AUSTRALIAN

SPACE WEATHER PLAN

Strategic Planning to 2010 and Beyond

Space Weather Sub-Committee of the National Committee for Space Science
AUSTRALIAN ACADEMY OF SCIENCE

Space Weather Committee of the
AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING

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AUSTRALIAN SPACE WEATHER PLAN

Executive Summary

The Space Weather Plan:
a) demonstrates the importance of space weather in today's society;
b) provides an outline of a space weather program to cater for the future;
c) elucidates the main directions for space weather monitoring for Australia over the next decade and beyond;
d) recommends the establishment of an Australian Space Weather Agency and sets its directions;
e) recommends national coordination of research through a self-managed determination of priority areas for research funding.

Space weather buffeting the Earth can take a costly toll of modern systems, systems that industry and society have come to rely on. Taking account and planning for Space Weather will be an ever-increasing aspect of infrastructure support. Australia has a recognised record in research and services in the space environment field and the time is ripe for a cohesive national Space Weather Plan to exploit that expertise for the future well being of Australia.

Space weather refers to conditions on the Sun and in the solar atmosphere that can influence the performance and reliability of space-borne and ground-based technological systems. Examples of activities and systems affected by space weather include:

- satellite operations,
- manned space flights,
- radiation in space and aviation,
- navigation systems,
- general electrical control systems,
- high-frequency communications,
- short-wave broadcasting,
- surveillance radars,
- geophysical exploration,
- electricity power grid distribution,
- long pipeline corrosion,
- insurance.

The burgeoning telecommunications and information technology fields are vulnerable to space weather. Australia will increasingly rely on satellites for communications and resource information (meteorological, geophysical prospecting, navigation, and remote sensing). Australia, like all modern societies, relies heavily on satellite systems for information, communications and navigation. There are high costs and high risks associated with the consequences of space weather events, as is becoming recognised by insurance companies. Numerous satellites have already failed or been degraded by disturbances in the space environment. Terrestrial communications, paging systems, and remote sensing devices have been disrupted or terminated following space weather extremes.

The effects of space disturbances on space or ground systems can have significant consequences. The electrical grid system in Quebec was triggered into a collapse for nine hours in 1989 because of a current surge caused by a solar eruption. Semi-conductors built into computing equipment are becoming more complex and more vulnerable to extreme space weather. A major U.S. computer that operated at sea level has failed at higher mountain altitudes where cosmic radiation levels were higher; German railway speed controls failed owing to space radiation; France has regulated against excess radiation to staff on airline flights. In Australia, short wave communication, GPS navigation data, and mining surveys have been unusable at times of severe space disturbances. These are some of the reported effects of space weather. In many cases there have been high costs associated with such events.

High-frequency (HF) communications constitute a large part of Australian Defence and emergency back up. These can be affected by solar disturbances. Users of HF include Telstra, Army, Navy and Air Force, maritime services, airlines and general aviation (particularly in remote areas), Police, Australian Customs, Australian Antarctic Division, State Government Agencies such as Water Authorities, State Fire Brigades and Emergency Services, and the Royal Flying Doctor service. Often, HF systems are the mainstay of public safety or emergency communications and can be degraded or disrupted by space weather.

Australia needs to understand the risks associated with extremes of the space environment in order to successfully manage those risks. The adoption of this Space Weather Plan is a start to devising and giving direction to a program of monitoring and research over the next ten years that will coherently build the technical knowledge and effective services required to accurately specify immediate and future space environment conditions.

Given that current and future systems underpinning Australian society are vulnerable to space weather, what can be done to mitigate the effects of space disturbances? Firstly it is vital to know when a disturbance is likely to occur and what its effects will be. This requires monitoring the space environment and recognising abnormal conditions before they reach extreme values. Monitoring space weather variations is a long-term task best conducted by an organisation dedicated to monitoring, forecasting and providing alerts of adverse conditions. Such a centre would be a national focus for space weather activities, for collecting and distributing relevant data in Australia and overseas, for application of research results from other groups, and for promoting the inclusion of space weather in future planning.

Monitoring of the Sun, interplanetary space, the Earth's magnetosphere and ionosphere provides the data from which research can develop improved methods of forecasting space weather. Australian space weather research matches overseas research in quality if not in quantity. However, the various groups concerned with that research are small and fragmented, each competing for funding. Their research could be more effective, in terms of space weather application, if groups pooled their efforts, decided the priorities for space weather research and promoted the subject as an overall Australian priority.

In promoting the research aspect to the funding agencies, it is equally important to promote the subject to those areas of government, industry and the public most affected by space weather. To this end, a coordinated program of public outreach should be adopted so that knowledge of the space environment can be appreciated and applied in planning for future systems.

As a result of the arguments and issues raised in this document the following recommendations are made.

Recommendations:

Space weather monitoring and services

1. *To take advantage of Australia's research and technological expertise, an Australian Space Weather Agency should be established to:*
    - *service Australia's increasing needs for mitigating the influences of space weather*
    - *develop applications for space weather prediction and services*
    - *support long term monitoring of space weather phenomena*
2. *The existing World Data Centre for Solar-Terrestrial Science should be the Australian warehouse for space weather data*

3. *Space Weather data should continue to be made freely available on an international exchange basis*

Research priorities

4. *In order to strengthen Australian research capability in space weather, the Academy of Science, in consultation with the Academy of Technological Sciences and Engineering, should draw up a list of research projects that are currently required to improve space weather forecasting in Australia.*
5. *This should identify research priorities, especially those relevant to Australia, and develop a five-year costed plan of priority research for space weather after consultation with the space weather community*

Public outreach

6. *The Academy of Science and the Academy of Technological Sciences and Engineering should devote specific campaigns and discussions to the subject of space weather and its effects on technological systems.*

Space Weather

What is space weather?
Most people are familiar with the effect of weather on their lives. Often this is relatively minor - determining what to wear and where to go; but on occasions, it is dramatic and costly as major events inflict severe damage and even loss of life.

Unseen and unknown to most people, there is another form of weather - space weather - which is of great importance to many modern technologies. And like ordinary weather, space weather constantly produces low-level effects on human technology; interspersed with occasional dramatic events.

The Sun is a huge generator of power (4 x 10^{20} megawatts) and is the main source of space weather. Its output varies over a period of 11 years. The maximum of solar activity occurred in the year 2000 and the next minimum is expected around 2007. The increasing importance of space weather for a technical society together with ever-present solar activity means that space weather disturbances have a higher profile than in the past.

The Sun-Earth Environment and Space Weather
The Sun-Earth environment is the region of space extending from the surface of the Sun out to, and including, the Earth's upper atmosphere and magnetic field. It is a harsh environment dominated by electromagnetic radiation and electrically charged particles from the Sun. It is subject to dramatic and violent change as events on the Sun blast streams of radiation and energetic particles towards the Earth. This is the domain of space weather.

Space weather results from changes in the speed or density of the solar wind, a continuous stream of charged particles flowing from the Sun past the Earth and into interplanetary space. This flow distorts the Earth's magnetic field, compressing it in the direction of the Sun and stretching it out in the anti-Sun direction. Fluctuations in the flow of solar wind cause variations in the strength and direction of the magnetic field measured near the surface of the Earth. Large abrupt changes in this dynamic medium are called geomagnetic storms.

At the same time, the Earth's ionosphere (the electrified layers of the upper atmosphere) can be severely disturbed by streams of charged particles. This degrades the ionospheric "mirror" that reflects High Frequency (HF) radio signals back to the Earth allowing cheap and convenient communication over a wide range of distances. HF is significant for many agencies including Defence, emergency services, broadcasters, and marine and aviation operators. High-Frequency communicators probably represent the largest Australasian group affected by solar storms. Communications on other frequencies, from VLF to satellite, may also be affected, making space weather and its prediction an essential factor in successful operations.

The Sun

The Solar Cycle
Solar characteristics vary cyclically. The most familiar cycle is typically 11 years in duration although cycles of different length and amplitude are not uncommon. The solar cycle is manifest in many properties of the Sun and is most evident in the appearance of sunspots on the solar disk. Sunspots are regions of stronger magnetic field and appear optically darker than the surrounding surface. At times, sunspots are rare and the Sun appears almost without blemish (solar minimum). As solar activity increases, sunspots become more common and it is normal for many groups of spots to be visible on the face of the Sun.

The traditional measure of the solar cycle is the number of sunspots statistically smoothed over a period of 12 months. The peak sunspot number of historical solar cycles varies greatly but five of the last six cycles have been large in amplitude. Using the conventional numbering system given to solar cycles, Cycle 19 (peak sunspot number of 201 in 1957) was the largest cycle on record; Cycle 21 (peak sunspot number of 165 in 1979) the second largest; and Cycle 22 (peak of 159 in 1989) equal third largest.

The present cycle (number 23) is a moderately large cycle in terms of sunspot number (a peak sunspot number of 121 in 2000) but solar activity has not been as great as expected.

Solar Features

The solar atmosphere of electrified gas constantly flows outwards from magnetic regions on the Sun. The solar wind is characterised by high speed streams, typically moving at 2-3 million kilometres per hour.

As it flows past Earth, the solar wind changes the shape and structure of the Earth's magnetic field. In the past, the solar wind did not affect us directly, but as we have become increasingly dependent on advanced technology, we are now more susceptible to its effects. Researchers are learning that variations in the solar wind flow can cause dramatic changes in the shape of the Earth's magnetic field, can damage satellites, and disrupt communications and electrical power systems.

Several solar features and events are connected with space weather. Solar flares are huge outbursts of energy seen on Earth at many wavelengths from X-rays through visible light down to the radio spectrum. They are the outcome of the release of stored energy as the magnetic fields at the Sun’s surface become twisted and distorted due to the differential rotation of the Sun. If the complexity of the magnetic field is sufficiently large, the energy can be released in an explosive event - a solar flare. Along with the production of electromagnetic radiation, the flare is often associated with the ejection of clouds of charged particles into the solar wind. This process is called a coronal mass ejection (CME) and occurs with flares and other types of events. The result of the material reaching the Earth is often a geomagnetic and ionospheric storm.

Coronal holes, another type of solar feature connected with space weather, are extremely large regions in the solar corona - the outer atmosphere of the Sun. They are regions of reduced temperature and density and are the locations of magnetic field lines which open into interplanetary space. Coronal holes contribute high speed streams to the solar wind which, when they reach the Earth, also produce space weather disturbances.

The Magnetosphere and Space

In our everyday experience, changes in the Earth's magnetic field are of little importance and a sensitive instrument is needed to detect them. However, 100 km or more above the surface of the Earth, the natural environment is quite different. The fringes of the atmosphere at these heights are strongly heated by the Sun's x-rays and ultra-violet light (and by other causes), causing negative electrons to be torn off atoms and leaving the remainder of the atoms positively charged. These electrified fragments react strongly to the magnetic forces and can be steered and trapped to form radiation belts around the Earth. Many satellite orbits are within the radiation belts which can increase dramatically during a storm.

The structure of the magnetic field near the Earth determines much of the motion and behaviour of the electrical particles found there. Satellites observing the Earth's magnetic field in space have found that the field is confined inside a cavity, the magnetosphere of the Earth. The space outside this is dominated by the Sun, and by the solar wind.

The Ionosphere

The ionised region in the Earth's atmosphere extending from about 60 km to above 1 000 km above the surface is known as the ionosphere, and above that is the magnetosphere. The ionisation of the upper atmosphere is largely governed by the radiation from the Sun. It varies with geographical location, time of day, season and solar cycle. Radio waves in the low frequency to high frequency bands can be bent by the ionosphere and received over long distances. Higher frequency waves travelling through the ionosphere from satellites can be also affected by space weather.

Cosmic Rays

Cosmic rays are fully ionised high-energy particles that make up the high-energy radiation environment in near-Earth space. The Sun's extended magnetic field (out to the limits of the solar system and beyond) and the solar wind plasma play major roles in controlling the intensity of the radiation at the Earth. The strength of the magnetic field in interplanetary space varies with the solar cycle and modulates the radiation in the Earth environment. Cosmic radiation originating outside the solar system is deflected away from the Earth during solar maximum when the solar magnetic field is strongest. In addition, some of the largest solar flare eruptions can generate dramatic increases in the radiation near the Earth and on rare occasions at the Earth's surface. Solar cycle variations are evident in the cosmic radiation intensity near the Earth.

Space Weather Forecasting

Observations of the Sun, interplanetary space, the magnetosphere, the ionosphere, and cosmic radiation form some of the inputs to international programs researching space weather prediction. They are used to develop prediction models of the near-Earth environment for space and terrestrial applications, such as satellite maintenance, emergency communication and surveillance systems.

Meteors and Near-Earth Objects

Although space weather usually concerns the electromagnetic energy and particle flux from the Sun to the Earth, there are larger particles traversing this region that can also influence our environment. Particles such as meteors burn up as they enter the Earth's atmosphere creating light and ionisation. Meteor trails may be used for short-burst communications but can interfere with radar. These particles can also cause direct damage to satellites.

Larger fragments travelling near the Earth may pose a threat to human population due to the possibility of hyper velocity collisions. The search and classification of such near-Earth objects (comets and asteroids with diameters exceeding 100 metres) and the study of mitigation techniques is known as Planetary Defence.

Potential impact of Space Weather on Industry and Society

Space weather conditions can directly affect radio communications, navigation, power supply, geophysical exploration, and through these can affect public safety, information services, defence, industrial processes, and transport.

Socio-Economic Effects

Public safety

Many of the socio-economic bases of Australian society are becoming dependent on national and international communications. Society has embraced a range of technology that is highly sensitive and increasingly vulnerable to space weather requiring new standards to be established. The Australian Government guides the development of standards for tomorrow's society. Society is already using defence and industry systems that operate in, or make use of, the space environment. Disturbances to the space environment require monitoring and forecasting in much the same way as meteorological conditions are forecast. Space weather is a vital factor in our planning of the future. There have already been occasions where space weather has caused the costly failure of terrestrial systems.

In preserving life in Australian conditions, radio communications and location identification are essential. Most modern sea, land and air distress systems rely on satellite or HF communications. Satellite navigation and position-finding are providing a safety net for many areas of work and recreation.

Aviation

Of all transportation systems within Australia, aviation is most affected by both terrestrial weather and space weather. Lack of attention to either of these factors can cause grave consequences. Vital navigation and communication, particularly when flying over remote areas, are significantly degraded by space weather. Radiation doses received by both passengers and crew are 20 to 30 times higher at cruising altitudes than they are on the ground, and major solar particle events can significantly increase this dose, especially over the Polar Regions.

Defence

As with emergency situations, Defence and coastal surveillance require good radio communications, high-resolution radar and modern direction-finding capabilities. In Australia, where the area under surveillance is large and sparsely populated, we are more dependent than many nations on secure and reliable communications. The best method for obtaining such reliability is to have multi-media resources, that is the use of a number of systems with the automatic ability to use the best available at any time. Both satellite and HF communication systems have some vulnerability to space weather and require well-informed management.

Defence also has other needs that range from secure communications from overseas to Australia, to special surveillance facilities as aids to general security.

Geophysical exploration

Aeromagnetic survey is a costly but efficient method of geophysical prospecting for minerals. However, magnetic surveys can be seriously disabled if sudden changes to the Earth's magnetic field occur during the flights and are not taken into account. Space weather conditions are a necessary ingredient in cost-effective geophysical surveying.

Industrial processes

As industrial processes become more sophisticated, there is an increasing use of high resolution electronic processes. These processes can be interrupted or degraded by changes in the Earth’s magnetic field at the time of major space weather storms. An example would be the increasing use of GPS satellite navigation for timing or positioning. A disturbance to the space environment that affects the positioning of terrestrial objects may have an effect on an industrial process. This is an area of concern that we expect to come to the fore over the next ten years as satellites are used in industrial processes.

Aviation and Space activities

High flying aircraft

The atmosphere absorbs much of the tissue-damaging radiation from the Sun. At ground level we are protected from it. However, as aviation and space flights take us higher in the atmosphere the protection decreases. During times of space storms the radiation hazard is increased. For the rare events that lead to dramatic radiation increases at the Earth’s surface there are implications for radiation safety in aircraft flying at high altitudes, particularly over polar routes, where the protection of the Earth’s magnetic field is lowest. European legislation is now in force to limit the exposure of airline staff to cosmic radiation.

Spacecraft

Geosynchronous satellites operate within the Earth's radiation belts. Spacecraft charging can seriously affect satellite communications during times of adverse space weather. The accumulation of electrical charge on a spacecraft due to the flow of solar wind past the craft, or into the radiation belts, can increase during a disturbance, sometimes resulting in disruption of the sensitive electronics on the craft. In the extreme, "phantom" commands resulting from charging effects can result in the loss of the satellite. Solar cells on satellites are also degraded by radiation damage caused by solar disturbances and their lifetime and effectiveness are thereby reduced.

Solar storms add energy to the Earth’s atmosphere. This heating causes the atmosphere to expand and increase the atmospheric drag, especially on low orbit satellites. Satellites must then expend fuel to be boosted back to their operational orbits or else continue operation at lower altitudes. In either case the operational lifetime of the satellites is reduced.

Global communication is being achieved through the use of constellations of satellites operating in space. The operational health of these satellites is dependent, in part, on solar storms and sudden changes to the space environment. As more satellites are launched the chance of satellites being disrupted by spacecraft charging or by rupture on collision with small particles will be increased. A close watch on space weather is essential for best practice management of these satellite systems.

Space operations

Over the next ten years numerous spacecraft missions are planned, some for terrestrial applications, some for space weather monitoring. Space weather storms present a real danger to the control and management of these satellites. The positioning and working life of spacecraft are dependent on space weather. Space weather monitoring, in space (as is being done on board FEDSAT) or on the ground, will provide the data at the time of any satellite fault and help determine the cause.

Space weather monitoring is a global activity and, through its geographic area and position, Australia and the Australian Antarctic Territory are well placed to participate in the global monitoring network.

Ionospheric Communication

HF communication is a cost effective means of reaching all areas of Australia, particularly the more sparsely populated rural areas and especially in times of emergency if no other communications are available. HF radio uses the ionosphere as a reflector for long distance radio paths. The electron density of the ionospheric layers, and the highest radio frequency that they can support, is dependent on the Sun’s output. At the low point of the solar cycle, EUV (Extreme Ultra Violet) radiation from the Sun is weak and the density of charged particles in the ionosphere is least. This means that only the lower frequency signals in the HF band (3-30 MHz) can be reflected. At the peak of the cycle, the EUV and the ionospheric density are both large and higher frequencies in the HF band can be reflected.

While the solar cycle is important in determining the most suitable HF frequencies, there are many other factors. These include the season, time of day, latitude, and the geometry of the radio circuit.

Ionospheric Disturbances and Communications

The response of the ionosphere to space weather storms is complicated as it depends on the time of the day, the season, the latitude, and the nature of the disturbance itself. In many cases, the highest frequency supported by the ionosphere is enhanced early and then depressed later in the storm. These variations about the average in ionospheric properties need to be anticipated by HF communicators.

Periods of severe disturbance will affect more than the radio frequencies. Irregularities in the ionosphere result in signals travelling by more than one path and this can produce interference fading and consequent difficulties in communications.

The reflection of VHF signals can also occur during auroras - spectacular curtains of lights arising from charged particles originating from the Sun. The aurora is associated with increased ionisation in the lower ionosphere and it is from this that the signals can be reflected. Auroras are associated with large geomagnetic and ionospheric disturbances and thus VHF transmission by this means occurs at times when HF may be experiencing problems. Auroras are most commonly seen at polar latitudes at which location HF transmission is most likely to experience problems.

Ionospheric disturbances have a similar variation during the solar cycle as do geomagnetic disturbances. In general, disturbances are more frequent at solar maximum although they also occur during the declining phase of the solar cycle.

Propagation of lower radio frequencies (VLF) is controlled by the lower regions of the ionosphere. Propagation of the signal occurs through the waveguide formed between the conducting Earth and the ionosphere. Propagation is therefore subject to variations of the ionosphere determined by the Sun and space weather. The intense flux of X-rays during a major flare increases the ionisation of the lower ionosphere and changes its ability to reflect in these VLF bands. Flares usually have a very rapid onset - measured in minutes - and this results in sharp changes in the amplitude and phase of signals as the waveguide height changes causing, for example, loss of signal and/or loss of lock in submarine cryptographic communications.

Satellite Communications and Ionospheric Variability

Radio signals from satellites at VHF frequencies and above are capable of penetrating the ionosphere, providing transionospheric communications. They can suffer degradation due to the background ionisation. Ionospheric scintillation and rotation of polarisation effects are related to the Total Electron Content (TEC) along the radio signal path.

Although satellite communication, at higher frequencies, is less subject to the vagaries of the ionosphere, it can be subject to interference from the Sun. Around the time of equinoxes each year the Sun, itself a wideband radio transmitter, passes behind a given geostationary satellite at some time of the day and thereby causes interference to the wanted signal.

Terrestrial systems

Surveillance Radar

Over-the-Horizon (OTH) radars use HF radio frequencies to probe the skies for many thousands of kilometres from their sites. Australia has three radars that will operate from East, Central and West Australia. These systems make use of the ionosphere to reflect radio waves beyond the horizon. They are very sensitive to changes in the height and density of the ionosphere and have associated ionospheric monitors providing operational data. These data are useful to other military and civilian customers and are to be channelled to the appropriate data centre. Equally, space weather data are needed for the successful operation of OTH radars.

Navigation

Modern navigation systems operate through satellites such as the GPS (Global Positioning System), GLONASS or Galileo systems. Operation of GPS requires that a number of satellites are visible and operational to the user at any one time. Because the satellite signals transverse the ionosphere they are affected in such a way that corrections for delays need to be taken into account unless the receivers have dual-frequency capability. The ionospheric correction is an important factor for the navigational system particularly when the ionosphere departs from average conditions and when a severe disturbance follows a space weather storm.

In certain parts of the world (equatorial and polar regions) ionospheric scintillation may briefly disrupt GPS navigation. This is of concern when GPS is used for precision aircraft control. As the use of navigational systems becomes more sophisticated and society becomes more reliant on them, there will be a greater need for accuracy in navigational positioning and space weather knowledge will play a vital role. GPS navigation is now used in emergency situations such as bushfires for finding critical locations in Australia. Even small errors in the navigation can give rise to serious consequences.

Power lines

Power lines act as long electrical conductors and when the Earth’s magnetic field changes during a space weather storm, voltages exceeding many thousands of volts can be induced between the ends of the line. Induced currents flow to ground through substation transformers and can cause the safety mechanisms to activate in order to preserve the power transformer from damage. In the past, major power distribution systems have been brought down for many hours at a great cost to industry. Such losses are more likely at higher latitudes in Australia.

Pipelines

Pipelines are used widely to transport gas, oil and water from their sources to processing plants and consumers. Damage to a pipeline is costly, directly and also indirectly through damage to the environment and the public. Electrochemical corrosion can be inhibited by maintaining the steel pipeline negative with respect to the surrounding soil. When a space weather event occurs the pipeline voltage need to be altered to compensate for the induced voltage.

International Space Weather activities

This section summarises some of the agencies, and nations, involved in space weather forecasting. It does not attempt to cover all such organisations. For instance, Asia is rapidly developing its space activities, Europe contains many smaller agencies in addition to ESA. USA has a centre for space environment but has many small groups and businesses operating in the space weather area.

USA

The three principal agencies undertaking significant space weather activity are the civilian Space Environment Center of the National Oceanic and Atmospheric Administration (NOAA), National Aeronautical and Space Agency (NASA) and the US Air Force (Air Force Weather Agency). NOAA is supported by the US Department of Commerce and works closely with the USAF under a National Space Weather Plan.

Europe

European effort in space weather monitoring and analysis has until recently lacked overall coordination. Various aspects of space weather are monitored by different organisations: solar observations are made through the French Meudon Observatory, radio propagation warnings are prepared by BAE systems p/l and a wide range of forecasts is made by the University of Oulu. Currently, the European Space Agency (ESA) is seeking ways to coordinate the present groups into a cohesive European Space Weather Centre but this is at an embryonic stage.

Russia

The Russian network of space weather monitors is still one of the largest in the world but its capability is limited by poor support and by lack of coordinated effort. The majority of the space weather monitoring is operated by the Institute of Applied Geophysics in Moscow in cooperation with the military.

Asia

In Japan the Communications Research Laboratory operates a space weather centre outside Tokyo. Data and analysis are carried out and distributed to organisations that use them. Kyushu University hosts the Space Environment Research Centre and Nagoya University has a solar-terrestrial environment laboratory both using some real-time data from Australia. In China, there is a space weather centre at the Beijing solar observatory and at the Chinese Research Institute for Radio Propagation. Although the Chinese network of monitors is extensive, the communication of data in near-real time from many sites is not available and therefore warnings of space disturbances are of limited value. Korea, Indonesia and possibly Thailand and Malaysia are developing space weather programs.

Africa

South Africa is establishing a space weather forecast centre with the help of Australian expertise. South Africa has the longer term objective of providing assistance to rural communications across the whole of Africa.

International bodies

Under the auspices of ICSU (International Council for Science) COSPAR (Committee for Space Research) is the prime organisation for coordinating international space science programs, including space weather, while SCOSTEP (Scientific Committee for Solar-Terrestrial Physics) specialises in Sun-Earth relations. The International Space Environment Service (ISES) provides a rapid exchange of space weather information. The International Union for Radio Science (URSI) sponsors symposia on subjects that affect radio and consequently space weather is now a discussion topic within URSI. The Cosmic Ray Commission of the International Union of Pure and Applied Physics (IUPAP) sponsors biennial international cosmic ray conferences that include the radiation aspects of space weather.

Future directions

Major efforts are being made, especially in the U.S.A and Japan, to understand the hazards of space environment in preparation for the use of space for research, industrial and military activities. Space programs are in place for monitoring and modelling the Sun-Earth environment and many more are planned as international cooperative efforts.

Such programs have a strong commitment to basic research in many areas of space-related science, including studies of the Sun, the solar wind and interplanetary medium, the magnetosphere, the ionosphere, the upper atmosphere and cosmic radiation. The "Living with a Star" (LWS) program is a major 10-15 year program of in-situ space and ground-based measurements currently in progress. Initial emphasis will be on understanding the fundamental physical processes that govern the state of the Sun, and its coupling to the terrestrial system. Several satellite systems are included under the umbrella of the program. The results will improve our ability to specify and predict conditions in the space environment at any given time. LWS has an international collaboration approach and Australia is an invited participant in the LWS program.

Several basic research areas representing significant gaps in our present understanding are being addressed:

* understanding and prediction of processes affecting solar activity, such as the solar cycle coronal mass ejections (CME's) and solar flares
* understanding of solar structures and signals that forewarn of solar radiation streams
* coupling between the solar wind, the magnetosphere and ionosphere
* the origin and energising of magnetospheric plasma
* the triggering and temporal evolution of geomagnetic substorms and storms
* improved global ionospheric specification and forecast and the evolution of ionospheric irregularities, including the onset of low latitude ionospheric irregularities, with particular emphasis on those processes affecting communication and navigation systems
* improved specification of thermospheric dynamics and neutral densities
* validation and enhancement of ionospheric and magnetospheric models, including data assimilation techniques, to improve operational forecasting and specification capabilities
* transmission of solar radiation energy through the magnetosphere to ground levels.

Issues for an Australian Space Weather Program

Australia is already dependent on space technology for many of its services, its information and its security. The national research priority "Safeguarding Australia" highlights the importance of security and safety in today's world. The risk to Australia's information and communications infrastructure will continue to increase as satellite technology expands into constellations of inter-related satellites. Infrastructure affected by space weather in the future will include the basic areas of communications, surveillance, earth resource management, meteorology, hazard management, and power supply among others.

Australia wishes to be able to make decisions that affect its future and will need to be part of the space-knowledgeable nations. At the present time there are the following issues in relation to space weather.

- Future technical systems will require greater prediction accuracy than currently possible,
- Technology is moving ahead rapidly into areas influenced by space weather

- Australia is very dependent on satellites and spacecraft for information, communications, and remote sensing
- Space weather activities in Australia are at international standards but are widely dispersed among government, university and the private sectors
- A strategy is needed to maximise the benefits of space weather activities for industry and social infrastructure.

To understand the space environment to the level required by the space industry, there are three areas to be addressed.

- Space weather monitoring and the delivery of space weather services.
- Space environment research.
- Outreach to the community.

Monitoring of the space environment is required to enable existing and future space applications to avoid or minimise the vagaries of space weather. Space environment research provides the tools with which space environment hazards may be overcome or reduced. Outreach encourages organisations to understand space weather risks, to competently plan for the future and make use of the tools as they become available.

Space weather monitoring and services

Monitoring, geographic and temporal, real-time

The Australian Department of Industry Tourism and Resources (ITR) has an excellent starting point by having the IPS Radio and Space Service network of solar, ionospheric and geomagnetic monitors that are linked by a real-time communications system. Geoscience Australia (GA) is monitoring the Earth's magnetic field and has access to geomagnetic data overseas and complements IPS observations. Similarly the Australian Antarctic Division (AAD) monitors cosmic radiation and DSTO has a chain of ionospheric measuring sites. Excellent campaigns of space weather measurements are made by Universities and by some private companies.

Forecasting techniques require the space weather data to be monitored at locations and times that allow for constant surveillance of solar, magnetospheric and ionospheric conditions. Thus solar observation needs to be carried out from sunrise on the east of Australia to sunset on the west. Geomagnetic, ionospheric and cosmic ray monitoring should take place throughout 24 hours and at locations that represent low, mid and high latitudes. There are existing networks of sites within Australia and the Antarctic Territory where ionospheric and magnetic measurements are made available in real-time. The IPS network includes 14 ionospheric stations from Papua New Guinea to Antarctica, the GA has a network of magnetometers across Australia and Antarctica.

For effective warning of space weather events, monitors should be stationed in space, upstream between the Sun and the Earth, and in the tail of the magnetosphere, behind the Earth from the Sun, through which solar particles enter the magnetosphere and the Earth's upper atmosphere. This relies on an extensive, and therefore expensive, satellite distribution in space. Australia's immediate response to space weather monitoring is best placed in utilising existing networks of terrestrial monitors and coordinating the collection of data, its analysis and the distribution of services. Space-based observations can be combined with ground-based data through data exchange.

Global data exchange

Because of the need for full 24-hour coverage of space weather, monitoring of the Sun, the ionosphere, the Earth's magnetic field and its radiation environment, has to be carried out on a global scale. This requires data from other countries around the globe to be exchanged with similar data from the Australian region. It is in Australia's interests to support and promote the free global exchange of space weather data and to play an active part in global monitoring consortia. Equally it is vital that Australia harnesses the data from different locations and organisations so that they may be used in improving space weather models. The World Data Centre for Solar-

Terrestrial Science within the Department of Industry Tourism and Resources can act as portal for encouraging the release and access to the data.

Real-time data; short-term forecasting; archival information

Space weather services are required in three times scales: immediate (real-time data), forecasts for the next few hours to days, and archived data. These services then provide, respectively, information for immediate action, the future context of space weather conditions, and information for designing and specifying systems and for confirmation of events.

Space weather services

IPS has provided services to operators of radio communications and other systems affected by space weather for over 50 years. In doing so IPS has developed a comprehensive range of services, many delivered in real-time.

IPS services depend on access to a wide range of Australian data. These include information from ionosondes, from solar observatories, and from magnetometers. IPS has responsibility for the World Data Centre for Solar-Terrestrial Science and the provision of data to assist space weather research.

The Sun-Earth environment requires continuous monitoring and IPS is the Australian link to the International Space Environment Service, ISES, an organisation which co-ordinates the global exchange of data. This link gives IPS access to significant information not available within Australia as well as an important role in scientific research that is vital in improving forecasting of the environment.

IPS also provides consultancy services that help people customise their communications systems to the effects of the changing ionosphere. IPS advises its clients on all aspects of the Sun-Earth environment and its effects on a wide range of technology.

Space weather disturbances may arise at short notice after events such as solar flares, coronal mass ejection and short-lived coronal holes. The sporadic nature of these events sets a limit to the timescales over which they can be predicted. A particle radiation event will occur on Earth within 30 minutes, while, in the case of a solar flare, the delay time between the flare and the onset of a geomagnetic storm is typically 1-3 days. In Sydney, IPS operates the Australian Space Forecast Centre (ASFC) which receives observations from two solar observatories in Australia (located near Narrabri in NSW and near Exmouth in Western Australia) and from other international sources. The role of the Centre is to provide warnings of major space weather activity and confirmations of actual events.

Space weather research in Australia

FEDSAT

FEDSAT, the Australian micro satellite designed and managed by the CRC for Satellite Systems (CRCSS) was launched into an 850 km orbit in 2002 and is making measurements of the magnetic field over Australia and the higher latitudes. FEDSAT carries a GPS receiver measuring total electron content data for magnetospheric and ionospheric studies.

TIGER auroral radar

As the Earth's magnetic field carves out a cavity around itself in the Sun's atmosphere, it stirs up the dynamic, complex electric current system that forms the magnetosphere - a place of high energy particle flows that carry energy from the solar wind into the ionosphere. As the sun's atmosphere changes, the electric currents change and the ionosphere changes. TIGER (Tasman Ionospheric Geospace Environment Radar) takes a 4 million square kilometre snapshot from Tasmania of the magnetospheric processes acting on the southern ionosphere.

A second cooperative radar is being designed for the South Island of New Zealand. This will enhance the ability of the radar to image the surge of currents that herald space environment changes entering the Polar Regions.

Australian Cosmic Ray observatory network

Understanding cosmic ray phenomena requires observations from a range of locations. The Mawson observatory, comprising low and high energy surface and high energy underground instruments, is the largest and most sophisticated observatory of its type in the Southern Hemisphere, and the only one at polar latitudes. Similar detectors operate at the Australian Antarctic Division headquarters and other Tasmanian sites.

The Mawson Antarctic observatory is part of the international *Space Ship Earth* program. Real time low energy observations from the member observatories will be available to industries affected by Space Weather. The observatories will also develop predictive space weather techniques based on the observations.

The high-energy telescopes are part of a new international collaboration between Japan, Australia, Brazil and Germany. Particular variations in this radiation appear to precede solar storm arrival by a day or more, offering a new predictive tool.

Satellite-to-satellite measurements of the upper atmosphere

La Trobe University is conducting an experimental program of measurements of satellite radio paths that traverse the ionosphere and the upper atmosphere of the Earth.

Other research activities

There are several others centres where research on subjects related to space weather are being carried out. These include Defence Science and Technology Organisation, Universities of Sydney, Monash, Murdoch, Adelaide, South Australia, UTS (Sydney).

Public outreach

Technology is rapidly moving into space and changes in industry and social infrastructure are becoming increasingly sensitive to space weather disturbances. The influence of space weather conditions on terrestrial systems needs to be understood and taken into account.

To best manage the risks associated with extremes of the space environment Australia must understand and gauge the risks. The adoption of an Australian Space Weather Plan will give direction to a program of space weather monitoring and research over the next ten years to coherently build the technical knowledge and effective services required to accurately specify immediate and future space environment conditions.

Public and private sectors are generally not aware of the space environment and space weather is not always considered effectively in planning. An information program that reaches out to industry, the community and to government will help integrate an understanding of space weather conditions into system planning and the mitigation of disturbance effects on society.

Future directions for Australia

It is proposed that Australia institutes a space weather program to optimise existing government, industrial and social infrastructure and prepare for future use of the space environment. To be effective the program needs to consist of the following elements.

Australian Space Weather Agency for space weather monitoring and services

Having access to the data is an essential ingredient in forecasting the effects of space weather. If Australia is to have access to data not collected here, there needs to be a body dedicated to the space weather service that can provide collateral in exchange. In other words, Australia should establish a national space weather agency capable of collecting data for which it has equipment and expertise and exchange it with other organisations overseas for data that are not collected by Australia.

Australia has a reputation for monitoring of ionospheric, geomagnetic and cosmic ray data, for specialist solar data and for an ability to automate the analysis of data into real-time services.

- ***It is recommended that an Australian Space Weather Agency should be established in recognition of the importance of space weather monitoring***
- ***It is recommended that Space Weather data should continue to be made freely available on an exchange basis globally***

Data archiving and access

In collecting data for space weather forecasting, it is geomagnetic, ionospheric, space, cosmic ray and solar data that are particularly important. Ready access to all these data will enhance and accelerate Australian research into space weather modelling. With IPS as a major centre of space weather data, there is good reason for IPS to draw in data from other organisations where practical. An example could be the collection and dissemination of geomagnetic data from FEDSAT, Geoscience Australia (GA), ionospheric data from the Australian Antarctic Division and DSTO and cosmic ray data from the Australian Antarctic Division.

Research priorities

Alliance with other organisations having specialist information and techniques is essential to maintain standards at the level expected by users. Research aimed at increased understanding of space weather systems and improved forecasting will need to be collaborative and be centred at the locations of greatest expertise. Regular meetings of allied groups will be needed to manage the work and its direction. Research coordination through self-management of priority areas for research funds is essential.

- ***It is recommended that the Academy of Science and the Academy of Technological Science and Engineering draw up a list of research items that are currently required to improve space weather forecasting in Australia.***
- ***It is recommended that the Academy of Science coordinates major research priorities in a consensual manner similar to the planning of astronomy priorities.***

Education and promotion

A campaign of education on space weather is proposed through several channels. These include government, public science forums and at specific regular meetings.

- ***It is recommended that the Academy of Science and the Academy of Technological Science and Engineering should devote specific campaigns and discussions to the subject of space weather and its effects on technological systems.***

Support for Australian organisations

The following agencies have a major input to the future monitoring and determination of space weather and its terrestrial effects:

- *Adelaide University (Physics Department)* researches the dynamics of the middle and upper atmosphere, and the coupling with the ionosphere and space environment. Collaboration with DSTO on meteor physics program.
- *Adelaide University (Centre for sub-atomic structure and matter)* researches mathematical applications for space weather processes and is supporting a World Institute for Space Environment Research as a centre for education and research into space weather.
- *Australian Academy of Science National Committee for Space Science* coordinates the formal dissemination of Australian space research externally.
- *Australian Academy of Technological Sciences and Engineering* has a working group examining the financial, scientific and other implications of space weather.

- *Australian Antarctic Division (AAD)* has active Space and Atmospheric Sciences (SAS) programs investigating the Antarctic upper atmosphere and the space environment and cosmic rays.
- *Defence Science and Technology Organisation (DSTO)* has a research program in ionospheric physics as it relates to radiowave propagation.
- *Geoscience Australia* (GA) monitors the Earth's magnetic field and studies transient changes to that field caused by space weather.
- *IPS Radio and Space Services* (IPS) monitors ionospheric conditions, transient magnetic variations. Provides space weather services, data services and operates the World Data Centre for Solar-Terrestrial Science.
- *La Trobe University (Physics Department)* conducts degree courses in space physics, oversees TIGER (Tasman International Geoscience Environment Radar) and has a well developed research program in ionospheric physics and upper atmosphere physics.
- *National Mapping Division of Geoscience Australia* monitors GPS signals to maintain a check on the reliability and accuracy of navigation signals.
- *Newcastle University (Space Physics Group)* is conducting research into magnetospheric and ionospheric processes caused by the interaction of the solar wind and the Earth's magnetic field.

International collaboration

As with national unity, so there is strength in working with overseas organisations to pool data which will support more advanced services than with our own data alone. As an example, Australia (IPS) can provide the US NOAA Space Environment Centre (SEC) with ionospheric services which SEC are not able to produce easily, in return for satellite data services for which IPS does not have data.

The existing international collaboration on cosmic ray and SuperDARN auroral radar programs must be maintained and enhanced and other research and monitoring collaborations established where appropriate.

Australia needs to keep in close communication with those agencies responsible for building a cohesive space weather program in Europe and Asia, as well as maintaining relations with existing groups in the U.S.A and Japan.

Recommendations:

Space weather monitoring and services

1. *To take advantage of Australia's research and technological expertise, an Australian Space Weather Agency should be established to:*
   - *service Australia's increasing needs for mitigating the influences of space weather*
   - *develop applications for space weather prediction and services*
   - *support long term monitoring of space weather phenomena*
2. *The existing World Data Centre for Solar-Terrestrial Science should be the Australian warehouse for space weather data*
3. *Space Weather data should continue to be made freely available on an international exchange basis*

Research priorities

4. *In order to strengthen Australian research capability in space weather, the Academy of Science, in consultation with the Academy of Technological Sciences and Engineering, should*

draw up a list of research projects that are currently required to improve space weather forecasting in Australia.

5. *This should identify research priorities, especially those relevant to Australia, and develop a five-year costed plan of priority research for space weather after consultation with the space weather community*

Public outreach

6. *The Academy of Science and the Academy of Technological Sciences and Engineering should devote specific campaigns and discussions to the subject of space weather and its effects on technological systems.*