Earth). Since its launch in 2010, NASA's Solar Dynamics Observatory (SDO) [11] has continuously imaged how the Sun displays its solar activity and drives space weather. Helioseismologists use Doppler data from the Helioseismic and Magnetic Imager (HMI) onboard SDO, to map these oscillations, both spatially and temporally. The velocity of the solar surface can be determined by measuring the shift of these lines caused by the Doppler effect, or by intensity variations. The critical measurement in helioseismology is the precise frequency of each mode of oscillation and this can be achieved if one maintains uninterrupted observations of the Sun at ground-level and/or through satellites.

At ground level, the Global Oscillation Network Group (GONG) suite of six instruments spread around the globe does the same thing. One of the six telescopes is located at the Learmonth Solar Observatory [12], in Western Australia. GONG is monitored by the Bureau of Meteorology – Space Weather Services and the US Air Force and has observed millions of resonant modes of oscillations in the solar atmosphere.

Computational analysis of solar oscillations imaged in the Sun's near hemisphere, the one that SDO and GONG and other instruments can see, consists of applying basic principles of wave optics to model *p*-modes propagating through the solar interior. It gives us seismic maps of large active regions in the near and the far hemispheres, information that we use for space weather predictions. [Fig. 2]

Mapping acoustic active regions

Synoptic seismic maps are presently being published by the Stanford's SDO JSOC server and are publicly accessible through jsoc.stanford.edu/data/farside. Figure 2 shows a farside seismic map for the recent period 21-23/03/2022. A large dark region on the farside map is detected (top arrow in Figure 2). This signature reveals that a wave path arriving or leaving that location experiences a reduction in its travel time (negative) when interacting with an accumulation of magnetic field, i.e. an active region (AR). The AR is estimated to appear on the near side eastern limb as observed from Earth on 27/03/2022 and it is big! The image also shows the line-of-sight magnetic field (measured in Gauss, in the near/visible hemisphere, rendered in blue/grey). Black and white spots represent

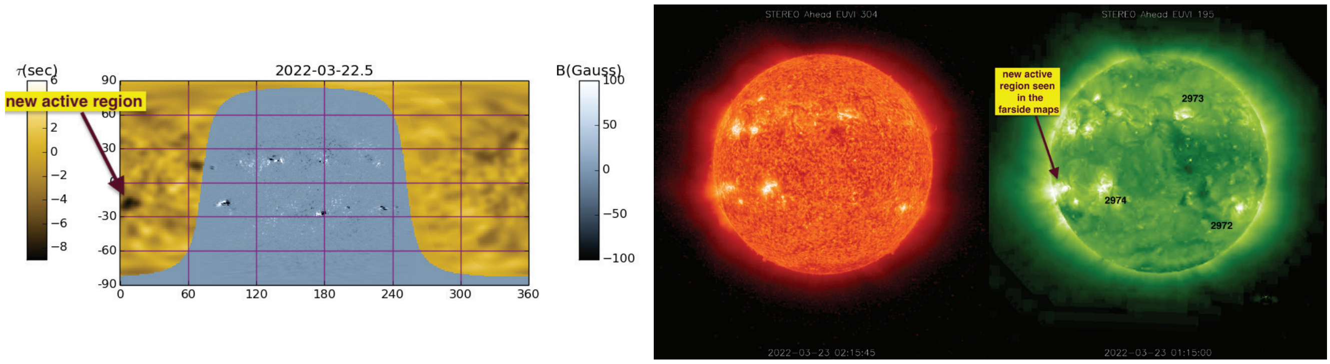

Figure 2: Left: Recent calibrated farside maps. The farside imaging (amber) is based on an analysis of sound wave travel time variations (measured in seconds), with locations of shorter travel times appearing darker. Time delays of as much as 10 seconds can be measured when an acoustic wave bounces inside the Sun multiple times.
Right: STEREO Extreme Ultraviolet Images (195 and 304 Å wavelengths) showing a view of the Sun at the same time, and comprising the new detected active region -arrowed- which SDO cannot see it yet. Active regions are labelled by numbers.

opposite magnetic field polarities. STEREO instruments had just picked up the signatures of the farside AR (second arrow in Figure 2), because STEREO-A slowly was catching up with Earth as it orbited the Sun, viewing the Sun from out-of-Earth vantage points.

Solar magnetism

Far-side imaging has been successful for predicting the appearance of large active regions and complexes of activity, but we have to admit that sometimes the resolution and the appearance of spurious signals require careful calibrations and interpretation. The next step is to develop computational algorithms that improve resolution and correlate seismic maps to exact magnetic flux details of ARs, a task essential for understanding solar explosive phenomena. Magnetic maps over the entire surface of the Sun for a given moment in time, are used in coronal field extrapolations and therefore for space weather forecasting and solar wind modelling (Fig. 3).

The next important question is: **Can we tell when an active region is about to flare?** Scientists work on predictors for ARs. Some predictors may refer to physical quantities, such as the amounts of electric currents that are injected into the Sun's outer atmosphere (corona) or the total magnetic flux of the AR. Others may be proxies of the free magnetic energy, which depends on the length of all connections between opposite magnetic polarities, or the "effective connected magnetic field strength" which is a measure of the magnetic flux associated with these connections. Predictions of solar eruptions and their severities and Earth-impacting potentialities are currently probabilistic. Improving the accuracy and lead times of these predictions is a top priority for scientists around the world. The need for practical space weather forecasts is growing more rapidly than ever before.

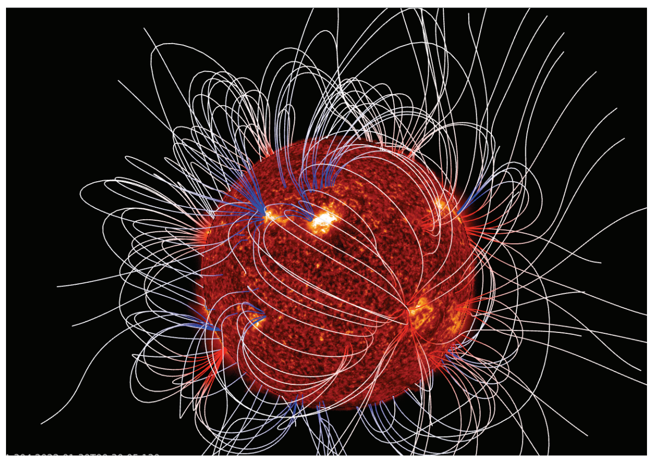

Figure 3: The PFSS (Potential Field Source Surface) model visualises global magnetic field lines of the Sun, derived from SDO magnetograms on 30th Jan 2022, the day when the Sun unlashed its CME on Earth and Starlink. The background shows the SDO Atmospheric Imaging Assembly (AIA) 30.4 nm image, taken on same day. PFSS provides a simple and effective model for the large-scale features of the global coronal magnetic field www.jhelioviewer.org/.

Machine learning

Machine Learning algorithms for solar far side pattern predictions can help us by rapidly extracting information from the myriads of solar data and quantitative relationships between seismic, magnetic and extreme ultraviolet observations. Generative Adversarial Networks (GANs) are popular deep learning methods useful for image generation. They can teach models to generate the input distribution as realistically as possible, and have been used for training and validation of farside solar data. Below QR codes link to movies of the SDO/AIA Images and the corresponding SDO/HMI Magnetograms which show the successful application of deep machine learning are compared against the AI-generated magnetograms of the Sun [13]. Future research requires that the found AI models can be applied to far side STEREO 304Å data or seismic maps to generate magnetograms of the far side of the sun. We have to remember, that there are no planned missions to continue observations of the solar farside, so we must rely on computationally derived helioseismic maps and the speed of AI algorithms to detect the locations and sizes of far-side ARs and give us adequate warning of their arrivals on the near side.

Conclusion

Helioseismology is essential for future research in space weather to deliver accurate and useful information. The momentum gained by solar physicists in this direction will only be sustained if we maintain and improve wider knowledge of fundamental science, of solar activity and space weather, not least by ensuring that policymakers and the general public are aware of research progress and how it can be exploited.

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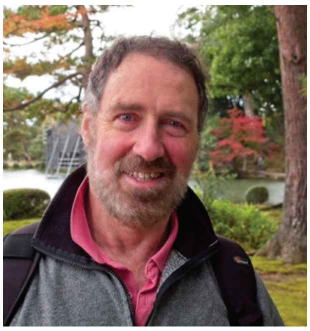

Prof Paul Cally's research interest are in Magnetohydrodynamic waves and instabilities, solar physics, helioseismology, MHD mode conversion, analytic and numerical solution techniques, applied mathematics, solar activity and solar and stellar dynamos. President of the International Astronomical Union Commission E2 "Solar Activity".

Mapping energy input to geospace

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Earth is a magnetised planet and is immersed in the Sun's outer atmosphere. These two facts drive the scientific discipline of solar-terrestrial physics, a subset of space science. This research area is different to astronomy. Researching the properties and dynamics of the near-Earth space environment is more important than ever before as human technologies move into space and the integrity of terrestrial infrastructure depends on space weather conditions. A key quantity is the energy input to the solar-terrestrial system.

The origins of space physics lie in pre-1950 research into geomagnetism, particularly the perturbations of the geomagnetic field associated with solar activity and observations of the aurora, a feature of magnetised planets. Of course, there is overlap in space physics and other areas of research. These links may be traced through investigations into the most common state of matter, the fully ionised gas or 'plasma' state. Therefore, research in space physics complements and informs other areas such as fusion energy research, industrial plasmas, astrophysics and parts of environmental science and geophysics.

Space Physics

Space physics matured into a separate research discipline beginning with the first launch of artificial satellites in the late 1950s. Since then, many planetary spacecraft missions have returned in-situ data (e.g. https://nssdc.gsfc.nasa.gov/planetary/). These, in addition to data obtained from ground-based sensors, fuel space science research within a collaborative, international framework. However, all these observational data sets only sparsely sample the vast volume of near-Earth space. Furthermore, in-situ observations come from moving platforms with limitations on spatial, temporal and energy ranges. Therefore, ground- and space-based data are combined with complex computer simulations. A major objective is space weather prediction capability, similar to atmospheric weather prediction, with practical goals of timely and accurate severe event forecasting and mitigation.

The recently released Australian Academy of Science Decadal plan for Australian Space Science 2021-2030 (https://science.org.au/AustraliaInSpace) provides details of the diverse research topics within space science. The plan details the importance of space science research for the space industry, risk assessment and mitigation for critical infrastructure and warns of skills shortages.

Sensors and data

Since Earth is a magnetised planet, the magnetometer is a common sensor deployed over Earth's surface and on spacecraft. Terrestrial electric field measurements have been used but these are often contaminated by atmospheric weather systems. Electric field measurements in Earth's ionosphere are used, as described later.

Sensors flown on spacecraft include induction coil and fluxgate magnetometers, electric field probes, imagers that operate over various bands of the electromagnetic (EM) spectrum, and charged particle detectors that can distinguish between ions (mass spectrometer) and energies. The induction magnetometer is the simplest sensor, based on Faraday's law of EM induction, and is well within the capabilities of a high school research project for detecting the magnetic signatures of moderate to large solar activity.

Space physics investigates the dynamic relationships between electrically charged plasma particles and electric and magnetic fields in space. While astrophysics relies on EM wave emissions from vast distances, space physics uses both EM and particle emissions predominantly within the solar system. Stars are fuelled by nuclear fusion and the Sun is no exception. The solar 'wind' is the Sun's particle emissions. Spacecraft that are designed and populated with sensors for monitoring solar emissions such as WIND, ACE, Solar Orbiter and Parker Solar Probe provide 'upstream' data such as the speed, density, pressure and magnetic fields in the solar wind.

Sensors on Earth in concert with Earth orbit and solar monitoring spacecraft form the data set for studies in solar-terrestrial physics. This research aims to understand, in order to predict, energy conversion and distribution pathways from space to Earth's environment. Space weather research explores the impacts on human technologies and infrastructure due to the location of Earth within the Sun's outer atmosphere.

Earth's magnetosphere

The relative velocity between the magnetised Earth and the ~450 km/s (average) solar wind particles forms a complex, dynamic, tear-drop shaped region in near-Earth space called the magnetosphere, as illustrated in Figure 1. Consider a location in the equatorial plane at the sunward side of the magnetosphere (left side of Figure 1). Application of the well-known right-hand rule with the geomagnetic field (B) directed up the page and solar wind velocity (mostly) flowing from left to right, gives a (Lorentz) force in or out of the page depending on the sign of the charged particle. This is conversion of kinetic into electrical energy which drives electric currents and forces plasma motion within the magnetosphere that maps to Earth's upper atmosphere where solar EM radiation modulates ionisation levels in the ionosphere. This dynamic, complex energy exchange and transport produces dynamic space weather patterns that have various impacts on LEO satellite integrity (e.g. Starlink final orbit failures), Global Navigation Satellite Systems (GNSS), HF radio propagation in the ionosphere, long terrestrial conductors (e.g. pipelines, electricity grids) and human radiation levels ranging from aircraft altitudes to space.

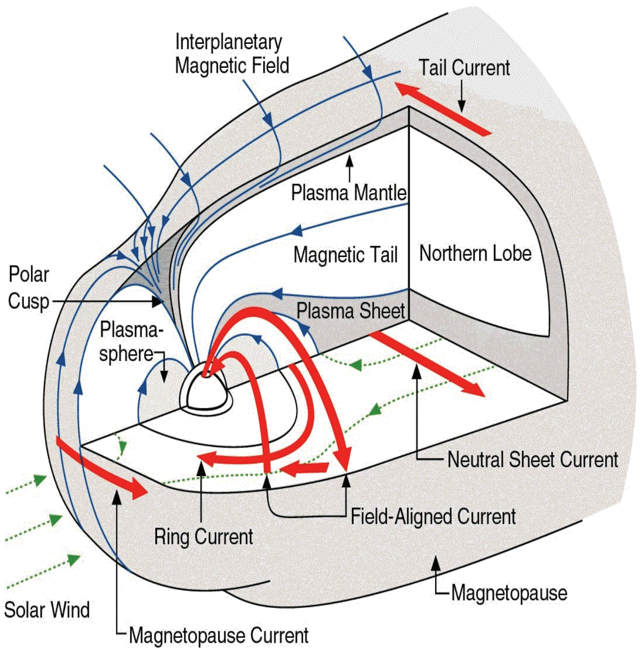

Figure 1: Sketch of the near-earth space environment. The Sun is at left. A typical distance from earth to the sunward 'nose' is 12 R_E.

Global scale dynamics

Predicting the 'when' and 'where' of space weather and its severity is a prerequisite for understanding impacts on human activity. Therefore, quantifying energy transfer from the solar wind to Earth's upper atmosphere informs the when, where and severity of space weather and impacts on human technology. The super-Alfvenic solar wind interacts in the relatively thin outer boundary of the magnetosphere to produce a vast electric dynamo, delivering up to ~10^{12} W to the ionosphere and thermosphere. The aurora borealis and aurora australis are spectacular manifestations of these processes. Stresses from the dynamo regions in the outer magnetosphere are linked to the ionosphere by large scale Birkeland (field aligned) currents (FACs) and impose an electric field on the finite conducting, northern and southern ionospheres.

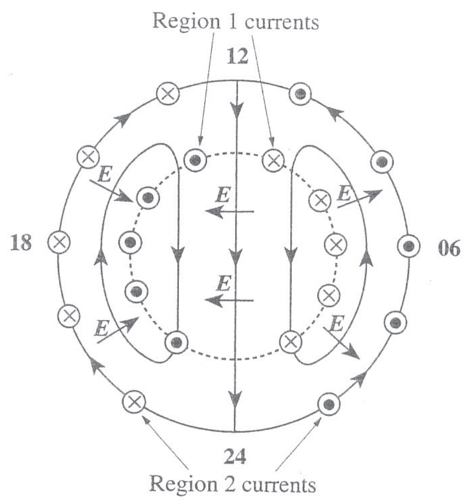

Figure 2: An idealised schematic of the electric field (E), Birkeland currents (dots, crosses) and plasma convection (solid lines) in the north polar ionosphere. The pole is located at centre with the outer ring extending to approximately 65° latitude. Region 1 is located poleward of region 2 currents [2].

The amount of energy captured by the magnetosphere from the solar wind depends on the interplanetary magnetic field (IMF) which is mostly of solar origin. Enhanced coupling with the magnetosphere is established for southward directed IMF draping over the upstream magnetopause. The merging of geomagnetic and solar wind magnetic fields on the dayside, with suitable solar wind properties, causes increased flux (and energy) in the tail. Research to discover details of these complex processes is ongoing and is often focused on the 'merging rate' on the dayside compared with the tail.

As magnetic flux and energy moves into the tail, the magnetosphere volume increases by an order of magnitude for solar wind conditions associated with interplanetary shocks, high speed streams and coronal mass ejections (CMEs). The solar wind and the IMF in particular are dynamic quantities, so the scale size and electrodynamic character of the magnetosphere frequently changes. The state of the system also depends on its recent dynamic history such that the same solar wind/IMF conditions do not necessarily reproduce the same system state.

The magnetosphere displays internal energetic release phenomena such as storms and substorms which correspond to global scale reconfigurations of the magnetotail and involve the most intense and extensive auroral displays. The general morphology of substorms is generally described in terms of three phases [3]. During the growth phase, energy is stored in the magnetotail. The expansion phase begins with substorm onset, signalling the explosive release of stored magnetotail energy via auroral displays, enhanced FACs and other magnetosphere-ionosphere interactions. In the recovery phase, the aurora and magnetosphere return to a quieter, nominal pre-substorm configuration. These internal dynamics compound the difficulties of trying to piece together an observational understanding of magnetosphere-ionosphere interactions based on statistical sets of sparse observations.

The time scale for magnetosphere-ionosphere reconfiguration determines the minimum time resolution required to specify the global state of the system. Estimates of the time scale are determined from the time it takes new solar wind conditions to propagate over the effective length of the magnetosphere and by the communication time scale across the magnetosphere. For typical solar wind speeds of 450 km/s, the time for flow from the upstream magnetosphere encounter to reach the nominal location of the last closed field line in the tail is ~600 sec. The one-way propagation time of a plasma perturbation wave across the magnetosphere is about 500 s, giving a round trip propagation time of ~20 min. Of course, the evolution of the system evolves between states via numerous important processes that occur on shorter time scales. However, the time resolution required to characterise the *global* configuration is on the order of 15 to 20 minutes.

Energy maps

A large scale, ground based system for monitoring the ionosphere plasma convection over the polar region (high latitude), top-side ionosphere is the Super Dual Auroral Radar Network (SuperDARN; http://vt.superdarn.org). The global electric field pattern at 1 or 2 minute intervals is derived from Doppler velocity estimates of the **E**-cross-**B** plasma convection illustrated in Figure 2. The magnetic field perturbations associated with the FACs may be obtained from low Earth orbit spacecraft.

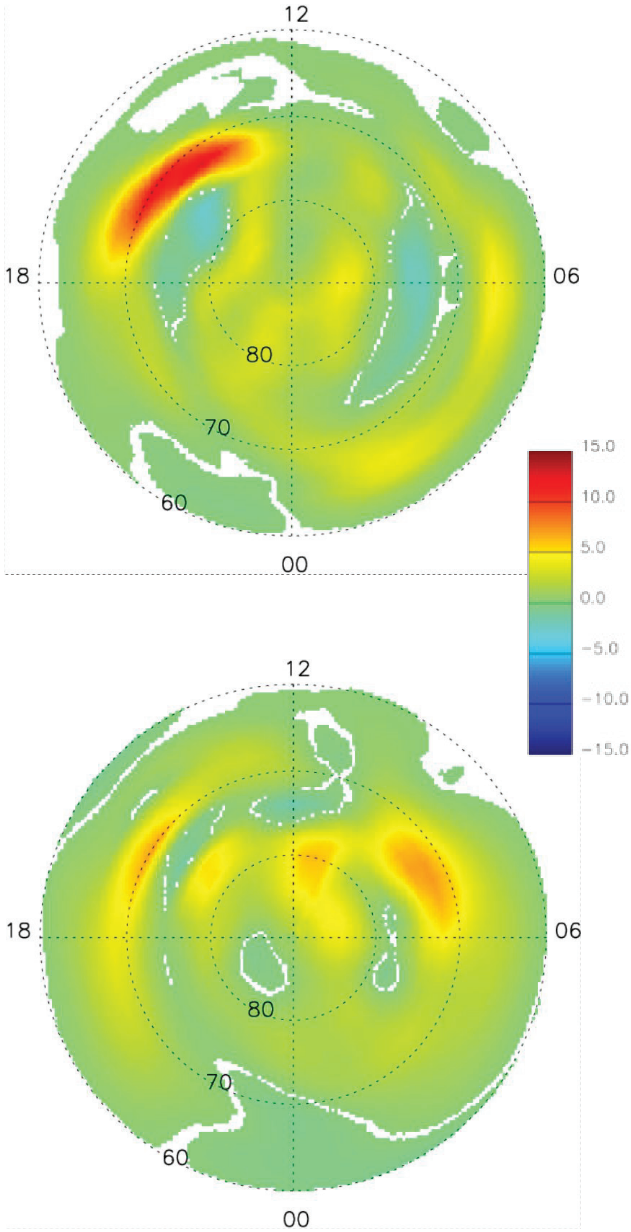

Figure 3: Spatial map of the Poynting flux (mW m^{-2}) over the north (top) and south (bottom) polar regions for 1400-1500 UT, 23 November, 1999 [4].

The Iridium constellation comprises over 90 spacecraft in 6 equally spaced orbit planes with near 90° orbit inclination at an altitude of 780 km. While these are tasked with communications business, the attitude control system contains a magnetometer. A unique collaboration between Iridium LLC, the Johns Hopkins University Applied Physics Laboratory, USA (PI: Dr Brian Anderson) and the University of Newcastle (Prof C.L. Waters) provides these global scale data to the space physics research community. Given the electric field (SuperDARN) and the magnetic field (Iridium), the Poynting flux may be obtained.

Figure 3 shows maps of EM Poynting flux input (+ve values) for the north (top) and south (bottom) auroral latitudes in units, mW m^{-2}. This interval represents a sustained period (~6 hours) of steady, average solar wind conditions (Vsw~450 kms^{-1}) with southward IMF. The total power, integrated over the 300 of latitude for each hemisphere is ~50 GW sustained for the duration of the steady solar wind conditions. The patterns are different, dispelling the belief that one hemisphere is the mirror image of the other. This underlines the importance of southern hemisphere sensors and research effort, particularly the role of Australian researchers and data collection. The south hemisphere shows a clear bias for the dayside. Maps of the FAC (not shown) identify the region 1 system located ~70° latitude where energy is enhanced, particularly in the afternoon sector of the north hemisphere. Significant amounts of energy are deposited over the polar caps, accounting for about 50% of the total. Ref [4] provides additional details.

Estimates of the Poynting flux (and input power) for more active periods are tricky since the resulting enhanced ionosphere electron density adversely affects the HF radar data coverage. If the input energy scales with the magnitude of the magnetic fields of the FAC, then the energy involved for storm periods may be up to 500 GW although this has not been measured on a global scale.

Data from LEO spacecraft (e.g. DMSP) yield both Poynting flux and particle precipitation energy estimates and show that the particle kinetic energy accounts for around 10% of the total. The input energy must transfer to atmospheric heating and expansion, increasing the drag on LEO spacecraft. Establishing the details of this energy transfer would require i) estimating what fraction of the input EM Poynting flux transfers to atmospheric heating and under what magnetic activity conditions and ii) obtaining and comparing EM Poynting flux with atmosphere heating data. Requests for resources to pursue these activities have been unsuccessful.

Summary

Space physics research strives to understand our place in space. The Sun is the closest source of energy which emits both EM and particle radiation that impacts human technology in different ways. Estimates of the global scale input energy are available using HF radar and LEO spacecraft data combined via simple multiplication (Fig. 3). Enhanced 'hot spot', differences in the north compared with the south hemisphere and the significant amount of energy not associated with the Birkeland currents are new findings that add to the intrigue of our dynamic, complex Earth-space relationship.

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About the author

Prof Colin Waters obtained a PhD in space physics at the University of Newcastle, Australia in 1993. He has taught undergraduate physics and supervised postgraduate students for 25 years. Research interests include computer simulations and experimental studies of near-Earth space, energy pathways and exchange between the magnetosphere and ionosphere and multi-channel data analysis techniques.

Mission to Planet Earth

Alex Held
Director of Centre for Earth Observation of the CSIRO Space and Astronomy Business Unit
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This note will largely focus on what's happening in the satellite earth observation field in Australia. Earth Observation (EO) refers to measurements of Earth system processes, and delivery of data to inform earth system science, government decision-making and industry growth.

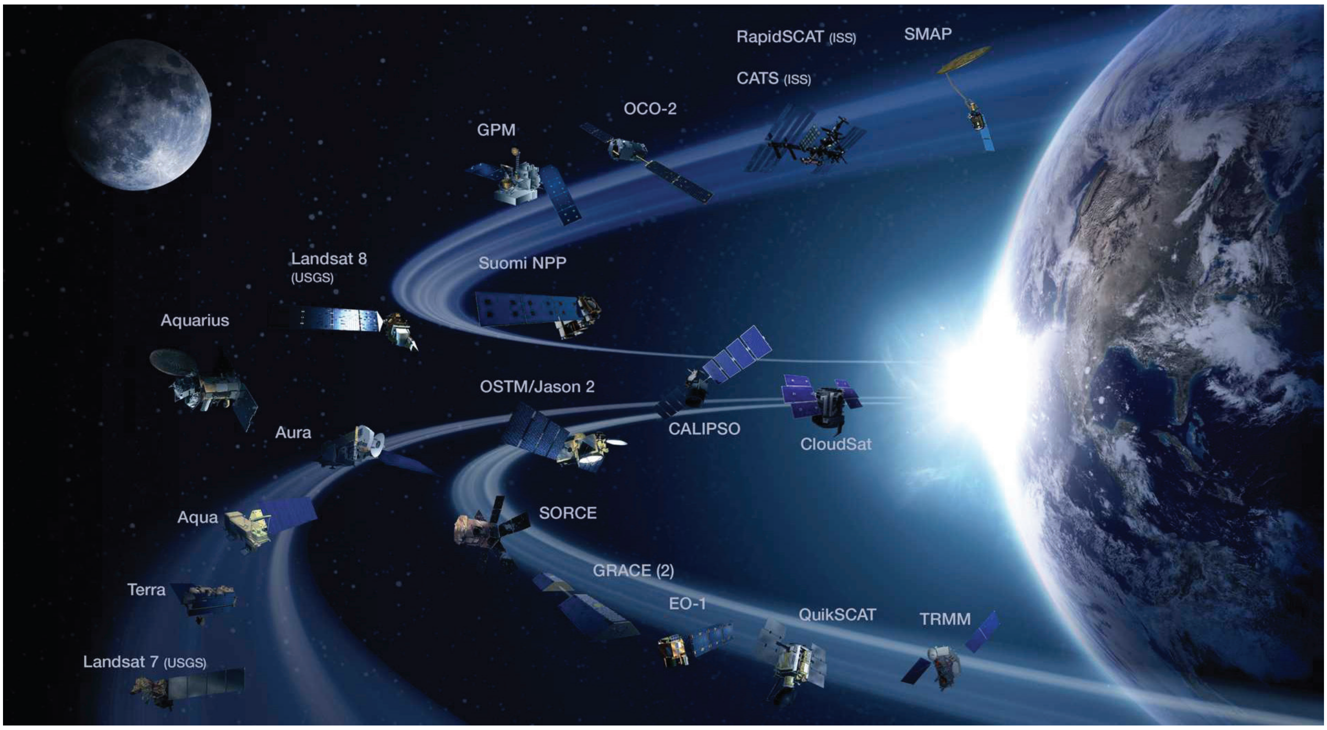

Figure 1: NASA's current Earth-observing satellite fleet (credit: NASA)

This term 'Mission to Planet Earth', coined originally by the U.S. space agency NASA in the late 1980s, seems highly appropriate still today, as we aim to become a multi-planetary species in a decade or two.

An Earth Observation satellite is a satellite on 'low-earth' orbit (200-700 km altitude) or even geo-stationary orbit (~35,000 km from earth) used or designed for earth observations (imaging, remote sensing, instrumentation). Satellite Earth observation data plays a vital role in Australian everyday life: Today, we count about 250 instruments onboard more than foreign 120 publicly funded earth observing (EO) satellites, that are measuring different phenomena of the earth system. EO data records now go back almost 50 years, constituting the longest, truly global environmental record there is. Much of this data is free and open for the science community and governments to access, so that we can evaluate changes in key climate variables, map land-use, calculate agricultural productivity and marine resources.

Australia: one of the largest users of EO data world-wide

Despite not operating any of these satellites ourselves, Australia is one of the largest users of earth observation data world-wide, largely due to the need to monitor a territory that covers nearly 10% of the earth surface, when we consider not only the size of our continent, but also the coastal- and Southern Ocean waters and the Antarctic territory that we look after. So, we are highly reliant on our good relations with countries which operate such satellites and that follow global open-data principles. Hence, for the last 40+ years, much of our emphasis has been on nurturing key international relationships that have helped secure access to this vital EO data. We have also supported several international earth observing missions, through establishment and sustained operation of satellite calibration infrastructure, that is installed at key sites around the country, including bright sandy desert areas in Western Australia, dry salt lakes in South

Australia and coastal waters in Great Barrier Reef region.

A 2021-2030 EO roadmap for Australia: On November 29th 2021, the Australian Space Agency launched the national 'Earth Observations from Space Roadmap 2021-2030' [1]. It outlines for the first time, the government priorities for future investment into:

1) implementation of a sustained national EO program, that supports operational satellite observations important for government,

2) development of new science missions, designed to test and space-qualify niche Australian technologies and support observational needs by our science community.

Once fully implemented, the ASA EO roadmap would constitute a national EO program that will help grow our national space industry, building on unique Australian innovation on EO data analytics and niche technologies, and importantly maintains our vital international relationships and calibration activities. This effort will take at least a decade, since we need to rapidly build the necessary capacity along the full industrial supply chain from manufacture, launch and operation of Australian-owned space hardware.

New Approaches to Access Australian Satellite Data

1. **Using OpenDataCube for Data Access and Analysis:** Focal areas in the new EO roadmap include those where our EO community in Australia has already been very strong, including good understanding of user-needs, applications development and 'BigData' EO data analytics.

2. **Using analysis-ready data for faster processing, feature extraction, lower storage and decision making:** When the raw EO data from the various satellites is pre-processed in some way in a standard and consistent way, for instance correcting the data for cloud interference, atmospheric effects and topography, to what is termed 'analysis-ready data' it takes away more that 50% of the effort and cost of using such data for research, industrial or government mapping purposes.

3. **Hyperspectral remote sensing:** Hyperspectral remote sensing ('imaging spectroscopy') is the method of acquiring digital images of earth in hundreds of narrow connecting spectral bands. This approach had also been used by astronomers to identify the composition of atmospheres and surfaces of planets, including the important detection of water on the moon and Mars. In Earth observation applications, hyperspectral remote sensing is used to detect different greenhouse-active gases and chemicals in the atmosphere, minerals on the earth surface, nutrient levels in vegetation and detection of camouflage and even toxic algae in water.

4. **'Wall-to-wall' complete spectral information from satellites:** 'wall-to-wall' mapping consists in mapping countries without gaps, rather than taking sample images here and there for research. So, the opportunity exists for Australia and partners to develop a new 'constellation' of such hyper-spectral sensors on satellites that can be operated on a sustained basis, to support key resource mapping and repetitive environmental-change monitoring and surveillance programs domestically and internationally.

5. **Illumination of the earth ground by the synthetic aperture radar (SAR):** SAR is an active sensor that operates in the 1-100 cm microwave part of the electromagnetic spectrum. It uses the reflection of sensor-generated microwaves to produce a representation of the size and location of objects on land or sea. SAR satellites are routinely used for 'all weather', day and night, tracking of ships and icebergs in polar regions, locate ships conducting illegal fishing and for environmental mapping purposes, including deforestation mapping, or crop growth mapping.

Conclusion

The future looks very bright in terms of Earth Observation in Australia. We have an agreed roadmap for the community to embrace; we have unique technologies to contribute to our international partners, including powerful data analysis tools and calibration data. Excitingly, we may soon have our own EO satellites built, launched and operated from Australia. This should stimulate the next generations of students and graduates to get into relevant technical and scientific fields, and find jobs in Australia.

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About the author

Dr Held also leads the Aqua Watch Australia Mission. Previously he served as Head of the CSIRO Office of Space Science and Applications, from 2004 - 2007, representing Australia at several space-related international committees, and served as member of the National Committee for Space Science of the facilities and infrastructures of the Australian Academy of Science.

Binar Prospector: An Australian resource prospecting mission to the Moon

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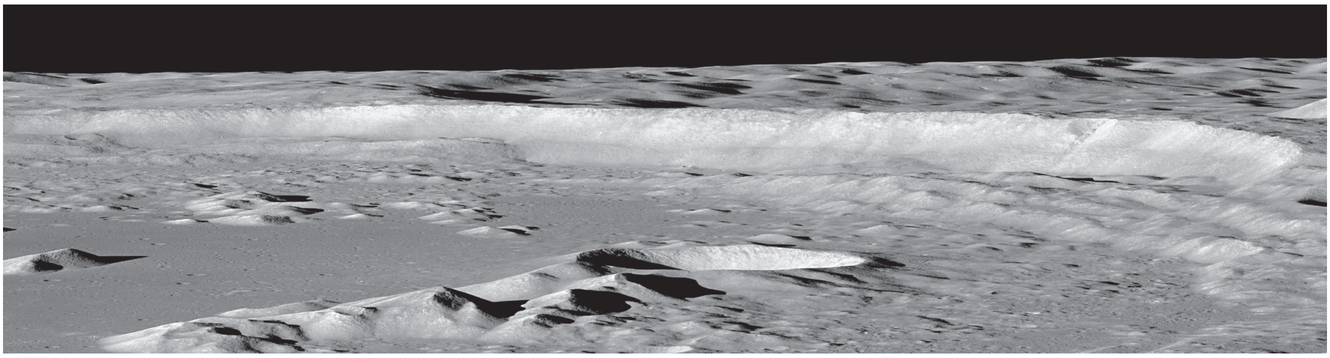
Binar Propector is an Australian lunar resource prospecting mission, focused on advancing the understanding of In-Situ Resource Utilisation (ISRU) opportunities in the lunar environment. ISRU is one of the key pillars of the NASA Artemis missions, and a critical strategic roadmap element for the Australian Space Agency. Using a pair of small 6U CubeSat orbiters, flying at extreme low altitude, the goal of the Binar Prospector mission is to identify mineralisation and water ice, allowing utilisation to occur within the capabilities of current space technology, and so enable human space exploration.



Rugged Lunar Height and Lows Courtesy NASA/Goddard Space Flight Center/Arizona State University

NASA Artemis program is a $100s billion effort to establish a permanent human presence on the Moon. This ambitious NASA 'Moon to Mars' plan involves building a new space station in lunar orbit and, eventually, a habitable Moon base. The initial Artemis space missions are focussed on lunar exploration, but NASA's long-term goals are event more ambitious. Australia is partnering with NASA in Artemis. NASA wants Artemis to be the catalyst for an off-Earth economy, so a key element in the program is the inclusion of private contractors in its delivery. One aspect of this is the Commercial Lunar Payload Services program. NASA is working with US companies to deliver science and technology payloads to the lunar surface.

To succeed, Artemis will require a lunar infrastructure, and nascent industry, that utilises resources found in situ at the Moon. In situ resource utilisation (ISRU) is a critical element of the program, but there are substantial technical obstacles to achieving it. For other elements of Artemis, NASA has a foundational experience and technologies. This is not the case for ISRU. A major ISRU element is the ability to generate rocket fuel, water and air in situ at the Moon, rather than flying it from Earth at astronomical cost. This requires a source of water. Although water ice is unstable over much of the lunar surface it has been found in permanently shadowed regions at the lunar poles, where extreme low temperatures and protection from direct solar radiation allow it to be stable. Water delivered to the lunar surface in the form of cometary impacts may become cold-trapped at the poles as ice. Because the Moon has a small gravity well, a successful ISRU program would dramatically reduce the costs of interplanetary exploration. It would enable a permanent human presence on the Moon, and unlock the rest of the Solar System for human exploration. The current program calls for mining water-ice in permanently shadowed craters at the lunar south pole, at temperatures down to 30K. No agency has demonstrated hardware that can operate in these conditions. For NASA, Artemis 1 will break the ground. Artemis 1 will be a test flight for the agency's Orion command module and Space

Launch System. It will also carry a dozen low-cost CubeSats as secondary payloads. The Artemis 1 CubeSats represent a radically different approach to science delivery, incorporating highly integrated miniaturised payloads into compact, lightweight spacecraft. This is the Binar Prospector model: take advantage of a unique aspect of Artemis (the ability to deliver small secondary payloads as rideshare), and deliver a key element of the program (ISRU), using a novel, low cost spacecraft class (interplanetary-class 6U CubeSats) that will have been trialled on Artemis 1. The Binar Prospector mission is focussed on geophysical exploration for strategic resources, finding those resources and mapping their distribution and abundance. Our goal is to identify ISRU opportunities in accessible locations, providing a resource alternative that would not require the development of untried new technologies capable of operating in darkness at 30K for extraction. Three Binar spacecraft are scheduled to fly.

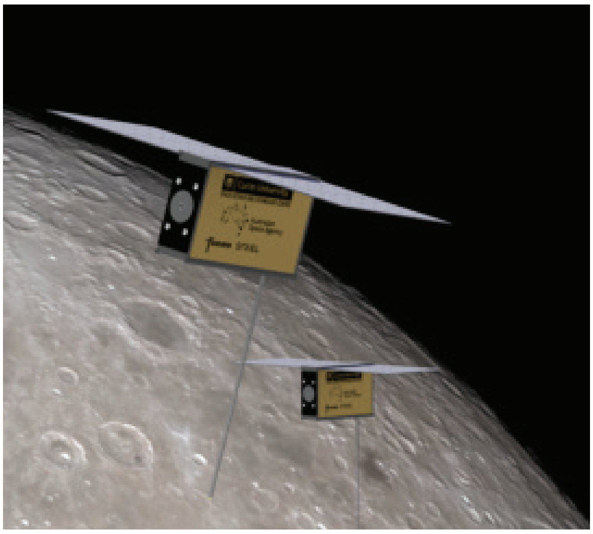


Figure 1: Binar-1 – named from the Noongar word for fireball –was deployed in low-Earth orbit. Contact was made with Binar-1 on October 21, 2021, confirming the satellite was powered up and operational.

The mission is led by Curtin University, with partners Sitael Australia and Fugro. The Binar Prospector team received funding via the Australian Space Agency Demonstrator Feasibility scheme (2021) to perform a detailed feasibility study for Prospector. Binar Prospector will take advantage of the new opportunity for rideshare to the Moon, and leverage the real potential of CubeSats for interplanetary missions: doing one job well in an environment that is not optimal for larger spacecraft. It will leverage Australian strengths in mining and remote operations; demonstrate technologies with a clear path to commercialisation; and will validate an interplanetary-class small spacecraft platform that can be a workhorse for future Australian missions.

How do we utilise resources in space?

Harvesting ice on the Moon is analogous to using ice for "life support" in Antarctica. We don't take liquid water to Antarctica. We use the ice that we find there and melt it. Harvesting ice on the Moon and performing electrolysis to split it into hydrogen and oxygen would be similar. Utilising resources like ore deposits would be analogous to mining on Earth, but do ore bodies even exist on the Moon? Right now, the simple answer is: we don't know. Binar Prospector will answer that question. It will fly payloads that can materially improve our understanding of the resource potential of the Moon, while being low cost and small form-factor. The mission will consist of two 6U orbiters, each carrying two payloads - a multi-aperture thermal IR imaging system and a magnetometer package - payloads designed to identify localised accessible ice deposits and mineralisation. Binar Prospector will have a novel mission architecture, with a propulsion system and fuel payload dedicated to enabling extremely low altitude passes over the lunar surface.

Thermal imaging will allow identification and mapping of hypothesised local small-scale cold traps containing ice [1]. The physical model to support the viability of localised ice deposits is well founded, but it requires data to confirm it, and then mapping to identify the distribution of these small cold traps. A thermal IR imaging camera payload flown at low altitude could accomplish this goal. Success would mean an accessible alternative to ice deposits at the poles. The DIVINER radiometer instrument on NASAs Lunar Reconnaissance Orbiter has gathered a stunning thermal imaging dataset, but with best resolution around 300m it is just below what is required to test the Hayne et al. (2020) hypothesis. Flying at low altitude, with a high resolution thermal imaging camera, Binar Prospector would map the surface at x5 this resolution over targets of interest.

A sustainable presence at the Moon will require more than just ice. Magnetometry delivers a geophysical dataset that is a prerequisite for economic mineral exploration. A high-resolution magnetic survey would provide a deeper understanding of the geology of the Moon, and its resource potential. Magnetometry can identify ore deposits at the Moon, but the current lunar magnetic survey has a spatial resolution of 60-100km. If this was the best dataset that we had for Earth it is unlikely that we would see even the largest terrestrial ore deposits. The Moon lacks a global magnetosphere. Its overall magnetic field is too weak to deflect the solar wind, but MAG/ER on Lunar Prospector [2,3] discovered a small surface anomaly that can do so. This anomaly – now known as Rainer Gamma – is about 75km in diameter, and has been referred to as "the smallest known magnetosphere, magnetosheath, and bow shock system in the Solar System." Rainer Gamma is now the target of dedicated lander missions. The JAXAs SELENE mission [4] provided a more detailed map of anomalies over a wider lunar region.

How can an Australian mission do better?

Flying twin small spacecraft on extreme low altitude allows us to gather higher resolution data. Constraining the electromagnetic noise environment within the spacecraft is critical for magnetometry, so having twinned observations is beneficial. It also allows immediate confirmation of any detected surface anomalies. Our modelling indicates that we can maintain an altitude of 18+/-9km with the propulsion system and fuel budget for a nominal mission lifetime of 3 months. Binar Prospector will deliver a x10 improvement on the current average magnetic survey resolution, and x20 better over targets of interest.

Binar Prospector is at one end of an Research and Development (R&D) path. Our current LEO spacecraft bus is at the other. Connecting them is a program of multiple launches over the next 3 years to iterate our platform and payloads to a point where we have an interplanetary class bus, instrumented to deliver a resource prospecting mission at the Moon. The Binar 1 launch in August 2021 successfully tested our prototype bus. Three Binar spacecraft are scheduled to fly in Quarter 3/2022, performing additional validation of the Binar platform, demonstrating a resilient system in a space environment, and testing deployable panels, radiation shielding, and a range of advanced communications solutions. Three more Binar 5, 6, and 7 will fly in 2023.

Binar Prospector will enable industry partners to develop technologies with a clear path to commercialisation, and remote operation capability from LEO to the Moon. And it will also pave the way for more missions. Binar Prospector will explore the potential of a radically new mission architecture. Prospector could define a new class of lunar missions, all focusing on low-altitude data acquisition using inexpensive spacecraft. Perhaps most important, it will validate a sovereign interplanetary-class small spacecraft bus. The R&D effort that goes into Binar Prospector will define a platform that can support multiple future Australian missions.

About the author

Director of Curtin's Space Science and Technology Centre, John Curtin Distinguished Professor Phil Bland was named a joint winner of the Scientist of the Year at the 2019 Western Australian Premier's Science Awards. His research explores the origin and evolution of the solar system through the analysis of meteorites. The asteroid '(6580) Philbland' is named in his recognition for contributions to planetary science.

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#PhysicsGotMeHere

This occasional column highlights people who have a qualification in physics but are in roles we might not traditionally associate with physicists.

Elizabeth Pearce

Australian Space Agency

Physics wasn't my best subject in year 12 but it was my favourite. My best subject marks wise was IT, so after high school I figured I should do that at uni. Fast forward 4 weeks and I quit uni. I hated the subject of IT, it was definitely not for me. So, I had an unintentional gap year working casually at Big W and hanging out with my friends. I loved physics but didn't think I was smart enough to do it for a career, but a friend encouraged me to try anyway. Others discouraged me, pointing out that there's not a lot of opportunity for physics-based jobs in Australia, but I pushed forward because I loved it.

Uni was hard. I didn't know how to study and just getting by on what I learned in lectures wasn't working anymore. I nearly failed first year, but it confirmed I did love the subject of physics. I pushed harder and managed to make it through.

I was properly introduced to space physics in my honours year. Physics is awesome, but physics IN SPACE is so much better! The sun, the ionosphere, the near-Earth environment are all so fascinating and so crucial to everyday life on Earth. After my honours year I had a choice between starting a PhD or getting a job at the Bureau of Meteorology. I chose the job. It was a 12-month position looking at the risk of blackouts in Australia from solar flares. The job was mostly data analysis and was a lot of fun. I had to source data from various sensors, including solar wind data and compare it with the timings of blackout events to look for any relationships. The role taught me how to analyse data and detect what were likely to be errors rather than true anomalies and how to clean that data in a way that maintained the integrity of the study. Diving deep into the data like that sparked a love of space weather that I have never shaken.

At the end of that job, I was offered a position at DST Group through their graduate program. I worked in a team looking at the needs of Defence for Position Navigation and Timing (PNT) for 6 years. I then moved on to alternative PNT starting a PhD with UNSW in cooperative intelligent transport systems (CITS). My focus was to apply integrity monitoring techniques (error detection and mitigation) used in GNSS receivers and apply it to positions calculated using cooperative positioning techniques (e.g. time difference of arrival of radio signals). This led me to a change in area at DST, leading a research program on how autonomous systems can help the army. Whilst this was fun, after 2 years I again reassessed my life and remembered my passion for space weather and space-physics.

Coincidentally, the Australian Space Agency had just opened. I saw this as an exciting opportunity to return to space physics and transferred into the agency leading the Space Situational Awareness and PNT priority areas. I have been involved in the creation of roadmaps, administering grants and engaging with stakeholders both nationally and internationally. Hopefully, in the near future the work I have done will have helped develop new capabilities for Australia and set our industry on an exciting new path to enter the global space market.

The key lesson I learn over and over is to do what you love. If you no longer love your work, it's time to reassess.

Product News

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The COMPex F2 excimer laser from Coherent has been designed to extend the available wavelength range of the COMPex family down to 157nm. As an alternative the COMPex F2 laser tube can be filled with ArF premix gas to achieve 193nm.

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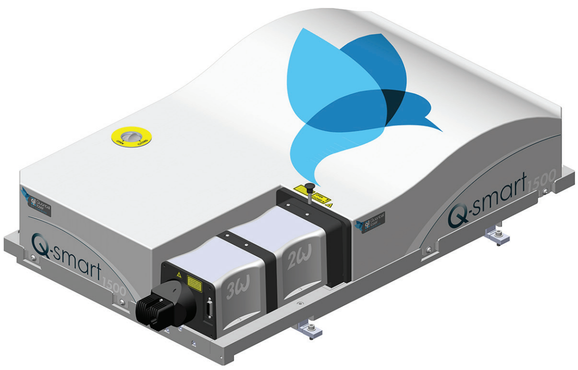

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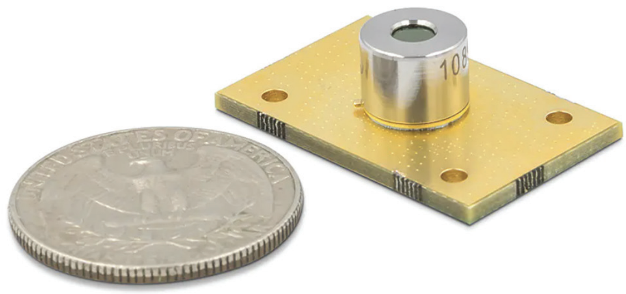

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