Australian Academy of Science National Committee for Space and Radio Science

Heliosphere Science Working Group, encompassing the Sun, Solar-Terrestrial connections, Planetary Magnetospheres, Aeronomy

Working Group Members:

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Context

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

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

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

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

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

Present Capabilities, Goals and Impacts in Heliosphere Science in Australia

Solar Physics - Capabilities

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Solar Physics – Goals

Overall Goals:

To understand, at fundamental and quantitative levels, the plasma environment throughout the solar system.

To develop capabilities to interpret observations and invert them to constrain and understand the physics of remote energy releases and transport and the interchange between plasma wave and charged particle phenomena.

Specific Goals:

To develop a quantitative, data-tested theory/simulation capability to predict (with high probability) if and when a CME will reach Earth and what its properties will be.

To develop high probability prediction capability of:

- solar flares with lead times as long and short as possible.
- CMEs and DSFs with lead times as long and short as possible.
- Solar Energetic Particle (SEP) events.

To develop a quantitative, data-tested theory/simulation capability to predict impacts of CME/flare events on near-Earth space, ionosphere and ground critical infrastructure. These predictions must be with sufficient lead-time to confidently produce relevant inputs to government and industry that will allow reliable warning and mitigation of space weather threats.

To develop a data-tested, relativistic correct theory/understanding of Type II and III radio bursts and related charged particle dynamics in the solar corona and throughout the universe.

To develop a comprehensive, full 3D theory for the origin and properties of the solar wind, including details of coronal heating, wind acceleration, transition mechanisms from structured coronal plasma dynamics to turbulent solar wind and the relative importance of different processes in explaining 1 AU observations and impacts.

To improve simulations and understanding of kinetic-plasma wave shock physics, including particle acceleration at planetary bow shocks and solar energetic proton events, and objects (satellites) moving through the upper atmosphere.

To improve simulations and understanding of particle acceleration and energy conversion in magnetic reconnection at small spatial and temporal scales.

To develop novel experimental data collection and analysis methods for the discovery of space phenomena.

To develop, launch and operate innovative satellites and sensors on small platforms for space exploration and discovery.

To collaborate with international efforts (e.g. COSPAR Space Strategy)

Solar Physics - Impacts

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

Understanding the complex plasma phenomena throughout the local solar system is key to exploring beyond and being able to determine if observed astrophysical phenomena require new physics (or not). Therefore, observation-truthed theory/models allow the extension of local solar fundamental plasma physics processes to astrophysical contexts and discoveries.

Understanding the solar corona and solar wind are two high profile, “Holy Grail” problems of solar physics and astrophysics. This leads to improved lead times and confidence in predictions of solar activity and conditions in the background corona which enables improved prediction and mitigation of major space weather events.

Participation in, and playing major roles in the research of NASA’s PUNCH mission and other internationally coordinated efforts.

High probability prediction of energetic solar processes (when and where of CMEs, flares, SEP etc.)

High probability predictions of impacts on various forms of human infrastructure and technology.

Allow for development of mitigation strategies for major space weather events with sufficient lead time to act effectively.

Determination of space weather threat levels for specific infrastructure entities.

Specific and effective guidelines and processes made available to critical infrastructure entities (space operations, AEMO, communications etc.) for space weather events of varying risk level

Enhanced diagnostic capabilities of astrophysical phenomena through improved understanding of the fundamental physics. Unambiguous determination of which observed signatures are related to what physical quantity and its measurement uncertainty.

Understanding of shock physics has impact in many areas of science and engineering that involve fluids, gases and plasmas; will benefit multiple research fields.

Understanding wave and particle interactions and behaviours over a broad range of plasma parameters and energies has direct impact on fusion energy research with the increasing demand for low cost, low environmental impact mass energy (electricity) production.

Insight	Aspiration	Actions	Impacts	Metrics
Why is the solar atmosphere so hot? What is the origin of the slow solar wind? What are the energy conversion pathways and time scales of the solar atmosphere? What quantities and what relationships are required for high probability prediction of CME/flare events? How do magnetised plasmas channel energy from large to small spatial and temporal scales and what are the signatures? Where can cross-disciplinary collaboration and applications be increased?	Energy transport and conversion in the solar atmosphere is sufficiently well understood (models are consistent with observations) to allow a detailed understanding of the how, when, where and severity of solar eruptions Realistic models and understanding of plasma shocks, magnetic reconnection, plasma wave emissions and instabilities and their origins. Broaden fundamental plasma research base and expertise to astrophysical, fusion and industrial plasma research areas. Correct the present imbalance between research and industry applications so that fundamental research is positioned and resourced as the foundation of innovation and application development.	Develop improved computational tools for simulations that span multiple spatio-temporal scales. Ensure adequate high-performance computational resources are available for internationally competitive simulations to be undertaken. Provide training to higher degree research students and sufficient resourcing of early- and mid-career researchers in experimental data analyses, numerical methods, high performance computing and cutting edge theory. Create and adequately resource a multi-disciplinary centre for plasma phenomena research and applications with relevant academic, industrial, international and government involvement.	Fundamental plasma physics research findings and discoveries will advance astrophysical, industrial and fusion applications. These will improve our understanding of processes and phenomena throughout the universe and in laboratory plasma devices (e.g. magnetically-confined fusion devices). Allow development and use of predictive models of solar eruptions and threat levels with adequate lead-times to inform space weather predictions. A cost-effective and coordinated cross-disciplinary plasma phenomena research focus that efficiently advances knowledge to enable innovative technology development with the proper resourcing and interaction between fundamental research and industry/application development.	Australia is a recognised, leading nation in space science/solar physics Predictions of solar eruptions have improved, making space-weather forecasts more accurate. Discoveries in solar/space physics phenomena are transferred to industrial, astrophysical and fusion plasma research and applications and vice versa. An adequately resourced, best-practice, coordinated approach to plasma phenomena research and applications is developed within a stable policy environment involving academic, industrial, energy sectors and government support and international expert interaction.
What sensor technologies and data processing methods can be used to probe the Sun, particularly the far-side? What useful information on the structure and evolution of active regions can be gleaned from solar acoustic waves?	Advanced sensor technologies, ground and space platforms and data analysis techniques (e.g. AI) are accessible and provide long-term data streams. The fundamental processes that control the characteristics of the solar wind are sufficiently well	Develop pathways for the translation of fundamental science results into space weather modelling/forecasting services. Access to solar experimental data including vector magnetic field and Doppler time series maps.	Improved understanding of solar wind formation mechanisms are key to building improvements in space weather modelling efforts and predictions of extreme space weather events. Improved understanding of stellar winds allows	Novel sensors are developed and flown on Australian manufactured systems. Australian developed and manufactured sensors are the product of choice for international space missions.

	understood to allow predictive modelling.	Development of new remote sensing methods and pathways to develop these.	accurate assessments of the habitability of planets beyond our solar system.	

Magnetosphere and Ionospheric Physics - Capabilities

a) Computer simulation and observational expertise of ultra low frequency (ULF) plasma waves for remote sensing near-Earth space (plasmasphere plasma mass density, electric field magnitudes for electron and ion energisation that disrupts spacecraft functionality).

b) Instrumentation for probing properties of the ionosphere: HF radars, ionosondes, TEC from GPS and associated tomography tools.

c) Ionospheric HF wave propagation and radar/ionosonde data analyses and interpretation.

d) Coupled troposphere-stratosphere-mesosphere-thermosphere-ionosphere modelling and data assimilation.

e) Data analyses and modelling of ionosphere coupling and forcing from the thermosphere and magnetosphere.

f) Real-time regional (mid and low latitude) ionosphere modelling; response to geomagnetic disturbances and effects on HF signal propagation.

g) Observations and interpretation of relationships between layer heights, spread-F, sporadic-E, delays between geomagnetic and ionospheric disturbances.

h) HF communications propagation prediction and advice services.

i) Modelling of geomagnetic induced currents (GICs) from ionospheric current to ground magnetic signature and spatial/temporal details of the GIC electric field. The Bureau of Meteorology (SWS) have also developed an electricity supply network model (with AEMO), with simulation capability of GIC impact on the Australian east coast electricity grid.

j) Equatorial plasma bubble observations, modelling and prediction capability.

k) Earth's ionosphere, cusps and auroral zones accessed via rocket experiments and CubeSats.

l) Theory and observations of thermal Langmuir waves detected by CubeSats in Earth's ionosphere, allowing reliable extraction of the cold plasma density and temperature.

m) Theory and data of the electrical signatures of dust impacts on CubeSats in Earth's ionosphere, allowing extraction of the dust particle sizes and numbers and in-situ assessment of space debris near Earth.

n) Capability to determine 3-D GNSS propagation and/or distortion through the ionosphere

Magnetosphere and Ionosphere – Goals

To determine how different observational techniques and data represent the complex, magnetosphere-ionosphere-atmosphere system.

To develop an integrated, multi-sensor observational network and platform (ground and space based) for viewing and understanding the atmosphere/ionosphere/magnetosphere system.

To predict and monitor the radiation types and levels at LEO, MEO and GEO and their effects on spacecraft operations and biology in space.

To understand (observation-consistent model) energy deposition, transport and coupling to the regional ionosphere from below (troposphere and thermosphere) and from above (magnetosphere/thermosphere) and how these are related to ionospheric variability, particularly density variations at LEO (<1000 km).

To unravel the mix of direct solar driven and internal magnetosphere processes that drive space weather related effects.

To understand the formation and effects of ionospheric sporadic-E layers; dynamics of descending layers, relation to meteors and thermospheric winds and airglow.

To determine the sources of daily variability in equatorial plasma bubble formation and other equatorial ionosphere gradients; particularly the relative impact of “seed” variables and conditions compared with background conditions and electrodynamics.

To understand the source mechanisms and propagation properties of travelling ionospheric disturbances (TIDs including MSTID, AGW, LSTID from polar latitudes), including time of arrival at all latitudes.

To develop an indigenous, surface to exopause atmospheric modelling and data assimilation capability that utilises data from a comprehensive space sensor network in order to accurately describe the complete physical state of the ionosphere-thermosphere system on regional and global scales, targeted to related research areas and operational space weather prediction.

High probability prediction capability of the following:

- Thermosphere-ionosphere particle densities at LEO to inform orbital dynamics and Space Situational Awareness.
- Radiation environment impacting satellite operations in LEO, MEO, HEO and GEO.
- Cosmic radiation conditions impacting aviation operations in the stratosphere and mesosphere.
- Geomagnetic and ionospheric storms at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
- Global ionospheric plasma densities at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
- Scintillation-producing ionospheric irregularities at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
- Aurora Australis occurrence at lead times of 0, 6, 12, 18, 24, 48 and 72 hours.
- Geomagnetically Induced Currents (GICs) in the Australian electricity grid and industrial pipelines.
- Quantification and distribution of relevant space weather effects and impacts at operationally useful lead times

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

Magnetosphere and Ionosphere – Impacts

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

Understanding of energy deposition and transport from space into Earth's climate system with impacts on climate modelling, and prediction and mitigation strategies for future effects of climate variability.

Enhance Australia's strong international reputation in space science as a capable and reliable provider of space environment data and knowledge.

Improvements in the accuracy (cm level) and operation and applications of GPS services with associated economic and societal benefits.

Improvements to the operation of JORN and other over-the-horizon radars, thereby significantly improving Australia's surveillance capability and national security.

Adequate training and retention of knowledge of space and ionosphere processes in the Australian workforce to support space and ionosphere related operations.

Ability to develop and sustain a "critical mass" and national capability in space systems and missions, to grow and sustain a space economy and export stream.

Provide essential components and indigenous expertise for a *sustainable* space industry and economy. This requires a coordinated, cooperative and adequately resourced combination from academia (research and training), industry (applications and exports), and government (stable policy framework), all suitably supported, encouraged, and impacted by progress.

Insight	Aspiration	Actions	Impacts	Metrics
What experimental data are necessary to identify the various mechanisms in atmosphere/ionosphere coupling? What are the energy exchange mechanisms between the various atmospheric and ionospheric layers? What is the set of physical drivers that cause ionospheric disturbances?	Understand the physical mechanisms of energy coupling from above and below, and their signatures between different atmosphere and ionosphere heights Understand the relationships between small and large spatial and time scale dynamics	Develop improved computational tools for multi-data ingestion and prediction purposes Identify and develop remote sensing tools for ingesting additional experimental data into prediction tools. Ensure access to experimental data sources and expand observing network.	Real-time operation of over-the-horizon radar detection and defence infrastructure. Improved understanding of space weather and cross-disciplinary impacts on effects on the atmosphere and Earth climate. Real-time, relevant data access to drive high quality	Model predictions agree with the observational data Sufficient observational data are available to develop realistic models (long-term data sets) and to drive predictive algorithms (e.g. GIC predictions for AEMO, GPS services etc.).

How can we improve measurements of the dynamics of the thermosphere? What data and analysis tools are required to provide high probability prediction of near-Earth space conditions and threat assessments? What tools and data are best for conveying research outputs and relevant warnings to critical infrastructure customers? What measurement of the ionosphere and near-Earth space provides information on which physical parameter? How do we combine multi-instrument data into a coherent, real-time view of the solar-terrestrial environment and its impact on space and ground based assets? How do we ensure the supply of qualified personnel to space related industries and defence?	in near-Earth space and the ionosphere. Build real-time multi-sensor data input and visualisation tools. High probabilistic prediction of adverse conditions for various customers. Develop accurate relationships between magnetic data and electricity grid and industrial pipeline impacts. Be able to identify and exploit the different responses of observational techniques to the system.	Identify and develop remote sensing methods for expanding relevant data sources. Deploy high spatial resolution observing network, with a focus on low and equatorial latitudes. Develop a cheap and energy efficient method for monitoring thermosphere dynamics 24x7. Develop a coordinated approach to space technology and research training.	prediction models for space weather impacted infrastructure. Allow development of targeted warnings and threat mitigation strategies for specific industries (e.g. energy supply, communications, GPS etc.). Improved prediction lead-times and accuracy of warnings of severe space weather events. Improved prediction of trajectories of space debris and space situational awareness. Improved predictions for stability and control of LEO satellites. A sustainable and qualified workforce to drive research and innovation in space technologies.	The specific warnings and mitigation strategies for each of the diverse infrastructure service operators are effective in protecting critical assets. The lead-times for warnings are expanded with high prediction accuracy The locations of space objects are known 24x7 The identification of space object at smaller sizes is improved Sufficient numbers of qualified personnel are available for the demands of the Australian space industry

Instrumentation and data - Capabilities

a) Capability to design, build, and test CubeSats and to operate them in space from Australia. Examples include CUAVA-1, M2, Buccaneer and CSIROSat. Several missions are being investigated without funding (at present), mostly focused on low Earth orbit projects but some are for Moon-Mars, planetary missions, and beyond.

b) Capability to design, test and fly sensors for space applications, such as GPS instruments, imagers, plasma wave receivers, plasma and gas thrusters, and radiation counters. Design and fabrication for electrical components of an instrument to detect thermal Langmuir waves (plasma noise spectroscopy) from a CubeSat platform and extraction of the electron temperature and density along satellite orbits in Earth's ionosphere and inner magnetosphere.

c) World Data Centre for Space Weather data service

d) Software and data products for AMPERE (Iridium constellation magnetic field data) and for SuperMAG, the global ground magnetic field initiative.

e) Ground magnetometer assets are declining at (Bureau of Meteorology) SWS, Australian Antarctic Division (AAD), Latrobe University and the University of Newcastle.

Instrumentation and data - Goals

To halt the present reduction in, and preserve existing, instrumentation assets across Australia, the southern ocean, Antarctica and equatorial regions.

To develop, test and use Australian relevant sensors from space-based platforms.

To improve near-Earth space monitoring capabilities by expanding the Australian network of ground-based instruments, including ionosondes, magnetometers and HF radars, and expanding the sensor network to include Australian space-based instruments with both remote sensing (e.g., GNSS Radio Occultation and topside sounding, combined electron temperature and density data from the ionosphere) and in-situ sensing (e.g., Langmuir probes and mass spectrometers) capabilities.

To obtain long-term observational data at small spatial and temporal scales over large regions.

To develop techniques (with reasonable cost) to monitor the dynamics of the thermosphere, providing 24x7 measurements on a regional basis.

To develop a comprehensive and coordinated platform for presenting space and Earth-based data from a diversity of instrumentation in a coherent manner.

To foster and develop indigenous skills and industry for spaceworthy sensors, deployment systems, command and control and necessary ground-based infrastructure to maintain and expand Australian spaced-based sensing.

Instrumentation and data - Impacts

Long-term data bases are essential for distilling and testing relationships on solar cycle time scales. These are critical for developing and using high confidence prediction theory/models.

Ability to develop and export satellite hardware systems and sensors that enable major scientific progress, creation of significant economic benefit, and provide sovereign capability in high profile and impactful ways.

Provide adequate observational data to test and refine scientific models of space weather impacts and their effects on a diverse range of infrastructure. This impacts the development and implementation of mitigation procedures and adequate lead-time guidelines for specific applications.

Provide adequate input data to be able to run and effectively use prediction models of space weather (e.g. sufficient magnetometer data for the GIC prediction model)

Coordinated multi-source data presentation platform in real-time is critical for timely and accurate monitoring and advisory services, in addition to the essential role in research and development of algorithms and applications.

Meteorite trajectory and orbit analyses

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

Recommendations from the Heliosphere Working Group

Recommendation 1. Value research
The importance of basic space science research should be recognised, valued and supported for its key role in Australia's space sector activity, application development and industries.

Recommendation 2. Workforce planning
There is presently an active internationally regarded space science research sector in Australia which leverages significant international IP through collaborations. However, the Australian community is small and comprises mostly senior rather than middle or early career workers. There is an urgent need for succession planning in order to ensure a sustainable space science capability able to meet national requirements.

Recommendation 3. Coordinated multisector R&D environment
In order to create Australian jobs in the space sector and provide an efficient and cost-effective path from innovation to industrial applications, the diverse Australian research activity in space physics and dynamics, laboratory plasma, gas and fluid physics, data science, prediction and computational modelling expertise, should be brought together within a coordinated, focused entity with a more stable funding structure, clearer government policy environment and clear objectives developed from the national interest (i.e. defence, infrastructure security and integrity, sustainable energy and resource production, environment management etc.).

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

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

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

Recommendation 4. Australia as a space science data platform
Australian territorial interests span an eighth of the globe, providing critical coverage of the southern hemisphere and Asia-Pacific time zones. However, the number of Australian data collection platforms and assets is declining. A national approach to operation of a sustainable

suite of data and sensor assets, with associated data processing and analysis capability, is necessary in order to support research activity, real-time critical information (e.g. GPS corrections for SBAS, space object tracking, surveillance accuracy), and space weather warnings and predictions.

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

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

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

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