Australian Government
Bureau of Meteorology

Review of the Bureau of Meteorology's Space Weather Service

Professor Paul S Cannon and Dr Terry Onsager
September 2014

Cover photo

Learmonth Solar Observatory, Western Australia, showing the 1 metre parabolic dish (monitors 15.4GHz discrete frequency) alongside the 2.4 metre parabolic dish (monitors 1415 MHz, 2695 MHz, 4995 MHz, and 8800MHz discrete frequencies). To the left with the wind vane anemometer is the GONG (Global Oscillation Network Group) building which looks inside the Sun using Helioseismology and to the right is part of the SOON (Solar Optical Observing Network) Building that contains the H-alpha polar axis telescope which observed the Sun's chromosphere.

Date of issue:

Published by the Bureau of Meteorology

1 Executive Summary

Space weather is increasingly recognized as a risk to national economies and to the safety of citizens, mainly through its impacts on technological infrastructure essential to modern society. This is partly a consequence of our improved understanding of the risks associated with extreme but relatively rare space weather events. It is also partly the consequence of technological evolution requiring ever more accuracy, autonomy and integrity while delivering this with ever smaller semiconductor devices. As is well understood, space weather can disrupt, degrade or affect a plethora of Australia's critical services such as HF communications systems, power grids, global navigation systems, satellites and even avionics and air passenger safety. Space weather is often a limiting factor in the delivery of our technology aspirations.

The review has demonstrated that Australia needs a space weather services capability to support government, industry and the military. The military requirement is overwhelming on its own and security issues preclude shifting this capability offshore. Support to the electricity industry during major and extreme storms is another national security issue – with potentially severe economic repercussions. Moreover, we believe that remediation of space weather effects on the new technologies associated with precision positioning (i.e. Global Navigation Satellite Systems, GNSS) is sufficiently important that it too requires a sovereign capability.

The Bureau of Meteorology (BoM) Space Weather Service (SWS) is assessed to be in the top tier of global space weather centres and arguably globally preeminent in ionospheric high frequency (HF) space weather services. SWS staff demonstrably understand the environment (see their academic papers) and also have a detailed understanding of the risks that space weather induces on technologies (see their wide variety of customers). The SWS delivers valued environmental services which specify, predict and forecast space weather (as demonstrated through letters of support); and it supports the engineering community through its consultancy business.

We consider that dispersing the functions of the SWS across government and industry would be inefficient, risky and would be difficult to manage from a security perspective. Moreover this approach would be unlikely to render a trusted data and advice provider.

Consequently, we recommend the long term support of the SWS in the BoM as the delivery agency of space weather services for the Commonwealth of Australia. To put this on a firmer footing a number of steps are recommended including reinforcing the position of space weather in the Meteorology Act, incorporation of space weather in the Critical Infrastructure Resilience Strategy and setting up appropriate governance mechanisms to guide the SWS.

In the short term we recommend that the Bureau's SWS be sustained with its current budget. However we have also made suggestions to improve the transparency, effectiveness and resilience of SWS management. By addressing these issues, the SWS should be able to develop new services and demonstrate its effectiveness over a wide range of technologies. If successful an increased budget and resources should be within reach.

In this context we believe that SWS would benefit from redirection of some of its R&D and service priorities to support new high value customers associated with emerging technologies. In so doing SWS must not prejudice its current world class HF services.

We have reviewed the options for cost recovery. The provision of some open and free forecasts remains a core requirement if SWS is to remain part of the international community, which provides to Australia free terrestrial and space based data on a quid pro quo basis. We believe that un-interpreted SWS environmental forecasts must remain free at the point of use for non-commercial and non-government users in much the same way that meteorological forecasts are free at the point of use.

We believe that the simplest cost recovery approach for forecast services is to recognise the importance of space weather services to other government departments and formulate an appropriate charge. We are not able to estimate the value of this cost recovery option. Where commercial customers require a tailored forecasting service specific to certain technologies, further cost recovery should be considered.

For other SWS activities we are of the opinion that there is potential for increased cost recovery from the current 6% to ~10 % through changes in the charging structure. Coupled with other initiatives this could increase to ~15% over 5 years. We are of the opinion that greater levels of cost recovery from software, courses, consultancy and product delivery can only be attained if significant licensable Intellectual Property is developed.

The report makes over 40 recommendations; a subset of the most important recommendations is given below using the same referencing system used in the main body of the report. In addition we have made recommendations for realignment of SWS against a variety of technologies and have also made a number of suggestions in respect to the SWS management structure.

1.1 Policy

R1. (Recommendation 1.) That the Bureau briefs the Australian Government that space weather poses threats to Australia and is recognised and classified internationally as a natural hazard.

R2. That the Bureau works across the Australian government to improve the understanding of the criticality of space weather services, in particular:

a) That the Bureau ensures that it complies with Section 6 of the Meteorology Act 1955 through the provision of space weather services amongst one of its many functions;

b) That the Bureau ensures that space weather is incorporated in the Critical Infrastructure Resilience Strategy (delivered through the Trusted Information Sharing Network) in order to effectively deal with both major and extreme space weather events. The following Sectors and their users would benefit from space weather preparedness strategies: Aviation, Defence, GPS based Positioning, Navigation and Timing systems (PNT), and Power and Energy systems.

c) That the Bureau establishes appropriate governance arrangements to better engage with stakeholders and ensure space weather services evolve in line with scientific and technological advances and customer demand.

1.2 Assessment of Current Performance

R8. That the Bureau develops a long term SWS research plan which is annually refreshed.

1.3 Impact

R10. That the Bureau establishes a sustained programme of monitoring access to SWS specialist pages and explores with clients the utility of the forecasts at least once a year.

1.4 The Next Five Years

R14. That the Bureau's SWS softens its focus on HF to facilitate the development of other products. Further that HF R&D only be undertaken when closely tied to customer requirements.

R16. That the Bureau works with the Australian Energy Market Operator (AEMO) and the power grid Transmission Network Service Providers (TNSPs) to develop a better understanding of space weather risks associated with Geomagnetically Induced Currents (GIC) and develop GIC products to assist mitigation of risks to the grid.

R17. That the Bureau works with National Positioning Infrastructure Plan sponsors, Air Services and other government agencies in support of the emerging technologies associated with precise positioning systems and services and develop appropriate space weather products.

R18. That, in recognition of the demand, the Bureau considers how its SWS can provision a high integrity 24*7 service as opposed to the current working day service.

1.5 Cost Recovery Options

R20. That the Bureau conducts market research, including webpage clients (R10), to ensure, where appropriate, they are realising the full commercial value of their space weather services.

R21. That the Bureau conducts a forensic review of cost recovery, in respect to space weather services, as they relate to government or quasi-government customers that benefit from space weather services.

R22. That the Bureau positions itself as either a regional or a global income generating International Civil Aviation Organisation (ICAO) Space Weather Centre. This needs to start immediately.

R35. That the Bureau works with the ARC, CSIRO and Defence to offset the costs of data curation.

Table of Contents

Index of Figures

2 Introduction

2.1 Objective of the Review

The Bureau of Meteorology (BoM) Space Weather Service (SWS) provides a broad range of space weather services associated with measuring, modelling and forecasting the near space environment.

In 2011, a review of the BoM’s capability to respond to future extreme weather and natural-disaster events was conducted (the “Munro Review”). This review identified the cessation of space weather services as one option (Option 20) for potential cost savings. Part of the Australian government’s response to this option is to hold an independent review to consider the future demand for space weather services in Australia and options for delivering these services. This review is designed to obtain an understanding of the national need for space weather services, the extent to which user needs are being met, and an assessment of the strategic outlook for space weather services in Australia.

2.2 Terms of Reference

The terms of reference of this review are:

1. Review the policy basis for the Bureau's Space Weather services;
2. Provide an analysis and international benchmarking comparison of the Bureau's Space Weather services, and use of observations and infrastructure, including:
    - their current status;
    - performance and impact;
    - scope;
    - manner of delivery;
    - adequacy of capabilities and resourcing to deliver the service;
3. Evaluate the extent to which the Bureau's Space Weather services meet user needs, especially those of significant user groups and high-impact users;
4. Assess the strategic outlook (over 5-10 years) for Space Weather services in Australian, regional and global settings and, in light of 1 to 3 above, provide advice on the capabilities required to meet the future challenges;

5. Comment on the potential for cost-recovery of Space Weather services;
6. Provide recommendations based on the above analyses, assessments and evaluations.

2.3 Space Weather Mitigation

A space weather service should ideally consist of four elements (*Figure 1*); an understanding of the environment which will necessarily include access to measurements and models; a detailed understanding of the risks that space weather induces on various technologies; the provision of services which specify, predict and forecast space weather; and finally support to the engineering community so that they can design, build and operate technologies which are as robust as possible. Forecast mitigation and engineering mitigation have to go hand-in-hand – neither one on its own provides sufficient resilience.

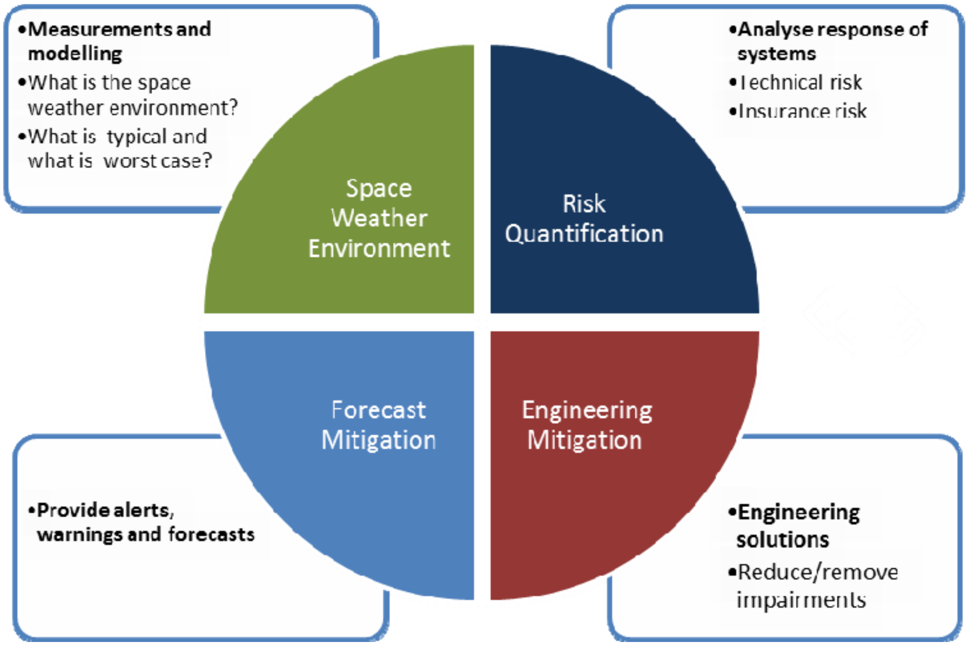


Figure 1: Elements of a Space Weather Service

2.4 Space Weather Primer

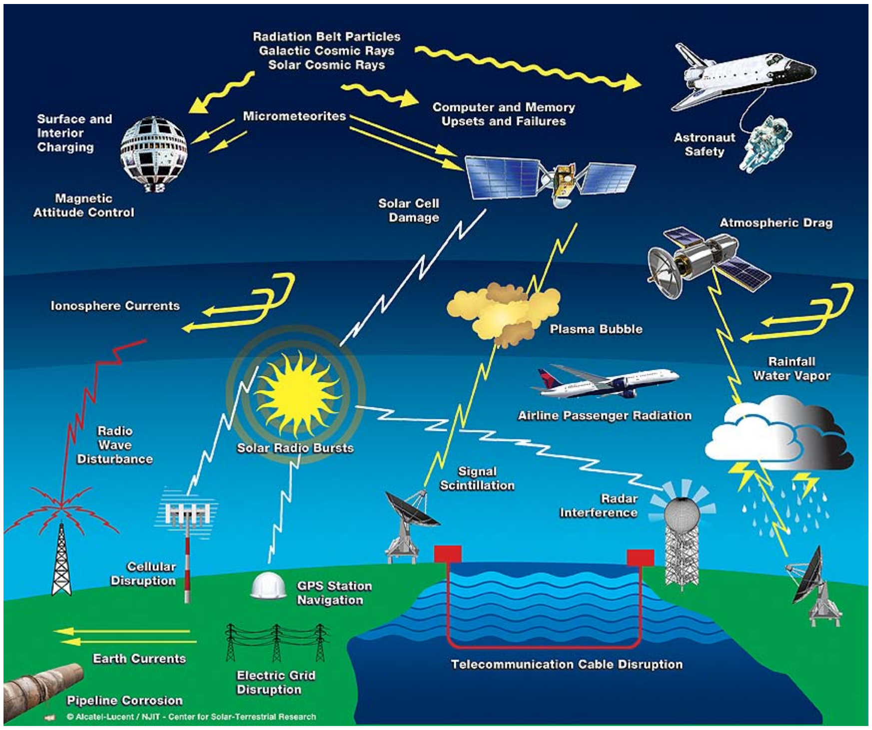
Space weather is a term that describes variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere, which can influence the performance and reliability of a variety of space-borne and ground-based technological systems and can also endanger human health and safety. Many of the systems affected by space weather are illustrated in

Figure 2. Just like terrestrial weather, space weather is pervasive, and compensating for its impact is a challenge.

Space weather exhibits a climatology which varies over timescales ranging from days (i.e. diurnal variations resulting from the rotation of the Earth) to the 11-year solar cycle and longer periods. Superimposed on this climatology are weather-like variations; on some days space weather is more severe than on others. Minor solar storms are relatively common events; in contrast the effects of extremely large events (superstorms) are only occasionally seen on Earth – perhaps once every century or two.

Although there is some influence from the atmosphere and from outside the solar system, most space weather starts at the Sun. The elements of the coupled Sun-Earth space weather system consist of Sun, solar wind, solar magnetic field, magnetosphere, and ionosphere, as illustrated in Figure 3*.*

The Sun is a nearly constant source of optical and near-infrared radiation. However, there is considerable variability during storm periods at extreme ultra-violet (EUV), X-ray and radio wavelengths. During these periods, the Sun is also more likely to generate high-energy solar energetic particles and the solar wind plasma speed and density, forming part of the solar corona, can increase substantially. Coronal mass ejections (CMEs) are one manifestation of the latter. Directly or indirectly the ionising radiation, the ionised particles and the plasma interact with the magnetosphere and the ionosphere below it to cause a variety of effects on technology and humans.



© Alcatel-Lucent / NJIT - Center for Solar-Terrestrial Research

Figure 2: Impacts of space weather (Image courtesy of: L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.)

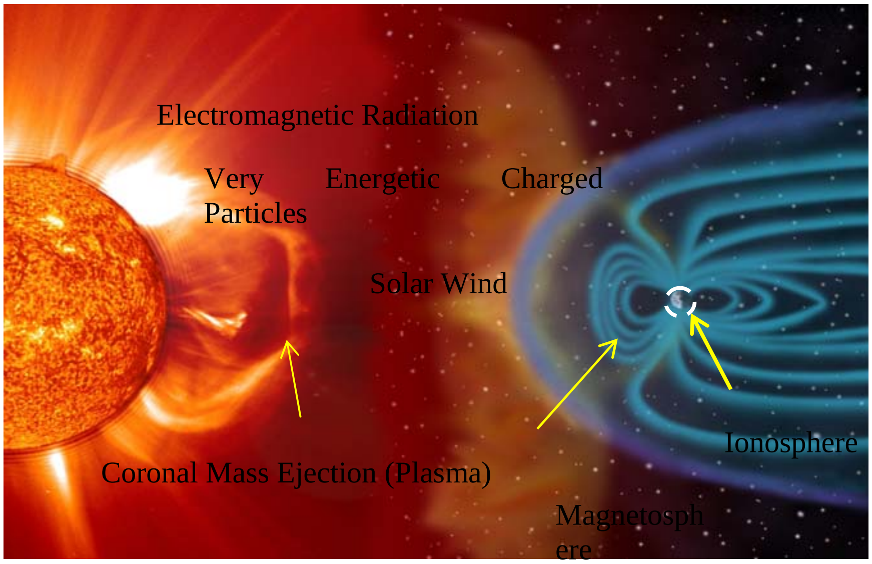


Figure 3: The space weather environment (image courtesy of NASA, adapted by Cannon).

2.5 Extreme Space Weather or Solar Superstorms

Explosive eruptions of energy from the Sun that cause minor solar storms on Earth are relatively common events. In contrast, extremely large events (superstorms) occur very occasionally – perhaps once every century or two. Most superstorms miss the Earth, travelling harmlessly into space. Since the start of the space age, there has been no true solar superstorm seen on Earth and consequently our understanding is limited. A superstorm which occurred in 1859, now referred to as the 'Carrington event' is the largest for which we have measurements; and even in this case the measurements were limited to the geomagnetic field.

In July 2012 a series of coronal mass ejections erupted from the Sun that could have caused storms on Earth as severe as the 1859 Carrington event. In this case, the intense solar ejecta were not directed at Earth, but rather were detected by a well instrumented NASA satellite orbiting the Sun far from Earth. This event illustrates the Sun's capacity to create extreme space weather, and it reinforces the fact that eruptions of this magnitude are more frequent than events encountered on Earth.

How often superstorms occur and whether the above are representative of the long term risk is not known and is the subject of important current research. The general consensus is that an Earth directed solar superstorm is inevitable, a matter not of 'if' but 'when'. One contemporary view is that a Carrington-level event will occur on Earth within a period of 250 years with a confidence of ~95% and within a period of 50 years with a confidence of ~50%, but these figures should be interpreted with considerable care.

The impact of a solar superstorm is both economic and a risk to human health and wellbeing. Unfortunately, there are few peer reviewed estimates of the economic consequences. *Figure 4* highlights the assessment of this risk to the UK. This matrix ranks risk in two dimensions: first by the probability of their occurrence and second by their relative impact on the UK (assessed in terms of potential to cause fatalities, injuries/illness, social disruption, economic harm and psychological impact). Severe space weather is ranked highly, ahead of explosive volcanic eruptions such as Eyjafjallajökull, and alongside severe cold and hot weather.

In the context of superstorms the role of space weather forecast centres is twofold. Firstly, they provide advice to governments and to industry during the design and implementation of new systems ensuring that they are sufficiently resilient. If this is done incrementally the costs should not be severe. Secondly, in the event of a solar superstorm, space weather forecast centres will advise Government during a time of potential crisis. Space weather forecast centres will be central to decisions, including the potential multi-day closing of airspace, how to compensate for the loss of HF communications and HF surveillance and the authorising of power blackouts if sufficient resilience has not been built in.

Figure 4: UK National Risk Register matrix for non-malicious risks (natural hazards and major accidents), including severe space weather.

2.6 Impacts and Mitigation

Major solar storms and solar superstorms can cause significant technological damage. As already discussed superstorms probably occur every century or two and major solar storms occur every ten to twenty years. An event in 1956 is the highest recorded for atmospheric radiation with August 1972, October 1989 and October 2003 the highest recorded radiation events measured on spacecraft. Both the 1989 and 2003 events had substantial, multi-technology impacts. Solar superstorms impacts are more fully described in UK Royal Academy of Engineering Reports [*Cannon et al.*, 2013a; b].

However, even day-to-day variations in the propagation environment have to be dealt with in, for example, HF and GNSS systems. In the following we have summarised some of the varied impacts of space weather – this is very much a summary and many technologies are omitted. Through input from users of space weather information in Australia (see Section 5 and Appendices A and D), mitigation actions for various space weather impact areas have been detailed. These include the ability to manage communication frequencies for aviation, emergency procedures to protect the electricity distribution network, and the maintenance of communication during emergencies supported by the Red Cross.

Electricity Network: Rapid variations of the geomagnetic field on time scales of a few seconds to a few tens of minutes, caused by space weather, induce an electric field in the surface of the Earth. This electric field, in turn, generates geomagnetically induced currents (GICs) in the power grid and in other grounded conductors. These currents can cause power transmission network instabilities and transformer burn out. For example, severe space weather caused damage to two UK transformers during the 13 March 1989 storm, the same storm that caused major disruption to the operation of the Hydro-Quebec grid. The Quebec power grid resulted in 2 Billion Canadian dollars of loss.

More recently in 2003, a large geomagnetic storm resulted in a power outage in Sweden, significant transformer damage in South Africa, and transformer heating requiring mitigating actions in North America. This storm illustrates how widespread the impacts can be, including at the fairly low latitudes of South Africa, which is at a lower magnetic latitude than most of Australia.

Forewarning of GICs can be used by the transmission companies to minimise network damage, through a phased escalation of risk as a coronal mass ejection is observed leaving the sun 150 million km away through to its passage past the space weather monitoring satellite at only 1.5 million km (30 minutes) away. These forecasts may entail bringing on extra generation capacity to secure the additional reactive power requirements. It may also include ensuring that any network elements undergoing maintenance are brought back online in order to spread the load. Load shedding may be necessary in extreme cases. Not calling a spaceweather storm can entail expensive repairs and economic consequences. Falsely calling a spaceweather storm subjects the generation companies to additional costs as they unnecessarily bring on additional generating capacity and cancel maintenance.

Satellites: Electrons, protons and ions cause electrostatic charging, displacement damage and cumulative dose (ageing) effects on satellites. A discharge, for example, can readily couple into sensitive electronics causing data upsets, false commands and even component damage. Satellite operators can benefit from SWS reports of solar activity to help explain uncommanded events on their spacecraft.

Using space weather measurements and models, forecasts can be made of the likely energetic particle environment and mitigating steps can be taken, including placing the satellite in hibernation and, where possible, redeploying its functions to ground based backup assets. Routine operations, such as software uploads and satellite station-keeping, can be scheduled to avoid times when the environment is hazardous. Satellite launches can also be delayed to avoid performing critical satellite operations under hazardous conditions. In addition, when anomalous behaviour does occur it is essential to assess the role of the environment and to determine mitigation measures.

We note that satellites, such as SOHO, STEREO, are important platforms for space weather monitoring, and Australia, through the CSIRO Deep Space Tracking Network, provides downlink and tracking services.

<u>Ionizing radiation effects on air passengers, crew and avionics</u>: High-energy cosmic rays and solar particles incident on the Earth spawn a multitude of other high-energy particles through nuclear interactions in the upper atmosphere. These high-energy particles generate secondary particles that reach a maximum flux at about 18 km and are then progressively attenuated by the atmosphere so that only the most penetrating component can be measured on the ground. Typically, at aircraft cruising altitudes the flux of ionizing radiation is ~ 300 times higher than at sea level and consequently these particles can have an impact on aircraft passengers and crew because of the increased exposure to ionizing radiation.

It should be noted that aircrew are the most highly radiated occupational group – even more so than those working in nuclear power stations. Long haul crew typically receive an occupational dose of 4-6 mSv (milli-Sieverts) per annum – by comparison 6 mSv is the typical dose for computerised tomography of the chest which is generally considered a significant radiation dose. By way of a specific example, an event on 20 January 2005 caused a factor 50 increase in the Antarctic region corresponding to a dose rate of ~3 mSv per hour at cruising altitudes.

A solar superstorm may increase the typical long haul flight exposure to ~20 mSv. While even the latter is not sufficient to increase lifetime population averaged cancer risks significantly (typically from 25% to 25.1%) there are some population groups – such as pregnant passengers and aircrew – who would be extremely concerned if they were flying during one of these events. Timely advice from government authorities to airline operators and to the public is important to assure public confidence and safety.

How to deal with these events is the subject of intense discussion at the moment. The most obvious solution is to reduce height quickly, but this introduces different risks. ICAO sponsored space weather forecast centres will have a significant role to play in the management of such events. Space weather forecast centres have only tens of minutes to warn of the radiation onset, but can advise as the event progresses and will be critical to post event analysis of risk.

<u>Global Navigation Satellite Systems (GNSS):</u> Ionospheric disturbances caused by space weather affect GNSS transmissions in a number of ways, and there are a number of compensatory approaches. The higher the required timing and positional accuracy the more difficult it is to compensate for the impact of space weather. Large changes in the integrated ionospheric electron density between a GNSS satellite and a receiver on the ground or airplane create errors in the positioning. At times strong, small-scale structure can form in the ionospheric density and disrupt the satellite signal altogether. In addition, bursts of radio

waves from the Sun at GNSS frequencies can increase the noise level in the receiver to the point where the satellite signal is unreadable for short periods.

Mitigation through engineering design has historically served the industry well (e.g.2-frequency GNSS and improved receiver design), but the move to precision GNSS (for example intelligent transport systems) requires significantly higher fidelity corrections.

High Frequency (HF) Communications and Radars: HF (3-30 MHz) point-to-point communications and broadcasting (often referred to as shortwave) relies on the ionosphere to propagate radio signals beyond the horizon. HF is a valuable alternative and complement to satellite communications, especially near the Earth's poles where geostationary satellites are not visible. The most prevalent (non-military) users of point-to-point HF communications are the aviation and shipping industries. The primary users of HF broadcasting are international broadcasters such as the Australian Broadcasting Corporation (ABC). The military makes great use of HF for both communications and radar applications. HF communications is also used by emergency services in land applications, such as the Royal Flying Doctor Service and Department of Fire and Emergency Services (WA).

Managing HF point to point services is often based on climatological models of the ionosphere and propagation to select the best operational frequencies. However, modern networked HF communications, involving automated channel assignments, can make use of forecast models to select the optimum frequency sets from which the channels are selected. Poor or large frequency sets can reduce the network data throughput significantly.

3 Policy Framework

3.1 Nationally

Australia has long recognized the importance of space weather, both for economic and security needs. Australia's services began shortly after World War 2 to support new applications of radio communication, and services have developed steadily since. As is well understood, space weather can disrupt, degrade or affect a plethora of Australia's critical services such as HF communications systems, power grids, GNSS, satellites and even avionics and air passenger safety.

Space weather is increasingly recognized as a risk to national economies and to the safety of citizens. This is partly a consequence of our improved understanding of the risks associated with extreme but relatively rare space weather events. It is also partly the consequence of technological evolution requiring ever more accuracy, autonomy and integrity while delivering this with ever smaller semiconductor devices. Space weather is often a limiting factor in the delivery of these aspirations.

In the United States space weather has been identified as one of the grand challenges for disaster reduction. A similar recognition has occurred in the United Kingdom, where space weather is now incorporated in the UK National Risk Register of Civil Emergencies. (Australia's closest equivalent is the Attorney-General Department's TISN.) Other European countries including the Netherlands, Sweden, and Norway have also identified space weather as a threat to their infrastructure and to society. Space weather was recently included in the national risk profile of South Korea.

In Australia, the Bureau's SWS provides a broad range of data, expertise and forecasts that support defence, navigation, aviation, resource exploitation and other industry sectors. For example SWS has, in the last few years, been pivotal in demonstrating space weather risks on the electricity grid. SWS also helps ensure the availability of HF radio communication and GNSS for public, aircraft, ship and military purposes. By so doing the Bureau makes a fundamental contribution to the security of the Australian national infrastructure and it supports Australian industry.

However, although there exists a demonstrable national requirement for space weather services, there is no explicit reference in the *Meteorology Act 1955* to space weather. A clear understanding of the applicability of this Act to Space Weather would clearly be advantageous, but the broad embrace and intent of the Act to address threats associated with space weather, in the context of meteorological and related threats, is evident. The Bureau should demonstrate through its actions that it understands the need to comply with this intent through the provision of space weather services.

Moreover, we understand that space weather has not yet been incorporated into the government's Critical Infrastructure Resilience Strategy – a strategy which emphasizes government-private partnerships and a non-regulatory approach, both of which are well suited to complex space weather risks.

We understand that Australia has not formally considered the impact to its critical national infrastructure and thus to its economy and social structure, of a solar superstorm.

3.2 Internationally

The growing international recognition of space weather risks coupled with the maturity of the Bureau's SWS, provides opportunities for the projection of Australia's technology and vision.

The long-term improvement of space weather services requires coordinated, committed partners from around the world. International coordination efforts are currently being addressed by numerous international organizations, including the World Meteorological Organization (WMO), the International Space Environment Service (ISES), the International Civil Aviation Organization (ICAO), and the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

The SWS has long been, and continues to be, a strong leader of international efforts to develop space weather capabilities. These efforts are advancing global capabilities and contributing to future operational and design decisions, for example through their support for international civil aviation. The SWS is well positioned to contribute expertise and observations from Australia and to benefit from the complementary assets of international partners.

3.3 Recommendations

There is usually an implicit requirement for space weather services but when there are budget constraints, there can be inadvertent risks to the ongoing funding of these essential government functions. Hence there needs to be well-documented, strong customer endorsement and clear oversight. We, therefore, make a number of recommendations.

➔ R1. (Recommendation 1.) That the Bureau briefs the Australian Government that space weather poses threats to Australia and is recognised and classified internationally as a natural hazard.

➔ R2. That the Bureau works across the Australian government to improve the understanding of the criticality of space weather services, in particular:

a) That the Bureau ensures that it complies with Section 6 of the Meteorology Act 1955 through the provision of space weather services amongst one of its many functions;

b) That the Bureau ensures that space weather is incorporated in the Critical Infrastructure Resilience Strategy (delivered through the Trusted Information Sharing Network) in order to effectively deal with both major and extreme space weather events. The following Sectors and their users would benefit from space weather preparedness strategies: Aviation, Defence, GPS based Precision Navigation and Timing systems (PNT), and Power and Energy systems.

c) That the Bureau establishes appropriate governance arrangements to better engage with stakeholders and ensure space weather services evolve in line with scientific and technological advances and customer demand. (see also Section 6).

➔ R3. That the Bureau works with other government stakeholders to understand the extent to which the risks of solar superstorms should be managed.

➔ R4. That the Bureau better promotes its role as the lead national representative organisation to international space weather bodies.

4 Overview of SWS

4.1 History

The Ionospheric Prediction Service (IPS) was set up in 1947 in response to a need to support HF communications in Australia and beyond when HF was the dominant long distance communications system. Its role was extended in 1957 to include short term alerts of short wave fades and geomagnetic disturbances. By the 1980s IPS services were in considerable demand and commercial HF planning software was developed along with consultancy services. The 1990s brought the advent of the internet, and this facilitated the delivery of various IPS services to Australian users and abroad. The Service was renamed 'IPS Radio and Space Services' in the 1980s to better reflect the breadth of services provided, and within the Bureau of Meteorology this has been generalised to 'Space Weather Services' (SWS).

4.2 Budget Overview

SWS forms part of the Hazards Prediction Program in the Bureau's Hazards, Warnings and Forecasts Portfolio (Hazards, Warnings and Forecasts Division). Supporting observations are delivered (from 1 July 2014) through the Special Networks function within the Observing Network Operations programme (Observations and Infrastructure Division). The overall cost of the space weather programme is around $3.8M per annum with 80-85% of the costs attributed to staff (~20 providing services and ~10 providing observational support). Of the remainder, ~ $225k per annum is spent on the observation network. Most of the staff are based in Sydney with the domain experts supported by local administrative staff.

4.3 Technical Functions

The Bureau defines the key deliverables of its SWS as:

> Space Weather services and advice for technological infrastructure operations in support of; national security, energy distribution infrastructure, aviation, maritime, emergency services, radio broadcasting, mining exploration, satellite navigation and timing, satellite communications and general public interest.

The SWS comprises a number of technical functions.

- Space weather forecast services;
- IT support;
- Observational support to underpin the forecasts;

- Research and development;
- Space weather and ionospheric radio system consultancy;
- Space weather and ionospheric radio system training;
- Commercial software applications;
- Data curation on behalf of the space and space weather research communities in Australia and internationally;
- International representation.

4.4 Space Weather Services

The SWS accomplishes its forecasting mission by combining observations with numerical models, the outputs of which are analysed by SWS staff members who have knowledge of the regional response to space weather storms. The forecasts are delivered to the public and customers by a variety of means including the internet.

The space weather services provided by BoM cover a broad range of space weather phenomena, including the conditions on the Sun, in interplanetary space, and in the magnetosphere and ionosphere. BoM system-specific products are heavily focused on HF radio support with a growing GIC capability. All of these services cover a range of relevant time scales and include multi-day forecasts and real-time alerts of ongoing disturbances.

We note that although some of the data-related products are also available on other organizations' web sites, it is valuable to have the full suite of products at the Bureau's SWS site to provide convenient user access to both the global context and the local conditions.

4.5 IT Support

We had little visibility of the IT support provided to SWS and also understand that this is currently being reorganised to provide better integration with core Bureau IT services.

4.6 Observational Support

Preparedness and mitigation require information about the global forcing of Earth's environment, which is primarily driven from the Sun, together with knowledge of the local conditions based on local measurements and expertise. Observations and analyses of the large-scale, solar-driven disturbances are necessary to predict the onset time and strength of an expected storm. Local observations and analyses are necessary to predict the unique conditions that impact the local infrastructure and systems.

BoM space weather services into the Australasian region are heavily based on real-time and archived data from the regional ground based space weather observing network operated by SWS and third party sources. For monitoring some of the global drivers (solar, solar wind, interplanetary magnetic field) into the regional space environment, these data are supplemented by data exchanged with similar organisations and include spacecraft data (although the regional ground based network also has some of these capabilities, e.g. solar observation).

4.6.1 Ionosondes

The SWS operates fifteen ionospheric sounders (‘ionosondes’) located across Australasia, islands surrounding it and Antarctica. Their data feed into all of the HF radio products. The ionosondes are predominantly SWS developed, type 5D, which build on a long pedigree of previous IPS developed ionosondes. An earlier ionosonde, the 4D was cloned by private industry (the ‘Type 42’) and are still used overseas. SWS also use the Canadian CADI ionosondes at higher geomagnetic latitudes in Antarctica and New Zealand. Their sophisticated digital signal processing makes them better suited to the highly irregular high latitude ionosphere.

4.6.2 Solar Observatories

SWS operate two solar observatories at Culgoora (CSO) in New South Wales and Learmonth (LSO) in Western Australia, making radio and optical observations. The LSO is operated in partnership with the United States Air Force (USAF), who provide extensive equipment, under a joint facilities agreement dating back to 1977, and also host US research equipment from the Global Oscillation Network Group, which makes solar magnetic and other measurements. Under the joint agreement, solar data and interpretation are made available from other USAF stations in their global Solar Electro-Optical Network.

4.6.3 Magnetometers

The SWS monitors variations in the geomagnetic field across the Australasian and Antarctic region using 30 magnetometers. Six are Bureau-owned and operated and eleven are a collaborative venture with the University of Newcastle Space Physics Group and the International Center for Space Weather Science and Education in Japan. Thirteen are third-party owned, mainly by Geoscience Australia. We noted that SWS complement, rather than supplement Geosciences Australia with the latter most interested in long period variations and SWS making measurements of short period variations.

4.6.4 GPS TEC Receivers

SWS operate six Global Positioning System (GPS) total electron content (TEC) receivers and use data from numerous (100+) third-party GPS receivers, predominantly run by Geoscience Australia.

4.6.5 Ionospheric Scintillation Monitors

SWS operate five Ionospheric Scintillation Monitors (ISM) with four at low-latitudes and one at higher latitudes. All are located where scintillation that affects ultra high frequency (UHF) SATCOM and SATNAV is prevalent during disturbed conditions.

4.6.6 Riometers

SWS operate four relative ionospheric opacity meters (riometers) on Antarctic stations to measure polar cap radio blackouts from solar particle events.

4.7 Research and Development

Research and Development (R&D) in SWS is firmly rooted in development rather than research – a philosophy with which we concur. The modelling R&D is led by customer needs - either through the identification of deficiencies in the Australian Space Forecast Centre (ASFC) operations or in support of the development of new products. (Note - ASFC is the forecast centre operated by the Bureau's SWS and was approved as a 'Regional Warning Centre' by the International Space Environment Services (ISES) in the mid-1990s.)

The SWS does not maintain sufficient numbers of research staff to support much basic research, and this is instead achieved through collaboration with external laboratories and universities. The focus instead is on the development of operational models and applications based on external research.

4.8 Consultancy

Consultancy and training are undertaken for a number of users and account for around 6% of the budget in 2013, but are highly variable from year to year, with a large component of this associated with one long term contract.

This single long term contract provides real-time data to the Modernised HF Communications System run by the Department of Defence. Here the unique benefit is the provision of tailored products for the home market, tailoring which relies very heavily on the availability of regional data streams. That the BoM is a trusted data and advice provider cannot be overstated.

4.9 Training

The SWS has two training modules, one is an HF Radio Course and the other is an Advanced Standalone Prediction System (ASAPS) training course. Together ~50 persons are trained per year.

4.10 Commercial Software

The SWS markets two software packages, ASAPS and the Ground Wave Prediction System (GWPS). An ASAPS single user licence is priced at $385 and a GWPS licence is priced at ~$137.

4.11 Data Curation

The SWS is accredited to the worldwide network of World Data Centres http://www.ips.gov.au/World_Data_Centre (now World Data System https://www.icsu-wds.org/). In this capacity, the SWS holds regional space weather data which it in turn provides to national (academic and Defence) and international scientists, engineers and space weather services. The latter is part of an international data quid pro quo.

The SWS also holds and curates the data for the Australian data contribution to the international SuperDarn project (led in Australia by the University of La Trobe), a project funded by the Australian Research Council.

4.12 National and International Representation

International cooperation is necessary to acquire and to maintain reliable access to space and global ground based measurements, to improve scientific understanding, to advance service capabilities, and to ensure the global consistency of the end products. The SWS has historically been, and continues to be an essential contributor to international space weather efforts. They have been one of the leading members of ISES, fostering growth in space weather services for decades, and now they are active and influential participants in WMO and ICAO efforts. SWS staff provide valuable input on space weather observing requirements, they have been key advocates for establishing procedures to address extreme space weather events, and they participate in the ICAO Ionospheric Studies Task Force. SWS staff have excellent knowledge of the space environment and space weather service needs, and they contribute their knowledge effectively through these international efforts.

5 Assessment of Current Performance

5.1 Current Scope

The Bureau's operational space weather services and its SWS business more generally, are very heavily biased towards HF systems with some embryonic services in other impact areas, e.g. GIC services. This reflects the historical need and its current customer base.

5.2 Space Weather Forecasting Performance

5.2.1 Technical

We consider that the Space Weather Service within the Bureau of Meteorology is a tier one global centre for general space weather services and is arguably the leading global centre for ionospheric HF space weather services.

Our view is supported by both the national and international community of service users - see Appendix A for letters of support. This is further discussed in Section 5.

As part of this review we requested a comparison of a number of key forecasts with the same outputs from the Space Weather Prediction Service (SWPC) in the US. The results are shown in Appendix B and demonstrate that the SWS provide global space weather forecasts which are comparable to those generated by SWPC. The SWS regional HF forecasts are without doubt better than anything which can be obtained from overseas sources. We were especially impressed with the 1-day T-index forecast skill (Appendix B, Figure 6).

The value of the SWS nowcasts and forecasts has been recognised by a number of customers as critical to their business – e.g. Airservices Australia. We, as reviewers, were impressed with the value provided to, and support from a variety of customers.

➔ R5. That the SWS continue the forecast verification procedures they have established and expand the scope to include specific customer-focused benchmarks and comparisons with international organizations.

5.2.2 Delivery

The Bureau's SWS delivers its space weather data, products and alerts through web, email, and sms messaging. The one important exception is the real-time T-index feed to Boeing in support of Defence HF communications services.

This service mix seems wholly appropriate as they together provide services well suited to the customer base. Web services, of course, provide a simple means of promulgating the space weather forecast to a large number of people and organisations. Uninterpreted, (or partially processed into indices) solar, geophysical and ionospheric data are posted and sent, and these are supplemented by value-added HF services. Aside from the HF products the user generally needs to interpret the data in the context of their own application.

We have refrained from commenting in detail on the individual services since SWS should know their customer base better than we do. The Discussion Paper [*Neudegg* 2014] contains descriptions of many of the services. We do though recommend that SWS set up robust systems to record who and which organisations use their web services so that on-going cost benefit monitoring can be maintained.

- ➔ R6. That SWS sets up individual and corporate registrations and subscriptions so that individual service use can be monitored.

A total of fourteen Australian and international organisations, with a focus on aviation, communications and safety management, have their own specialised client pages (open at the moment but soon to be password protected) which are optimised to support the organisation's business. In most – possibly all – cases these user specific pages are an (automatic) aggregation of data and products which could be derived from the general pages.

5.3 Observations Performance

One objective rationale for maintaining and developing the Bureau's SWS is its regional observation and modelling capability. The SWS collects and archives a unique data set of measurements in the Australasian region, measurements which are valued by the national user communities. Our impression is that their availability is high – although we have no specific information on this.

We note that the SWS ionosondes represent a significant and necessary investment serving the core business - HF forecasts and predictions. The network must be maintained and possibly developed further. We further note that the design of ionosondes is a niche area and the associated software to facilitate autoscaling of the ionograms is not only a niche engineering activity, but requires very particular scientific knowledge and experience. We are concerned that placing the ionosonde observation staff in a separate observations division will prejudice the development of this knowledge over the long term.

We also note that maintaining and developing an in-house design is expensive and the cost of an off-the-shelf design may be less. Where the break point occurs will likely be dependent on the staff cost model used in the Bureau.

- ➔ R7. That the Bureau reassesses how the SWS develops and procures ionosondes to order to achieve the best value for money outcome.

5.4 R&D Performance

SWS R&D has sustained SWS forecasts at the forefront of space weather services for many years.

Moreover, SWS staff have a respectable publication record for a service delivery organisation (see Appendix C which we requested in support of this review). SWS staff are often recognised as contributing authors rather than lead authors, which is to be expected from an organisation that seeks to benefit from basic research undertaken elsewhere.

We note that the approach to research appears to be dependent on individuals rather than on an agreed plan. As part of a repositioning of the SWS, which we discuss in Section 6, we propose the following actions.

➔ R8. That the Bureau develops a long term SWS research plan which is annually refreshed.

➔ R9. That the Bureau, through the SWS, considers expanding their focus in the following areas:

  - Ionospheric data assimilation models which will optimally lever the considerable volume of data held by SWS and lead to future product improvements;
  - Products and services for GNSS users requiring precise point positioning;
  - The expanded development of products and services to support the mitigation of Geomagnetically Induced Currents on the electrical power network.

We note that there is potential to reach out to the Bureau’s wider R&D programme, perhaps in the context of data assimilation techniques. We are also conscious of the wide remit of the SWS and that it needs to draw on academia to develop its services. We are aware that this already takes place, but strengthening this would be useful. Recommendations are made elsewhere in this report in this context.

5.5 Training Performance

The SWS has been, and continues to be, a popular provider of training which represents a valuable business development activity. We note that defence staff typically account for around 40% of the ~50 training delegates per year - and repeat business is perhaps the best metric of a quality product.

5.6 Commercial Software Performance

There are two competitors to ASAPS for long-term HF propagation predictions. One is VOACAP, for which there is no ongoing development owing to the retirement of the developers, and the other is REC533 (now ITUHFPROP) which is a collaborative and adhoc development by the ITU. ASAPS, therefore, stands unique in that it is supported and under progressive development.

HF propagation predictions using both ASAPS and VOACAP have been compared against 5 MHz beacon measurements and against ionosonde measurements [*Walden*, 2012]. The ASAPS signal-level predictions are comparable to those of VOACAP, while frequency predictions by ASAPS are more accurate than those by VOACAP for UK near vertical incidence skywave links. Whilst this one paper does not prove the superiority of ASAPS over its competitors, it does serve to illustrate its competiveness.

HF systems continue to evolve and, subject to the limitations suggested later in this report, ASAPS needs to evolve further. We understand that there are aspirations to include polarisation coupling in the model. We also suggest that wider bandwidth system predictions and further digital modulation schemes might also be incorporated.

5.7 Consultancy Performance

SWS consultancy income is highly variable and generally very low, with the highest point in the last four financial years being around $250k in FY 2010-11.

Consultancy services have been provided since the mid-1980s to customers who require a detailed analysis of how radio systems should be designed and operated to account for space weather. The vast majority of these are HF radio systems where coverage and availability has to be determined as a function of frequency, solar activity, season, time of day etc. Such studies include modelling of component systems such as antennas. A scan of the companies and organisations to whom consultancy services have been provided reveals an eclectic mix of large and small, public and private organisations, some in Australia and some overseas, including aviation industry and operators, defence organisations, media and communications, industry bodies, and government regulators and service providers. Throughout the review we heard overwhelmingly positive comments on the consultancy work.

5.8 National and International Representation

Through their effective participation in international groups, the SWS has demonstrated their high level of expertise, and they have established the relationships necessary to work with international partners to advance the global coordination needed to improve services in Australia and globally.

5.9 Resourcing – staff

Without a detailed understanding of the SWS business model it is difficult to comment on the specifics of the SWS resourcing to deliver its wide range of functions. However, it is useful to compare the Australian SWS with the UK services.

As already noted the SWS costs around $3.8M to run, including forecasting, data curation, instruments and IT. The cost for the core forecasting activity is ~$2.2M.

In the UK, the Met Office has recently taken responsibility for space weather forecasting. It provides a 24*7 service at an annual cost of £1.6M (~$2.9M AUD) http://www.metoffice.gov.uk/news/releases/archive/2013/space-weather-forecasts. Currently it has no observation network and is not responsible for data curation as this is handled elsewhere in the UK. It leverages its measurements from either open global data sources (which SWS also does) and from regional data separately funded in the UK and in Europe. The latter does not appear to be an option in Australia. The Met Office considers these costs to be a minimum to provide a 24*7 service and interact with its customers. It should also be noted that the Met Office service is embryonic and its forecasts have not yet been evaluated.

Given the different services – one is 24*7, one is not – one makes observations one does not – one curates data, one does not - the comparison is not simple. However, a reasonably fair comparison would be to compare the $2.2M SWS (working day only costs) with the $2.9M Met Office costs. Making due allowance for the latter's 24*7 provision the SWS and Met Office costs appear to be comparable.

5.10 Resourcing – facilities

We believe that further integration with the Bureau is a good thing – but of course there will be some teething problems in the first few years. The Bureau provides to SWS a (potential) policy framework, links to common customers, observation sites and rationalisation of the IT systems.

We have already discussed the benefits of a 24*7 capability which will probably need to be supported by backup computer systems in order to meet contractual service level agreements. Both are, of course, standard in the Bureau.

6 Impact

In order to explore the impact of the Bureau's SWS we took evidence from members of staff, from representatives of government departments, from other national organisations and from stakeholder companies (Appendix D). In so doing we sought to understand their current and future needs.

This oral evidence was supported by *Neudegg* [2014] which describes the work of the Bureau's SWS and technology requirements for space weather prediction and mitigation. The oral evidence was also supplemented by letters and emails, as summarised in *Table 1*. These have been collated by sector in order to illustrate the wide customer base for Bureau space weather products. They range from operational users, such as the Australian Defence Forces, through to aurora watchers, radio amateurs and citizen science. An extended version of *Table 1* which includes a summary of the letter contents can be found in Appendix A. Appendix A also includes copies of a number of the supporting letters – as summarised in *Table 2*.

Table 1. Letters - Statistics

Type	Number
Overseas Space Weather Services	7
Emergency Services (including radio communications support)	4
Industry (Australia)	5
Industry (overseas)	3
Overseas Radio Services	4
Mineral Exploration and mining	2
Defence	3
Research & Education (Australia)	6
Research & Education (overseas)	6
Radio Amateurs (HAMS) (Australia)	24
Radio Amateurs (HAMS) (overseas)	17
Aurora Watchers and Astronomers	36
General Interest & Citizen Science	46

Table 2. Supporting letters reproduced in Appendix A

Topic	Author
Space Physics and Space Weather	Australian Academy of Science Newcastle University (Prof Brian Fraser) WMO (Jerome Lafeuille)
Data Centre User	Leo McNamara
HF Radio	Ray Farmer Wireless Institute of Australia (Phil Wait)
Power Industry	ENERGEX
Research	University of Tasmania (Prof King)
Emergency Services	EMCOM/WICEN (John Patterson)
Industry	Plextek (Marcus Walden)

These various sources of evidence demonstrate the following.

- The SWS is held in high esteem and has a significant impact in a number of areas.
- The Australian Defence Forces operationally rely on SWS services and products to support military HF communications systems and do so 24*7. (SWS provide real-time updates of T-indices in regional maps and other products via a contract with Boeing which are used to provide network frequency management.)
- The Australian Defence Forces also rely on the SWS to support their HF Radar (JORN) operations, research and training.
    a) T-indices with ASAPS are used for propagation predictions.
    b) Solar and ionospheric warnings are used to understand and verify JORN operations and DSTO experiments.
    c) The SWS sensor network contributes data to international data bases (WDC/WDS) from the Australasian region and thereby influences international model development such as the International Reference Ionosphere (IRI).
    d) SWS provides a repository of synoptic and climatological data of the local ionosphere (WDC/WDS).
- The SWS provides to Airservices Australia a dedicated webpage and Airservices has consulted SWS a number of times in support of HF communications and the new Ground Based Augmentation System (GBAS). Appendix A (letter from John Farmer) provides further details of how and why SWS is important to Airservices and Appendix D provides further related information derived from the oral evidence. Some airlines have their own pages; some report just HF conditions, some also report the high energy particle environment that can affect the aircraft, passengers and crew. We accept that the setup costs are low and the maintenance costs are insignificant since the pages are automatically populated.
- Through proactive dialogue with national electricity grid operators, SWS forecasts now form part of the management and protection of the national electricity grid (see Appendix A and the letter from Energex to better understand how SWS services are currently used and see Appendix D to see how the onset of a solar storm is managed by the electricity industry).
- The Australian Communications and Media Authority (ACMA) benefits from the SWS with respect to radio spectrum management via equipment procurement and consultancy advice for siting and operation of a multi-site HF direction finding system, which is used to locate interfering signals, mostly from sites abroad. SWS provide a number of dedicated products to facilitate operation of these systems. The ACMA business plan assumes continued free services from the Bureau.
- Industry – mostly HF equipment manufacturers - are dependent on SWS HF forecasts, consultancy and software to support their businesses. Appendix A (letter from Walden) and Appendix D provides further details of how SWS benefits industry.

- The research community, carrying out both space physics research and applied research (e.g. geodesy), value the SWS for its data and its expertise. Appendix A, and specifically the letters from the Australian Academy of Science, from Dr Leo McNamara in the USA, from Prof King at the University of Tasmania and from Prof Fraser at the University of Newcastle provide further information.

- The SWS provides important safety of life services. We particularly noted that Red Cross disaster management communications relies on SWS HF forecasts to maintain its communications. The SWS also supports Australian scientists working in polar regions where Iridium satellite telephones (operating in the UHF bands) are detrimentally affected by space weather. Appendix A and the letter from EMCON, together with the letter from John Farmer in the context of HF Radio Club Inc, describes how SWS forecasts are used to support safety of life services.

- Amateur (HAM) radio operators, aurora watchers and a host of other non-professional users in Australia and beyond clearly value the service (see Appendix A, letter from the Wireless Institute of Australia).

- The Bureau, through its SWS, is internationally recognised as a leading organization in space weather (eg Appendix A and a letter of support from the WMO). The Bureau provides data and expertise to partner organizations, and SWS staff lead and contribute to multi-national activities which strengthen global capabilities.

On request, the SWS provided access statistics for the specialised web client pages. An analysis of these statistics was undertaken to examine how often the specialised web pages are accessed and/or how often the data is accessed from the page (whichever is the lowest). This analysis demonstrated that for at least five of the fourteen specialised web services, there was no majority user IP address. This suggests that the page is being accessed by other than the designated user and reemphasises the need to password protect these pages.

We were very pleased to see that the user community is actively accessing their specialised pages and presumably acting on the advice provided.

➔ R10. That the Bureau establishes a sustained programme of monitoring access to SWS specialist pages and explores with clients the utility of the forecasts at least once a year.

7 The Next Five Years

7.1 Outlook

Stakeholder input to this review from both government and industry representatives indicates a growing national need for space weather services, consistent with the increasing global recognition. We believe that government and commercial users will increasingly require regional space services fed by local as well as global instrumentation. Stakeholders repeatedly indicated that the breadth and depth of knowledge and impartiality can only be provided by a single government entity.

7.2 Initiatives

In order to provision the national requirements we believe that some rebalancing of the Bureau's SWS will be needed. To do this we believe that the Bureau will need external advice provided through an appropriate advisory mechanism.

➔ R11. That the Bureau establishes appropriate governance arrangements to better engage with stakeholders and ensure space weather services evolve in line with scientific and technological advances and customer demand (see also R2c).

We also suspect that space weather research needs to be better coordinated in Australia and as the applications grow this will become more important. Consequently, we recommend a nationally coordinated programme of R&D and service delivery.

➔ R12. That the Bureau works with other agencies (eg ARC, CSIRO, Defence and Geoscience Australia) and the universities to effectively implement the long term national research plan (refer to R8).

We can also see huge benefit if the Bureau sponsors a Space Weather workshop similar to those held in Europe and the USA. It should include user groups and national and international scientists. This will provide a vehicle to both promote SWS capabilities and better understand customer needs.

➔ R13. That the Bureau hosts an annual Space Weather Workshop.

7.3 Realignment of Space Weather Services and Activities

In Section 1 we summarised the potential impact of space weather to a number of technologies. We have found that SWS covers two of these topics (space weather forecasting and HF products) very well, some a little and some not at all. Consequently, we have used an augmented version of this list to propose a realignment of SWS (Table 3) which may be a useful starting point for implementation of Recommendation 11. In this table green indicates a mature capability, red no (or almost no) capability and orange an intermediate state. The revenue prospects can be similarly interpreted.

Points to note:

- While the use of the HF radio bands shows no sign of diminishing there are a number of other high value and potentially ground breaking technology problems urgently seeking solutions.
- We believe that the SWS needs to be ready to support the electricity network operators and AEMO in order that they can mitigate the effects of space weather induced GICs.

Table 3. Reviewer Proposed Realignment of SWS. (Green indicates a mature capability, red no (or almost no) capability and orange an intermediate state. The revenue prospects can be similarly interpreted.)

Service or Application	**Current Provision**	**Provision in 5-years**	**Revenue Prospects**	**Comments**
Space weather environment nowcasts and forecasts	🟩	🟩	🟥	Maintain awareness of new science and adapt and improve forecasts as appropriate to maintain cutting edge capability.
Electricity network services	🟧	🟩	🟩	Current low level capability should be improved to support government and industry. Critical issue for superstorms and important issue at other times.
Spacecraft protection services	🟥	🟧	🟥	Small customer base in Australia so limited revenue steam. Both provision and revenue stream lie in the red to orange categories.
Services for ionizing radiation effects on air passenger crew and avionics	🟥	🟧	🟧	Identified by ICAO as an area of concern. SWS should work with national authorities and airlines to explore this area.
GNSS system services	🟧	🟩	🟩	Precision GNSS is a technology of the future. SWS should ride the wave. Low level R&D capability in place and some limited products.

Service or Application	**Current Provision**	**Provision in 5-years**	**Revenue Prospects**	**Comments**
Satellite Communication	🟧	🟧	🟧	Some support to SATCOM services is required in support of Australian scientists using Iridium in Antarctica. It is also of potential importance to maritime and aircraft communications.
HF communications and radars	🟩	🟩	🟩	Maintain capability. Redeploy some R&D to support new and growing technologies.
Citizen science, amateur radio, aurora watchers etc	🟩	🟩	🟥	Maintain, but do not expand. Use to project BoM and SWS to the public.
Consultancy	🟧	🟩	🟩	See section 7.6.

**fix 7.6??

- Delivery of the National Positioning Infrastructure Plan will require a regional space weather service to meet its aspirational accuracy. (This GNSS-based system will create a uniform, high-accuracy, positioning capability that will have applications for private industry and government (e.g., precision agriculture and intelligent transportation) and will improve public safety (e.g., by reducing traffic accidents). The required accuracy of this national system will require both a dense space weather measurement network and a model of the space weather disturbances in the ionosphere to feed back into the positioning system.).

- We also believe that the SWS will be required to provide regional advice and forecasts in support of the emerging Ground Based Augmentation (GBAS) technology for aircraft approach and landing.

In summary:

➔ R14. That the Bureau's SWS softens its focus on HF to facilitate the development of other products. Further that HF R&D only be undertaken when closely tied to customer requirements.

➔ R15. That the Bureau works closely with Defence to support the Defence HF Communications infrastructure refresh due in 2019.

➔ R16. That the Bureau works with the Australian Energy Market Operator (AEMO) and the power grid Transmission Network Service Providers (TNSPs) to develop a better understanding of space weather risks associated with Geomagnetically Induced Currents (GICs) and develop GIC products to assist mitigation of risks to the grid.

- ➔ R17. That the Bureau works with National Positioning Infrastructure Plan sponsors, Air Services and other government agencies in support of the emerging technologies associated with precise positioning systems and services and develop appropriate products.

Finally, we are concerned that the absence of a robust 24*7 service precludes SWS from certain contracts and services. The current service is based on the working day coupled with on-call staff. A 24*7 service is a prerequisite of providing a monitoring and protection service against extreme space weather. Moreover, it will be necessary if SWS develop overseas service opportunities such as becoming one of the ICAO Regional or Global Space Weather Centres.

- ➔ R18. That in recognition of the demand, the Bureau considers how SWS can provision a high integrity 24*7 service as opposed to the current working day service.

8 Cost Recovery Options

8.1 Introduction

Only certain SWS activities can be considered for cost recovery since inappropriately applied charging may precipitate reciprocal charging (for data from international partners for example). This would prejudice the development of new science and the “core business” of space weather forecasts.

8.2 Measurements

The SWS has an enviable measurement network but it is difficult to envisage cost recovery in this area which does not risk reciprocal charging.

8.3 SWS Forecast Services

The provision of some open and free forecasts remains a core requirement if the Bureau, through the SWS, is to remain part of the international community, which provides to Australia free terrestrial and space based data on a quid pro quo basis. We believe that un-interpreted SWS environmental forecasts must remain free at the point of use for non-commercial and non-government users in much the same way that meteorological forecasts are free at the point of use.

Yet, there are some customers that require a tailored service specific to certain technologies and here cost recovery might be achieved.

➔ R19. That the Bureau considers a direct charge for SWS tailored forecasts if they are used for commercial purposes.

In this context we suggest that

➔ R20. That the Bureau conducts market research, including webpage clients (R10), to ensure, where appropriate, they are realising the full commercial value of their space weather services.

For government and quasi government customers providing a public service we recommend a SWS surcharge on top of Bureau SLAs for meteorological services. This would certainly be the simplest approach and would not then require these charges to be passed onto, for example, the electricity generating and distribution companies who are, defacto, operating on behalf of the State and Federal Governments.

Such an approach would also answer the concerns of those companies who expressed disquiet that charges might be levied. Not surprisingly there was a concern over the cost –

but there was also a concern regarding the associated legal overhead of setting up a contract for a service they expect to receive free – like a meteorological forecast.

Due to its simplicity we believe that this approach should be considered for electricity grid protection, Airservices and all other applications which are linked to the national infrastructure, or national security, or for which the government has international treaty obligations.

- ➔ R21. That the Bureau conducts a forensic review of cost recovery with respect to space weather services, as they relate to government or quasi-government customers that benefit from space weather services.

Moreover, in the short term:

- ➔ R22. That the Bureau positions itself as either a regional or a global income generating International Civil Aviation Organization (ICAO) Space Weather Centre. <u>This needs to start immediately.</u>

- ➔ R23. That the Bureau works with Defence to explore the extent to which the Bureau's SWS can be better utilised, including providing support to the Australian Space Operations Centre (AUSSpOC). This Defence organisation currently derives its Space Environment information from NOAA and from SWPC. Other parts of the defence forces have declared a requirement for a sovereign space weather capability. It does not appear sensible that two parts of Defence are obtaining space weather support from the SWS, and AUSSpOC are deriving their support from overseas.

- ➔ R24. That the SWS reviews its web page access protocols and requires user registration for client pages in order to better understand the customer base.

We understand that the latter may be best accomplished by benefiting from integration with the Bureau.

In the longer term:

- ➔ R25. That the Bureau works with the national stakeholders to position its SWS as the lead national laboratory for ionospheric corrections in the context of precision GNSS products. As businesses grow the Bureau may require a profit sharing agreement.

8.4 Software Sales

The SWS market two software packages, the Advanced Standalone Prediction System (ASAPS) and the Ground Wave Prediction System (GWPS).

ASAPS can be purchased to run on a PC or similar and since records began in the mid-1980s 2279 copies have been sold, representing an average of ~75 copies sold per annum. Current sales are ~50 per annum and with a unit price of ~$385, this represents a typical contemporary income of ~$19k per annum. ASAPS can also be purchased as a kernel for incorporation in high value equipments. Since 1995, 71 copies have been sold, with 66 purchased by one customer and typically only one or two copies sold per annum in other years. These are potentially much higher value sales and also provide SWS with access to high end users.

GWPS has sold approximately 350 copies over 15-years or around 23 per annum. With a unit price of $137 the total annual income is ~$3k.

These software sales will never pay for SWS operations, yet they should be priced and marketed appropriately.

- ➔ R26. That the Bureau ensures the appropriate price is set for its ASAPS and GWPS software modules.

- ➔ R27. Those who need an HF prediction program will know of ASAPS and, therefore, we do not recommend any change to the marketing of ASAPS. We do though recognise that ASAPS will need to be continuously developed in order to provide the expertise needed for post-sales support.

- ➔ R28. That the Bureau considers marketing the ASAPS kernel abroad as its sale could provide both income and prestige.

- ➔ R29. That the Bureau discusses with industry what enhancements they seek for both ASAPS and GWPS - perhaps in support of digital modems, perhaps in support of higher bandwidth systems. In particular these discussions should centre on those industries which are interested in ASAPS and GWPS kernels.

8.5 SWS Consultancy

Consultancy provides a potential route to increasing cost recovery, but in so doing SWS must recognise the legitimate concerns of industry that government should not do their job and do it at a discount. To significantly build SWS consultancy services SWS would need to market itself more proactively since this is currently only done by word of mouth and SWS web pages. Whether, SWS has the staff and inclination to do this is not clear. It is possible that the Bureau can assist in this regard through its Business Development Office.

A degree of realism is also required. Consultancy in the SWS is currently largely restricted to HF planning and this is unlikely to grow significantly. In order to grow its consultancy, SWS must, therefore, seek work in other space weather topic areas, notably GICs and precise point positioning. It will, however, take some time to build this up.

Some specific ideas are noted below.

- ➔ R30. That the Bureau seeks repeat SWS business where it can rather than looking for new customers. A mail drop to previous customers and a copy of the annual report is a good way of reminding these customers that the SWS is ready to help.

- ➔ R31. That the Bureau considers the strategic development of SWS Intellectual Property Rights which can be licenced. Precise point positioning is one area where this may be possible.

- ➔ R32. That the SWS better engages with the ABC who were, until our meetings with them, unaware of SWS's wider capabilities. ABC uses an overseas consultant to support it at the HF Coordination Committee meetings and the Bureau may wish to better engage with the ABC, or indeed with other national HF planners, to determine if it can help.

- ➔ R33. That the Bureau considers whether it wishes the SWS to build a consultancy capability assessing radio propagation issues related to the troposphere as well as the ionosphere. As an example, we note that the 2cm accuracy specification for precision GNSS services requires tropospheric corrections as well as ionospheric corrections. Both require an understanding of the atmospheric environment coupled with an understanding of radio propagation. The integration of the SWS into the Bureau provides an opportunity to deliver a unified national service dealing with the effects of the atmospheric environment as a whole on radio propagation. We understand that there are already skills in the SWS to undertake tropospheric propagation modelling as well as the ionospheric modelling.

8.6 SWS Training

The SWS has two training modules, one is an HF Radio Course and the other is an ASAPS training course. Together around 50 people are trained per year.

- ➔ R34. That the Bureau reassesses the price of these courses. We believe that an increase should be acceptable to most government and corporate customers.

8.7 Data Curation

Australia uses other countries space assets - including NASA, ESA and JAXA satellite meteorological data - and it is vitally important that Australia repays this through contributing products where and when it can. This includes ground based Australian and Antarctic space weather data from the SWS. We note that Australia also contributes to international space weather data gathering through the operation of spacecraft tracking facilities, such as support to the US National Aeronautics and Space Administration (NASA) through the CSIRO managed Canberra Deep Space Communications Complex (CDSCC) at Tidbinbilla ACT and more recently to the European Space Agency (ESA) at Perth and New Norcia ESANET facilities in WA.

It has already been noted that the SWS undertakes data curation for the benefit of academia and Defence in Australia as well the SWS itself. Consequently, in discussions with other government departments the costs of this activity should be considered.

- ➔ R35. That the Bureau works with the ARC, CSIRO and Defence to offset the costs of data curation.

8.8 Summary and Conclusions

We believe that the simplest cost recovery approach for forecast services is to recognise the importance of space weather services delivered through the Bureau's SWS to other government departments and formulate an appropriate charge. We are not able to estimate the value of this cost recovery option. Where commercial customers require a tailored forecasting service specific to certain technologies, further cost recovery should be considered.

For the software and courses, consultancy and tailored product delivery, we are of the opinion that there is potential for increased cost recovery from the current 6% to ~10 % through changes in the charging structure. Coupled with other initiatives this could increase to ~15% over 5 years. We are of the opinion that greater levels of cost recovery from software, courses, consultancy and product delivery can only be attained if significant licensable IP is developed.

We have identified that the SWS is carrying out data curation activities which support Department of Defence (DoD), Australian Research Council (ARC) university grants and others. It is reasonable that these be the subject of cost recovery from the host government departments. We are not able to estimate the value of this cost recovery option.

9 Some Comments on SWS Management Structure

9.1 Introduction

9.2 Current

The service element of the SWS lies in the Hazards, Warnings, Forecasts Division which is managed out of Melbourne and consists of ~20 staff. From 1 July 2014 the observation support staff (~10) lie in the Observations and Infrastructure Division (also managed out of Melbourne).

The current management of the SWS function is fairly loose and was probably optimised to serve one predominant service type – HF. The SWS is run in a cooperative manner and the staff appear to get on well. Specifically we noted that:

- SWS has been led by an acting manager for over 18 months which is far from ideal. The acting Manager is the lead scientist, is the primary connection into the Bureau's management structure, is the lead interface to clients and more. These roles need to be separated and devolved.
- He is supported by four group leaders, some of whose roles were difficult to distinguish and whose personal responsibilities and targets may overlap.
- We were left with the feeling that the staff are clear in their own minds about their responsibilities and deliverables (power grid services, ionosphere services, modelling, etc.) but that they were not working to a coordinated strategic plan.
- There was an impression of less than optimal financial models.
- IT services and observations have historically been managed locally. This has the advantage that the staff can be flexibly deployed, but has a number of disadvantages – not least an absence of integration with the Bureau at large.

9.3 Recommendations

Given our broader assessment that the SWS needs to refocus some of its resources on other customer groups and integrate better with the Bureau we recommend an overhaul of the SWS management to more clearly separate out roles and responsibilities. The following is one approach – but there are others.

➔ R36. That a confirmed Manager of the SWS (MSWS) who has the confidence of the Bureau management is a prerequisite for going forward. That person should:

- ideally have knowledge of the space environment coupled with the appropriate management skills;
- be the interface to the Bureau at large;
- be the interface to the Observations and Infrastructure Division;
- be an outward facing, visionary leader;
- should engage the Critical National Infrastructure sector groups;
- be responsible for ensuring that SWS is the lead Australian organisation for all space weather services;
- be responsible with the Science Manager for setting up a research pipeline;
- be responsible for a SWS strategy and an annual report.

➔ R37. That an Ops Manager (OM) is required, in order to:

- In the short term, be responsible for ensuring that the values, processes and systems in SWS are integrated with those of the Bureau.
- Run and build the consultancy business against suitable targets.
- Deal with day-to-day budgetary issues, internal reporting and staff issues.
- Liaise with the Bureau's IT support.

➔ R38. That a Science Manager (SM) is required, in order to:

- Be responsible for the forecast service and for the underlying research.
- Ensure that supporting R&D is focused and useful and supports the current and future service strategy. We found a high appreciation of the state of the art amongst the individuals, but recommend that efforts are better coordinated. A significant task for this individual will be to rebalance the research portfolio so that HF R&D continues while increasing support for other services.
- Supervise all research and forecasting staff.

➔ R39. That there are a number of other roles which need to be resourced. Whilst the roles can be shared, clear ownership of each role is needed. These include:

- International liaison and representation.
- National liaison with stakeholders.

- ➔ R40. That the SWS leadership team be cleared to SECRET, given that two of the most important customer groups are part of the Australian Department of Defence Only by so doing can services and underlying developments be tailored to these user groups.

- ➔ R41. That consideration be given to providing the SWS with access to classified documents and to the classified computer network. This would open up new business opportunities and ensure that the work of the SWS is directed to best support the Defence Forces. We recognise that this is not trivial.

- ➔ R42. That controls be put in place to ensure that the observations needs of the SWS are delivered effectively and efficiently. IT services and observations were recently subsumed into the Observations and Infrastructure Division reducing the headcount in SWS from ~30 to ~20. While we agree that this rationalisation makes sense in regard to IT services we recommend caution in respect to observations, noting that the techniques appropriate to space weather are both similar (GPS for example) and very different (ionosondes for example) to those used in the meteorological community. Measuring and characterising the ionized atmosphere is, however more often different than similar. A pragmatic approach might be to hold the observations budget in the SWS Section, but manage the staff out of the Observations and Infrastructure Division. This would introduce a constructive tension between Observations and Infrastructure Division and SWS. It will ensure that a dialogue is maintained, ensure that Observations and Infrastructure Division delivers a product which is fit for purpose and will still provide the anticipated rationalisation and costs savings.

10 Summary

We are confident that Australia needs a space weather services capability to support government, industry and the military. The military requirement is overwhelming on its own and security issues preclude shifting this capability offshore. Support to the electricity industry during major and extreme storms is another national security issue – with potentially severe economic and social repercussions. Moreover, we believe that remediation of space weather effects on the new technologies and infrastructure associated with precision GNSS is sufficiently important that it too requires a sovereign capability.

The Bureau's SWS is assessed to be in the top tier of global space weather centres and arguably globally preeminent in HF space weather services. SWS staff demonstrably understand the environment (e.g. see their academic papers) and also have a detailed understanding of the risks that space weather induces on technologies (e.g., see their wide variety of customers). The SWS delivers valued environmental services which specify, predict and forecast space weather (as demonstrated through letters of support); and it supports the engineering community through its consultancy business.

We consider that dispersing the functions of the SWS across government and industry would be inefficient, risky and would be difficult to manage from a security perspective. Moreover this approach would be unlikely to render a trusted data and advice provider.

Consequently, we recommend the long term support of the SWS in the BoM as the delivery agency of space weather services for the Commonwealth of Australia. To put this on a firmer footing a number of steps are recommended including an assessment of the position of space weather in the Meteorology Act, incorporation of space weather in the Critical Infrastructure Resilience Strategy and the setting up of appropriate governance mechanisms to guide SWS.

In the short term we recommend that the SWS be sustained with its current budget. However we have also made suggestions to improve the transparency, effectiveness and resilience of SWS management. By addressing these issues the Bureau's SWS should be able to develop new services and demonstrate its effectiveness over a wide range of technologies. If successful an increased budget and resources should be within reach.

In this context we believe that the SWS would benefit from redirection of some of its R&D and service priorities to support new high value customers associated with emerging technologies. In so doing the SWS must not prejudice its current world class HF services.

We have reviewed the options for cost recovery of forecast services and consider (government) interdepartmental service level agreements would be preferable to a plethora of costly bilateral contracts. Where commercial customers require a tailored forecasting service specific to certain technologies, further cost recovery should be considered. Consultancy targets should be set – and in this context recommendations are provided – and a reassessment of software and training module pricing needs to be carried out. Moreover, we have identified that the SWS is carrying out data curation activities which support Defence, ARC grants and others. It is only fair and reasonable that these be the subject of cost recovery from the host government departments.

11 Acknowledgements

The authors would like to thank Dr David Neudegg and his staff in SWS, Sydney for their help and patience as we sought to understand SWS. We also would like to thank Dr Ray Canterford, the sponsor of this study, and William Loizides and Dr Sue Barrell as the study customers for their advice.

12 List of references

Cannon, P. S., et al. (2013a), Extreme space weather: Impacts on engineered systems - a summary *Rep.*, ISBN 1-903496-96-9, Royal Academy of Engineering, London, UK.

Cannon, P. S., et al. (2013b), Extreme space weather: Impacts on engineered systems *Rep.*, ISBN 1-903496-95-0, Royal Academy of Engineering, London, UK.

Neudegg, D. (2014), Review of the Bureau of Meteorology's Space Weather Service: Discussion Paper *Rep.*, *File 30/005815*, Bureau Of Meteorology, Australia.

Walden, M. C. (2012), Comparison of propagation predictions and measurements for midlatitude HF near-vertical incidence skywave links at 5 MHz, *Radio Science*, doi: 10.1029/2011RS004914.

13 Abbreviations

Abbreviation	Meaning
ABC	Australian Broadcasting Corporation
ACMA	Australian Communications & Media Authority
AEMO	Australian Energy Market Operator
AFRL	Air Force Research Laboratory (USA)
AMSA	Australian Maritime Safety Authority
ARC	Australian Research Council
ARINC	Aircraft Radio Inc
ASAPS	Advanced Stand Alone Prediction System
ASFC	Australian Space Forecast Centre
ASWB	Australian Space Weather Board
BoM	Bureau of Meteorology
CME	Coronal Mass Ejection
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DoD	Department of Defence
EMCOMNET	Emergency Communications Network (Red Cross)
EUV	Extreme Ultra Violet
GIC	Geomagnetically Induced Current
GNSS	Global Navigation Satellite System
GONG	Global Oscillation Network Group
GMDSS	Global Maritime Distress and Safety System
GPS	Global Positioning System
GWPS	Ground Wave Prediction System
HF	High Frequency

ICAO	International Civil Aviation Organization
IMO	International Maritime Organization
IP	Internet Protocol
IPR	Intellectual Property Rights
ISES	International Space Environment Service
IPS	Ionospheric Prediction Service
IRI	International Reference Ionosphere
ITU	International Telecommunications Union
MF	Medium Frequency
NASA	National Aeronautical and Space Administration
PNT	Positioning Navigation and Timing
R&D	Research and Development
SATCOM	Satellite Communications
SATNAV	Satellite Navigation
SEP	Solar Energetic Particles
SLA	Service Level Agreement
SWS	Space Weather Services
SWPC	Space Weather Prediction Centre
TEC	Total Electron Content
TNSP	Transmission Network Service Provider (power grid)
UHF	Ultra High Frequency
UNCOPUOS	United Nations Committee On Peaceful Uses of Outer Space
USAF	US Air Force
WMO	World Meteorological Organization

Appendix A – Letters and emails of support

This appendix has been removed to reduce the size of document and is available upon request

Appendix B - SWS Forecast verification statistics

B.1 T index

T index forecasts produced by the ASFC are for the Australian region and there are no competing forecasts, so no direct comparison is possible. Figure 5 shows error statistics for the years 1996-2013, with the observed mean for each year at the top, with mean error, root mean squared error and linear association below, comparing forecast lead times of 1, 2 and 3 days.

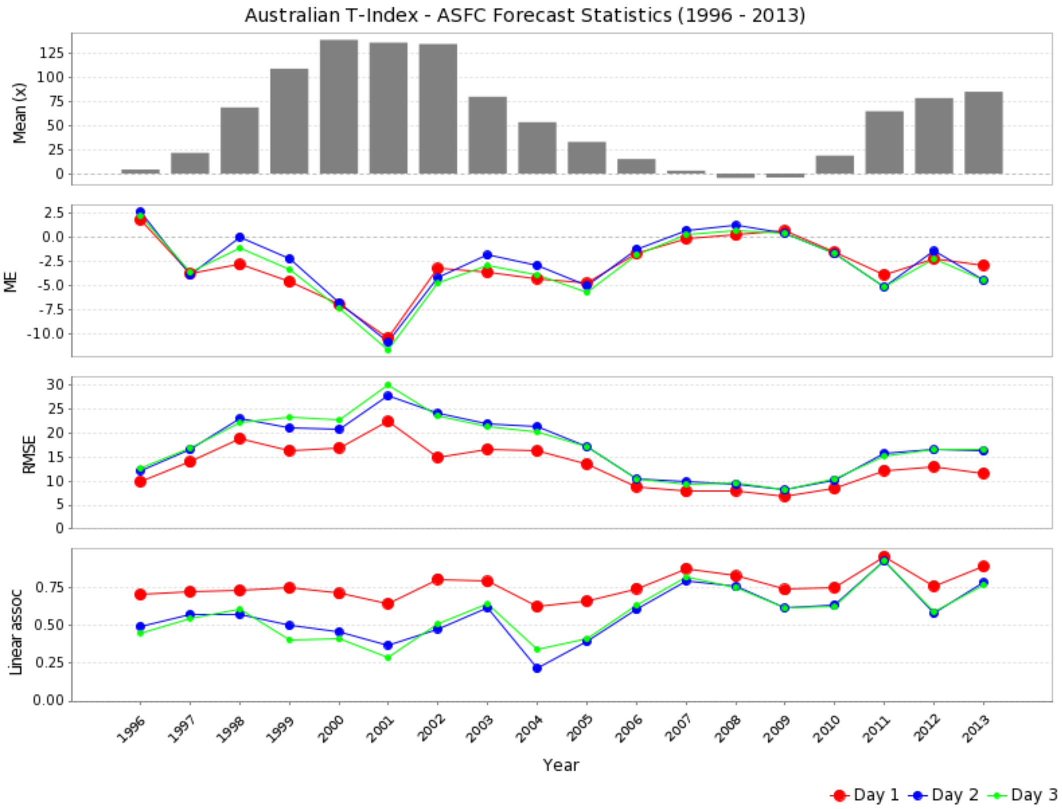


Figure 5: T-index error statistics for the years 1996-2013

These charts show that the forecasts are generally the least accurate during solar maximum when conditions are more variable and forecasting is more difficult. The performance during the current solar maximum appears to be somewhat better than the previous maximum. There does appear to be a small upward trend in linear association over the period.

Figure 6 compares the T index forecast skill (compared to the mean of observations over the whole period) with a number of reference forecasts (all of which are available at the time of forecasting):

- Recent observation mean (over the previous 30 days)
- Persistence (the observed value for the previous day)
- Recurrence (the observed value 27 days prior)
- A simple forecast model (Bob) based on the previous few hourly observed foF2 values from a collection of vertical ionosondes in the Australian region. Bob only produces Day 1 forecasts.

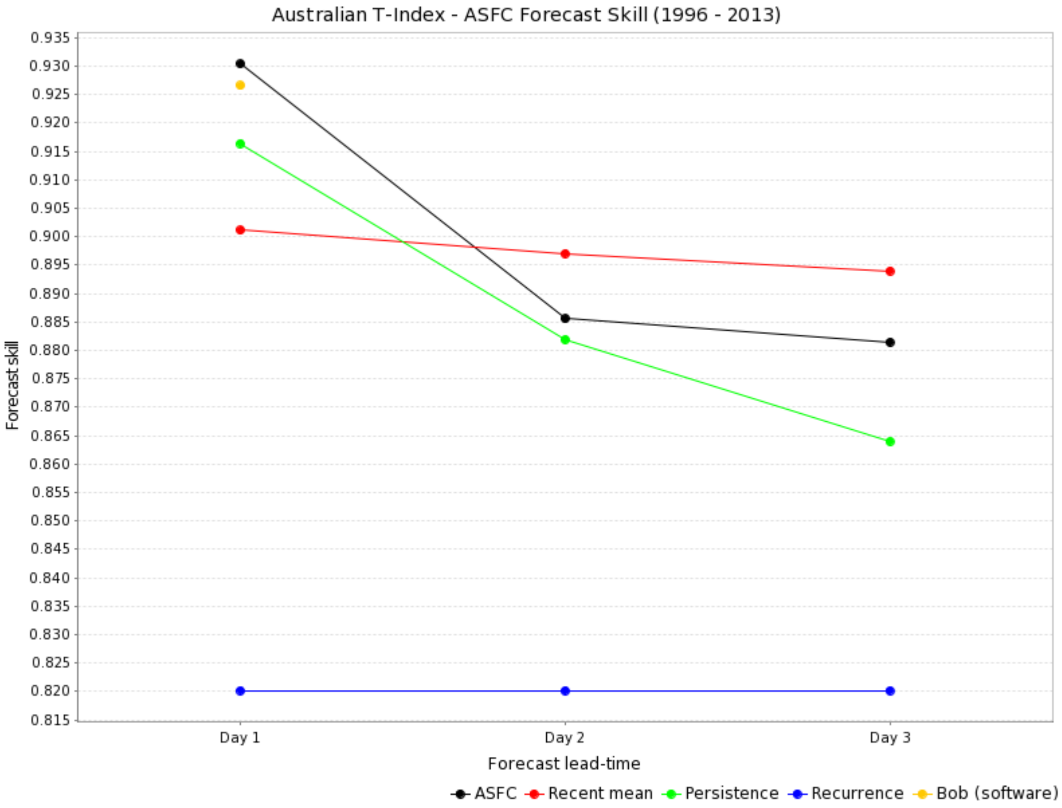


Figure 6: T-index skill

The Day 1 forecasts have higher skill than the reference forecasts, but the Day 2 and 3 forecasts are not even as good as the recent mean. Clearly there is room for improvement.

B.2 Ap index

The ASFC produces 1, 2 and 3-day forecasts of the Ap index which can be directly compared with those of similar organisations.

Figure 7 compares the Ap index forecast skill (compared to the mean of observations over the whole period) with a number of reference forecasts (including SWPC). The ASFC forecasts for Day 1 have higher skill than all the reference forecasts (including SWPC). For Day 2 and 3, SWPC leads the pack.

Figure *8* compares ASFC and SWPC error statistics for Day 1 forecasts.

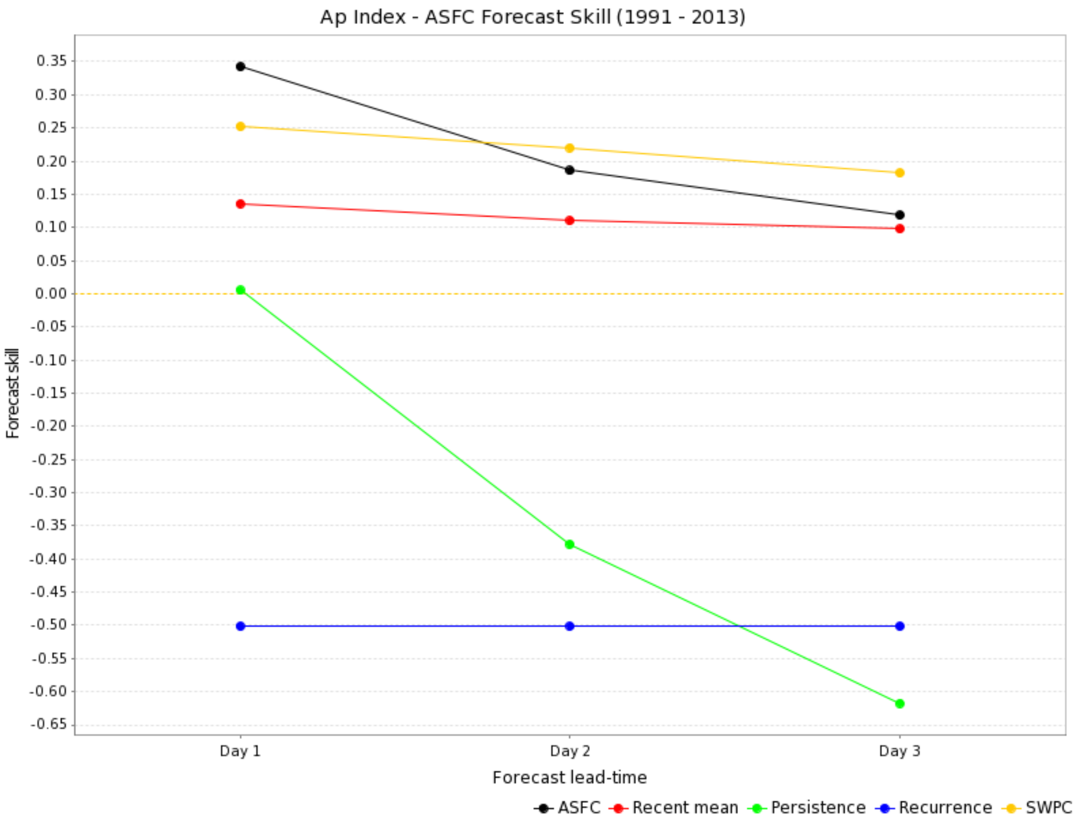


Figure 7: Ap-index forecast skill

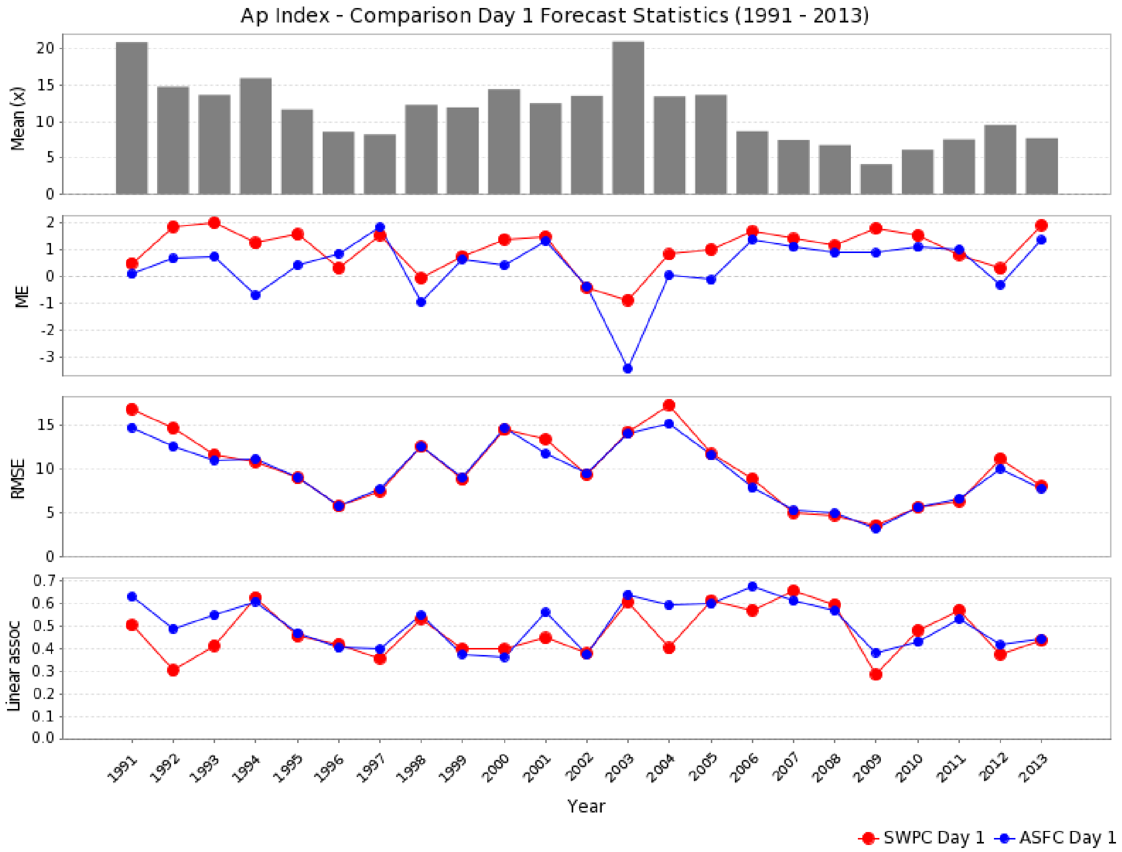


Figure 8: ASFC and SWPC forecast skill for Day 1.

B.3 Solar Activity

The ASFC produces Day 1, 2 and 3 solar activity forecasts in the following categories.

Very low (X-ray events less than C-class)

Low (C-class X-ray events)

Moderate (1 to 4 M-class X-ray events)

High (5 or more M-class X-ray events, or 1 to 4 M5 or greater X-ray events

Very high (5 or more M5 or greater X-ray events)

These categorical forecasts can be verified by counting actual X-ray events. However, the skill of the forecasts cannot be directly compared against those of other organisations, which are generally probabilistic forecasts of C, M and X events.

Figure 9 shows skill scores (proportion correct, Hanssen-Kuipers Skill Score, Heidke Skill Score) along with mean observed sunspot number for each year. There is an inverse correlation between these scores and the level of activity.

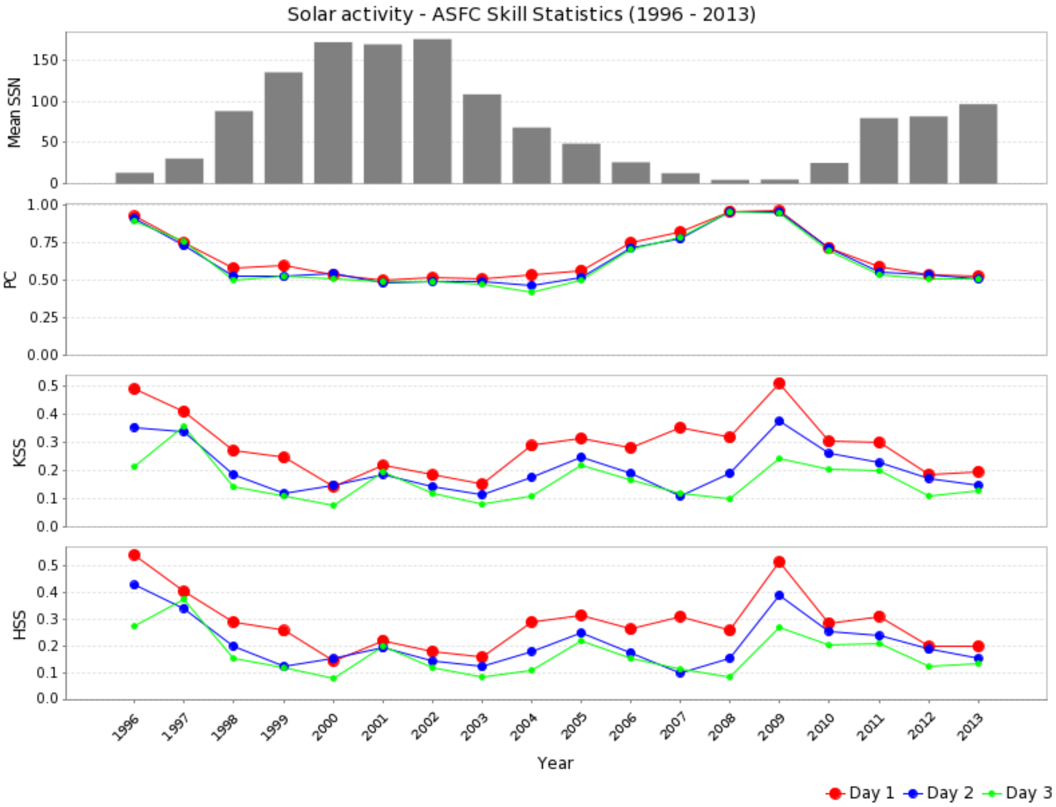


Figure 9: Solar Activity Skill Scores

Appendix C – SWS Bibliography

2002

Cole D. G. and Wilson C. D., The ITU-R and radiowave propagation, WARS02 (Worskshop on Applications of Radio Science) Conference Proceedings, March 2002

Lynn, K. J. W., R. Gardiner-Garden, M. Sjarifudin, M. Terkildsen, J. Shi, and T. J. Harris (2008), Large-scale travelling atmospheric disturbances in the night ionosphere during the solar– terrestrial event of 23 May 2002, *J. Atmos. Sol. Terr. Phys*., 70, 2184–2195, 2002

Otsuka Y., K. Shiokawa, T. Ogawa, P. Wilkinson, "Geomagnetic conjugate observations of equatorial airglow depletions", *Geophys. Res. Lett* 29, 10.1029/2002GLO015347, 2002

Wilkinson P. J. (editor) "WARS02 Proceedings", ISBN 0-9580476-0-X, 2002

Parkinson M. L., P. L. Dyson, M. Pinnock, J. C. Devlin, M. R. Hairston, E. Yizengaw, and P. J.Wilkinson "Signatures of the midnight open-closed magnetic field line boundary during balanced dayside and nightside reconnection" *Annales Geophysicae* 20: 1617–1630, 2002.

Greet P, R Morris, G Burns, A Klekociuk, D Murphy, P Dyson, B Fraser, B Vincent, P Wilkinson, S Dennis, C Barton, K McCue, R Francy, J Gras and C Dick, "Physics of the middle and upper atmosphere", Pub in *Australian Antarctic Science* ed H J Marchant, D J Lugg and P G Quilty, Pub Artemis Publishing Consultants (ISBN 1 876934 05 0), 2002.

2003

Campbell W. H, Barton, C E., Hopgood, P., Cole D. G, Australian magnetic field effects during geomagnetic storms, *Earth Planets and Space*, 55 (10), pp 591-599, Japan, 2003

Cole, D.G., ITU-R perspectives on radiowave propagation, Proc. URSI Commission F Open Symposium on climatic parameters and diffraction in radio wave propagation prediction, Fortaleza, 17-20 November 2003

Cole D.G., Wilkinson, P.J, Patterson, G., Marshall, R.A., Caruana, J, Yuile, C.,Space weather prediction and space weather services, Proceedings of the Australian International Aerospace Congress, Brisbane, July 2003

Cole D.G., Space weather: its effects and predictability, *Space Science Reviews*, 107 (1-2), pp295, Kluwer Academic Publishers, 2003

Neudegg D.A. refereed ‘Substorm associated changes in the high-latitude convection’, P.T. Jayachandran, J.W. MacDougall, E.F. Donovan, J.M. Ruohoniemi, K. Liou, D.R. Moorcroft and J.-P. St-Maurice, *Geophys. Res. Lett.*, paper GRL 2003GL017497. 2003.

Wilson, C. D., Cole, D. G., Vipond, L. A., Antenna specification by the ITU: Why, How and Where next? Abstracts of Papers, Eighth Australian Symposium on Antennas, Sydney, 2003

Wilkinson, P.J., Cole, D.G., Ionospheric work in Australia, The Low frequency Universe, LOFAR Symposium, University of Sydney, 2003

2004

Cole D.G., Space Weather and a plan for the future, Proceedings of the 5th Workshop on Applications in Radio Science, Hobart, February, 2004

Morris R.J., D. P. Monselesan, M. R. Hyde, A. M. Breed, P. J. Wilkinson and M. L. Parkinson, “Southern polar cap DPS and CADI ionosonde measurements: 1. Ionogram comparison” *Advances in Space Research*, 33. 923 – 929, 2004.

Morris R.J., D. P. Monselesan, M. R. Hyde, A. M. Breed, *P. J. Wilkinson*, “Southern polar cap DPS and CADI ionosonde measurements: 2. F-region drift comparison” *Advances in Space Research*, 33. 937 – 942, 2004.

Otsuka Y., K. Shiokawa, T. Ogawa, P. Wilkinson “Geomagnetic conjugate observations of medium-scale traveling ionospheric disturbances at midlatitude using all-sky airglow imagers”, *Geophysical Research Letters*, 31, L15803, doi:10.1029/2004GL020262, 2004.

Shiokawa K., Y. Otsuka, T. Ogawa, P. Wilkinson “Time evolution of high-altitude plasma bubbles imaged at geomagnetic conjugate points” *Ann. Geophys*, vol 22, 3137-3134, 2004

Suzuki, S., K. Shiokawa, Y. Otsuka, and T. Ogawa and P J Wilkinson “Statistical Characteristics of Gravity Waves Observed by an All-Sky Imager at Darwin, Australia” *J. Geophys. Res. (Atmos)* Vol 109, D20S07, doi:10.1029/2003JD004336, 2004

Thomas R M, M A Cervera, A Ghaffar Ramli, Effendy, P Totarong, K M Groves, P J Wilkinson “Seasonal Modulation Of GPS Performance Due To Equatorial Scintillation” Geopysical Research Letters Vol 31, L18806, doi:10.1029/2004GL020581, 2004

Wilkinson P. J., (2004) “Ionospheric Variability and the International Reference Ionosphere”, *Advances in Space Research*, 34 (9), 1853-1859, 2004

Wilkinson P. J. (editor) Worskhop on Applications of Radio Science, “WARS04 Proceedings”, ISBN 0-9580476-1-8, 2004

2005

Cole D.G., Kennewell, J.A., Wilkinson, P.J, An Australian Space Weather Plan, Proceedings of the Australian Institute of Physics Congress, Canberra, February 2005

Cole D.G., Neudegg D., Patterson, G., Phelan, P., IPS radio propagation and space weather services, Proceedings of the Australian Institute of Physics Congress, Canberra, February 2005

Neudegg D.A. refereed "On the morphology of long-duration negative ionospheric disturbances", by D. Fotiadis and S. Kouris, *Radio Science* paper#2005RS003395, November 2005.

Ogawa T., E Sagawa, Y Otsuka, K Shiokawa, T.I. Immel,el, S.B. Mende, and P.J. Wilkinson "Simultaneous ground- and satellite-based airglow observations of geomagnetic conjugate plasma bubbles in the equatorial anomaly" *Earth Planets Space*, 57, 385–392, 2005

Shiokawa K, Y Otsuka, T Tsugawa, T Ogawa, A Saito, K Ohshima, M Kubota, T Maruyama, T Nakamura, M Yamamoto and P J Wilkinson "Geomagnetic conjugate observations of nighttime medium- and large-scale travelling ionospheric disturbances: FRONT3 campaign" *J. Geophys. Res (Space)* vol 110, A05303, doi:10.1029/2004JA010845, 2005

Wilkinson, P.J, Pulehetoa, S., Cole D.G., Hyde, M., Neudegg, D., Paterson, B., Webster, A New South Pacific ionosonde station - Niue, *Proceedings of the International Association of Geomagnetism and Aeronomy*, Toulouse, July 2005

Wilkinson, P.J, Cole D.G., Kennewell J.A., A Comparison of the Australian Space Weather Plan with developing international space weather needs, Proceedings of the Australian Institute of Physics Congress, Canberra, February 2005

2006

Cole D.G., Wilkinson, P.J., Future data management at the WDC for Solar-Terrestrial Science, Proceedings of the Australian Institute of Physics Congress, Brisbane, December, 2006.

Cole D.G., Space: new horizons, new hazards, Proceedings of the Australian Earth Sciences Convention, Melbourne, July, 2006

Caruana, J., Cole D., Barclay, L., Amplitude and time distributions of ionospheric scatter, Proceedings of the Australian Institute of Physics Congress, Brisbane, December, 2006

Caruana, J., Cole D.G., Barclay, L.W, Ionospheric scatter parameters from digital ionograms, Proceedings of the 6th Workshop on Applications in Radio Science (WARS), Leura, February, 2006

Neudegg D.A. refereed "Decoupling of lower atmosphere pressures: a consequence of solar storms", by P. Madonia et al., *Geophys. Res. Lett. Paper#2006GL026520,* April 2006

Wilkinson P. J. (editor) "WARS2006 Proceedings", ISBN 0-643-09318-4, 2006 (http://www.ips.gov.au/IPSHosted/NCRS/wars/wars2006/index.htm

2007

Giersch, O., Kennewell, J., Lynch, M., "Proposed Observations of Coronal Mass Ejections using the Mileura Widefield Array", Proceedings of the 7th Australian Space Science Conference, Sep 24-27, 2007, Sydney, NSW.

ITU-R P.372-8 Combination of Radio Noise. (Revision of Recommendation) by John Caruana. *International Telecommunications Union Recommendation*, Based on method in Statistical addition method for external noise sources affecting HF-MF-LF systems, Neudegg D.A., *Radio Sci.,* 36, 6, pp1659-1667, 2001. February 2007.

McNamara, L. F., D. T. Decker, J. A. Welsh and D. G. Cole, Validation of the Utah State University Global Assimilation of Ionospheric Measurements (GAIM) model predictions of the maximum usable frequency for a 3000 km circuit, *Radio Science*, Vol. 42, RS3015, doi:10.1029/2006RS003589, 2007

Neudegg, D. A., refereed "On the occurrence of reversed flow events in the cusp ionosphere observed by EISCAT Svalbard radar", by Y. Rine et al., *J. Geophys. Res (Space).paper#2007JA012366.* March 2007

Ouyang G., Wang J., Wang J., Cole D., Generating a 3D TEC Model for Australia with Combined LEO Satellite and ground based GPS Data Sets, *Proc GNSS Conference, Institute of Navigation*, Fort Worth, September 2007

Trichtchenko, L., A. Zhukov, R. van der Linden, S. M. Stankov, N. Jakowski, I. StanisJawska, G. Juchnikowski, P. Wilkinson, G. Patterson, and A. W. P. Thomson "November 2004 space weather events: Real-time observations and forecasts", *Space Weather*, Vol. 5, S06001, doi:10.1029/2006SW000281, 2007

Wang Jian, Ouyang Gary, Wang Jinling, Cole David, Analysis on Temporal-Spatial Variation of Australian TEC, *Proc IAGA, IUGG*, Perugia, Italy, July 2007

Wilkinson P. J., "The future of the ionosphere", The Proceedings of the 10th International Conference on Ionospheric Radio Systems and Techniques, London, United Kingdom, 2007

Wilkinson P.J., "Ionosphere", in *Encyclopedia of the Antarctic*, Editor Beau Riffenburgh, published by Routledge, Taylor and Francis Group, 2007.

2008

Brockman, A., Giersch, O., Kennewell, J., "An Investigation of Solar Magnetic Indices for Space Weather Forecasting", *Astronomical Society of the Pacific Conference Series*, GONG 2008/SOHO XXI, Aug 11-15, 2008, Boulder, Colorado.

Giersch, O., Kennewell, J., “Type 3L Radio Emission as a Predictor for Solar Particle Events”, Proceedings of the Australian Institute of Physics 18th National Congress, Nov 30 – Dec 4, 2008, Adelaide, South Australia.

Marshall R.A., C.L. Waters and M.D. Sciffer: Spectral analysis of pipe-to-soil potentials with variations of the geomagnetic field in the Australian region, *Western Pacific Geophysics Meeting, EOS, Transactions American Geophysical Union*, Cairns, QLD, Australia, 2008.

Marshall R.A., J. Kennewell and D. Neudegg: Generation and use of a real-time estimated Dst-index at the Australian Space Forecast Centre, AIP meeting, Adelaide, December, 2008, Australia.

Neudegg D.A. referee for *"An Antarctica to Spain HF Ionospheric Radio Link: Sounding Results"* (paper number 2007RS003812) by C.Vilella, D. Miralles, and J-L. Pijoan, *Radio Science*, February 2008.

2009

Alfonsi L., G de Franceschi, P J Cilliers, B Hopperman, M Materassi, C N Mitchell, V Romano, S Skone, P Spalla, P Spencer, A W Wernik, P Wilkinson and P Yin, (2009) “UAMPY: Upper Atmosphere Monitoring for Polar Year 2007-2008”, *Conference Proceeding Vol 97 Italian Research on Antarctic Atmosphere*, Editors: M Colacino and C Rafanelli. 2009.

Davis C. J., S. A. Bell, R. Stamper, A. W. V. Poole, L. A. McKinnell, and P. Wilkinson , “A potential lag between the open solar magnetic source flux and solar EUV and X-ray emissions as measured by the Earth’s ionosphere during total solar eclipses”, *Ann. Geophys*., 27, 2449–2456, 2009.

Giersch, O. D., Brockman, A., “Recovering Inversion Lines from GONG, Magnetograms and Implications for Space Weather Forecasting”, *American, Geophysical Union Fall Meeting*, Dec 14-18, 2009, San Fransisco, California.

van de Kamp, M., P. S. Cannon, and M. Terkildsen, Effect of the ionosphere on defocusing of space-based radars, *Radio Sci*., 44, RS1003, doi:10.1029/2007RS003808. 2009

Kumar, V. V., M. L. Parkinson, P. L. Dyson, R. Burns: The effects of thunderstorm-generated atmospheric gravity waves on mid-latitude F-region drifts, *J. Atmos. Solar-Terr. Phys*., **71**, pp. 1904–1915, doi: 10.1016-j.jastp. 2009.07.006, 2009.

Lobzin, V. V., I. H. Cairns, P. A. Robinson, G. Steward, and G. Patterson (2009), Automatic Recognition of Type III Solar Radio Bursts: Automated Radio Burst Identification System Method and First Observations, Space Weather, 7, 04002, doi: 10.1029/2008SW000425,http://onlinelibrary.wiley.com/doi/10.1029/2008SW000425/abstract

P.S. Maher, R.A. Malaney: "A Novel Fingerprinting Location Method Using Ray Tracing", *IEEE Global Telecommunication Conference GLOBECOM 2009*, pp. 1-5

Marshall R.A., G. Patterson, C. Thomson and C. Yuile, Near real-time geomagnetic data from an Australian region space weather network: data acquisition to service delivery*, IAGA 11th Scientific Assembly*, Sopron, Hungary, 2009.

Marshall, R.A., G. Patterson, J. Kennewell, C. Waters, M. Sciffer, Development and application of geomagnetic indices at the Australian Space Forecast Center, *IAGA 11th Scientific Assembly*, Sopron, Hungary, 2009.

Uozumi, T., S. Abe, K. Kitamura, T. Tokunaga, A. Yoshikawa, H. Kawano, R. Marshall, R. J. Morris, B. M. Shevtsov, S. I. Solovyev, D. J. McNamara, K. Liou, S. Ohtani, M. Itonaga, K. Yumoto. (2009), Propagation characteristics of Pi 2 pulsations observed at high- and low-latitude MAGDAS/CPMN stations: A statistical study, *J. Geophys. Res.,* 114, A11207, doi:10.1029/2009JA014163.

Neudegg D.N., .R. Marshall, Detection of IMF shocks and sudden impulses, ASSC, Sydney, September, 2009.

Neudegg D.A., 2008 Editors' 'Citation for Excellence in Refereeing' for *Radio Science* journal. AGU Publications Committee, Feb 2009.

P. Wilkinson, D. Neudegg, G. Patterson. Space weather reports for Antarctica during the International Polar Year. *Conference Proceedings of 11th Ionospheric Radio Systems and Techniques (IRST-11)*, Published by The Institute of Engineering and Technology, London (ISBN 9781849191234). April 2009

Wilkinson, P. , "Space Weather Studies in Australia", *Space Weather*, 7, S06002, doi:10.1029/2009SW000485, 2009.

2010

Abe, S., H. Kawano, K. Matsuyama, B. Shevtsov, R. Marshall, K. Yumoto: Plasmasphere diagnosis by applying three FLR-detecting methods to data from MAGDAS/CPMN conjugate stations, *JPGU meeting*, Makuhari, Chiba, Japan, May, 2010.

Bouya, Z.,Terkildsen, M., Neudegg, D., "Regional GPS-based ionospheric TEC model over Australia using Spherical Cap Harmonic Analysis", *38th COSPAR Scientific Assembly*. Held 18-15 July 2010, in Bremen, Germany.

Cole D., National Committee for Space Science, Decadal Plan for Australian Space Science: Building a National Presence in Space, Australian Academy of Science, Canberra, September, 2010

Giersch, O., "Automated Region Detection and Sunspot Analysis using GONG Imagery", *Journal of Physics: Conference Series, GONG 2010/SOHO XXIV*, Volume 271, Issue 1, June 28 – July 2, 2010, Aix-En-Provence, France

Kumar, V. V., M. L. Parkinson, and P. L. Dyson: On the Temporal Evolution of Mid-Latitude F-region Disturbance Drifts, *J. Geophys. Res*., 115, A08325, doi: 10.1029/2009JA015229, 2010.

Lobzin, V. V., I. H. Cairns, P. A. Robinson, G. Steward, and G. Patterson (2010), Automatic Recognition of Coronal Type II Radio Bursts: The Automated Radio Burst Identification System Method and First Observations, *ApJ*, 710, L58-L62, doi: 10.1088/2041-8205/710/1/L58; http://iopscience.iop.org/2041-8205/710/1/L58

Marshall, R. A., C. L. Waters, and M. D. Sciffer (2010), Spectral analysis of pipe-to-soil potentials with variations of the Earth's magnetic field in the Australian region, *Space Weather,* 8, S05002, doi:10.1029/2009SW000553

Marshall, R.A., The Australian region space weather network, *International Space Weather Initiative Workshop*, Cairo, Egypt, 6-10 November 2010.

Marshall, R.A., MAGDAS in Australia, *International Space Weather Initiative Workshop*, Cairo, Egypt, 6-10 November 2010.

Neudegg, D., M. Layoun, S.T. Hutchinson, R.A. Marshall, M.Terkildsen, Variations near the ionospheric F2 layer peak at solar minimum, *COSPAR*, 2010.

Neudegg D.A. refereeing PhD thesis: *"Wind-Wave Mapping of the Southern Ocean using the TIGER SuperDARN Radars"* by R. Greenwood. La Trobe University Melbourne, April 2010.

Prikryl, P., Spogli, L., Jayachandran, P. T., Kinrade, J., Mitchell, C. N., Ning, B., Li, G., Cilliers, P. J., Terkildsen, M., Danskin, D. W., Spanswick, E., Donovan, E., Weatherwax, A. T., Bristow, W. A., Alfonsi, L., De Franceschi, G., Romano, V., Ngwira, C. M., and Opperman, B. D. L., Interhemispheric comparison of GPS phase scintillation at high latitudes during the magnetic-cloud-induced geomagnetic storm of 5–7 April 2010, *Ann. Geophys*., 29, 2287-2304, doi:10.5194/angeo-29-2287-2011, 2011.

Richards P.G, R.R. Meier, and P.J. Wilkinson "On the consistency of satellite measurements of thermospheric composition and solar EUV irradiance with Australian ionosonde electron density data", *J. Geophys. Res (Space)* vol 115, A10309, doi:10.1029/2010JA015368. 2010

Smith, E., R.A. Marshall, C.L. Waters, and M.D. Sciffer, A Risk Assessment of Space Weather Effects on the Australian Power Network, Australian Space Science Conference, Brisbane, Australia, 27-30 September, 2010.

Uozumi, T., K. Yumoto, Y. Fujita, H. Watanabe, K. Imamura, M. Sakai, S. Abe, K. Kitamura, Y. Yamazaki, A. Yoshikawa, H. Kawano, Y. Kakinami, D. McNamara, A. B. Rabiu, I. A. Adimula, A. Bhattacharya, S. Alex, S. Gurubaran, S. L. G. Dutra, B. M. Shevtsov,……. and R. Marshall: Enhancement of Equatorial Electrojet during the July 22, 2009 Solar Eclipse Event, *JPGU meeting*, Makuhari, Chiba, Japan, May, 2010.

Wilkinson, P.J, Cole D.G., The Role of Radio Science in Disaster Management, *URSI Radio Science Bulletin*, December, 2010

Yamazaki, Y., K. Yumoto, T. Uozumi, S. Abe, M. G. Cardinal, D. McNamara, R. Marshall, B. M. Shevtsov, and S. I. Solovyev (2010), Reexamination of the Sq-EEJ relationship based on extended magnetometer networks in the east Asian region, *J. Geophys. Res*., 115, A09319, doi:10.1029/2010JA015339.

2011

Bouya, Z., Terkildsen, M., Francis, M., "EOF Analysis applied to Australian Regional Ionospheric total Electron Content,based on GPS Observations and SCHA". *Eighth European Space Weather Week,* November 28 - December 02, 2011 - Namur, Belgium.

Francis, M. Terkildsen, Z. Bouya, Real-time regional ionospheric total electron content mapping (talk), , IUGG General Assembly, Melbourne 2011

Greenwood, R. I., M. L. Parkinson, P. L. Dyson, and E. W. Schulz: Dominant ocean wave direction measurements using the TIGER SuperDARN systems, *J. Atmos. Solar-Terr. Phys*., 73, pp. 2379–2385, doi: 10.1016/j.jastp.2011.08.006, 2011.

Marshall, R. A., E. A. Smith, M. J. Francis, C. L. Waters, and M. D. Sciffer (2011), A preliminary risk assessment of the Australian region power network to space weather, *Space Weather*, 9, S10004, doi:10.1029/2011SW000685.

Marshall, R.A., The Australian region space weather network, *AOGS 8TH Annual Meeting*, Taipei, 8-12 August 2011.

Marshall, R.A., MAGDAS activities in Australia, *International Space Weather Initiative Workshop*, Abuja, Nigeria, 17-21 October 2011.

Neudegg D.A. refereeing. Statistical Study of Pc 1-2 Wave Propagation Characteristics in the High-Latitude Ionospheric Waveguide, H. Kim, M. R. Lessard, M. J. Engebretson and M. A. Young, *J.Geophys. Res. (Space) Paper # 2010JA016355*, 2011.

Steward, G. A., V. V. Lobzin, P. J. Wilkinson, I. H. Cairns, and P. A. Robinson. 2011. Automatic recognition of complex magnetic regions on the Sun in GONG magnetogram images and prediction of flares: Techniques for the flare warning program Flarecast, *Space Weather*, 9, S11004, doi:10.1029/2011SW000703 http://onlinelibrary.wiley.com/doi/10.1029/2011SW000703/abstract

Takla E.M., K. Yumoto, P.R. Sutcliffe, V.M. Nikiforov and R. Marshall (2011), Possible association between anomalous geomagnetic variations and the Molise Earthquakes at Central Italy during 2002, *J. Phys. Earth and Planet. Interiors*, 185, 29–35.

Uozumi T.,K. Yumoto,1,2 T. Tokunaga, S. I. Solovyev, B. M. Shevtsov, R. Marshall, K. Liou, S. Ohtani, S. Abe, A. Ikeda, K. Kitamura, A. Yoshikawa, H. Kawano, and M. Itonaga (2011), AKR modulation and Global Pi 2 oscillation, oscillation, *J. Geophys. Res*., 116, A06214, doi:10.1029/2010JA016042.

Yamazaki, Y., K. Yumoto, M. G. Cardinal, B. J. Fraser, P. Hattori, Y. Kakinami, J. Y. Liu, K. J. W. Lynn, R. Marshall, D. McNamara, T. Nagatsuma, V. M. Nikiforov, R. E. Otadoy, M. Ruhimat, B. M. Shevtsov, K. Shiokawa, S. Abe, T. Uozumi, and A. Yoshikawa (2011), An empirical model of the quiet daily geomagnetic field variation, *J. Geophys. Res*., 116, A10312, doi:10.1029/2011JA016487.

2012

Bouya, Z., M. Terkildsen, M. Francis, D. Neudegg, R. Marshall, “Australian Regional Ionospheric Disturbance Index Based on the Principal Component Analysis and GPS Data”, *AOGS – AGU (WPGM) Joint Assembly* 13 -17 August, 2012. Singapore.

Bouya, Z., M. Terkildsen, M. Francis, D. Neudegg and R. Marshall, Australian Regional ionospheric Disturbance Index Based on the Principal Component Analysis and GPS Data, *AOGS 9TH Annual Meeting*, Singapore, 13 to 17 August, 2012

Carter, B., M. Francis, M. Terkildsen, E. Yizengaw, R.A. Marshall, R. Norman, K. Zhang, Observations of equatorial plasma bubbles over northern Australia, 12th ASSC, 24-27 September 2012, Melbourne, Australia.

Giersch, O., Kennewell, J., “Solar Radio Interference to the GNSS”, Proceedings of the 13th Australian Space Science Conference, Sep 30-Oct 2, 2012, Sydney, NSW.

Giersch, O., “GONG Inter-site Ha Flare Comparison”, Journal of Physics: Conference Series, Eclipse on the Coral Sea: Cycle 24 Ascending (GONG 2012, LWS/SDO-5, and SOHO 27), Vol 440, 12–16 November 2012, Palm Cove, Queensland, Australia

Marshall, R. A., M. Dalzell, C. L. Waters, P. Goldthorpe, and E. A. Smith (2012), Geomagnetically induced currents in the New Zealand power network, *Space Weather*, 10, S08003, doi:10.1029/2012SW000806.

Marshall, R., M. Terkildsen, G. Steward, D. Neudegg and Z. Bouya, The IPS Extreme Space Weather Service, *AOGS 9TH Annual Meeting*, Singapore, 13 to 17 August, 2012.

Marshall, R.A., Space weather and critical infrastructure in the Australian/New Zealand region, *TIEMS Space weather and challenges for modern society conference*, Oslo, Norway, 22-24 October, 2012.

Neudegg, D., R.A. Marshall, M. Terkildsen, G. Steward, Significant Events To Date in Cycle 24, 12th ASSC, 24-27 September 2012, Melbourne, Australia.

Neudegg D.A., Refereed 'Verification of space weather models', Wintoft et al., *Journal of Space Weather and Space Climate*, July 2012.

K. Wang, C. Yuile, The application of an online data visualization tool, PtPlot, in the World Data Centre (WDC) for Solar-Terrestrial Science (STS) in IPS Radio and Space Services, Australia. *Proceedings of 1st ICSU-WDS Conference (2011), Global Data for Global Science, Data Science Journal*, Kyoto, Japan, 86-90, 2012

2013

Bouya, Z., M. Terkildsen, M. Francis, "Regional Ionospheric Monitoring and Forecasting Using GNSS Techniques" *The 2nd Asia Oceania Space Weather Alliance (AOSWA) Workshop*, November 4-7, 2013 Kunming China.

Bouya, Z., Terkildsen, M., Francis, M., "Monitoring and forecasting Regional Ionospheric perturbations over Australia based on GNSS techniques." *EGU General Assembly 2013*, held 7-12 April, 2013 , Vienna, Austria, id. EGU2013-3856.

Bouya, Z., Z M. Terkildsen ,M. Francis, "Regional climatological model of TEC over Australia", 13th Australian Space Science Conference(ASSC), September 30-October 2, 2013. Sydney Australia.

Bouya, Z., D. Neudegg, M. Terkildsen, M. Francis, A. Kelly, R. Marshall, G. Steward, M. Parkinson, Monitoring and forecasting regional ionospheric perturbations based on GNSS techniques, AOGS Conference, Brisbane, Australia, August, 2013.

Burstinghaus, E.J., T. Saha, K. Yumoto, R. Marshall , C. Waters, The Importance of Non-Uniform Geoelectric Fields in Calculating GIC Distributions, *Power and Energy Society General Meeting (PES), 2013 IEEE*, 10.1109/PESMG.2013.6672289.

Carter, B. A., Francis, M. J., Terkildsen, M., Yizengaw, E., Marshall, R**.,** Norman, R., Hooper, G. and Zhang, K.: An investigation into the day-today occurrence of GPS scintillation events in the Australian longitude sector, Paper presented at the International Global Navigation Satellite Systems Symposium 2013, Gold Coast, QLD, Australia, 16–18 July 2013.

Carter, B.A., M. J. Francis, M. Terkildsen, E. Yizengaw, R. Marshall, R. Norman and K. Zhang, On the day-to-day occurrence of equatorial plasma bubbles over South-east Asia during equinox months, AOGS Conference, Brisbane, Australia, August, 2013

Carter B.A., E. Yizengaw, M. J. Francis, M. Terkildsen, R. Marshall, R. Norman and K. Zhang, The day-to-day occurrence of equatorial plasma bubbles measured from Vanimo, Papua New Guinea, *Fall AGU Meeting*, San Francisco, December 2013.

Francis, M. Terkildsen, Z. Bouya, A. Kelly, A Regional and Empirical Approach to 3D Ionospheric Modelling (talk), AOGS Annual Meeting, Brisbane 2013

Imajo S., A. Yoshikawa, T. Uozumi, S. Ohtani, R. Marshall, B. M. Shevtsov, V. A. Akulichev, U. Sukhbaatar, K. Yumoto, Effect of the dawn terminator on Pi 2 pulsations, *SGEPSS meeting*, Kochi University , Japan, November, 2013.

Kelly, A., M. Francis, Space Weather forecast verification at IPS (talk), AOGS Annual Meeting, Brisbane 2013

Marshall, R. A., H. Gorniak, T. van der Walt, C. L. Waters, M. D. Sciffer, M. Miller, M. Dalzell, T. Daly, G. Pouferis, G. Hesse, and P. J. Wilkinson (2013), Observations of geomagnetically induced currents in the Australian Power Network, *Space Weather*, 11, doi:10.1029/2012SW000849.

Mwitondi, K., J. Bugrien, K. Wang, Using Optimized Distributional Parameters as Inputs in a Sequential Unsupervised and Supervised Modeling of Sunspots Data, *Journal of Software Engineering and Applications*, 2013, 6, 34-41, doi:10.4236/jsea.2013.67B007 Published Online July 2013.

Prikryl, P., Y. Zhang, Y. Ebihara, R. Ghoddousi-Fard, P.T. Jayachandran, J.Kinrade, C. N. Mitchell, A.T. Weatherwax, G.Bust, P.J. Cilliers, L.Spogli, L.Alfonsi, V.Romano, B.Ning, G.Li, M.J. Jarvis, D.W. Danskin, E.Spanswick, E.Donovan, and M.Terkildsen, An interhemispheric comparison of GPS phase scintillation with auroral emission observed at the South Pole and from the DMSP satellite, *Annals of Geophysics* , Vol 56, No 2 (2013)

Wang, K., C. Yuile, D. Neudegg, A. Kelly, C. Thomson, G. Patterson, M. Hyde, M. Terkildsen, R. Marshall, Y. Tian, Antarctic Space Weather Data Managed by IPS Radio and Space Services of Australia, *ICSU-WDS International Forum on Polar Data Activities in Global Data System*, Tokyo, Japan, 14–16 October 2013.

2014

Carter, B. A., E. Yizengaw, J. M. Retterer, M. Francis, M. Terkildsen, R. Marshall, R. Norman, and K. Zhang (2014), An analysis of the quiet time day-to-day variability in the formation of postsunset equatorial plasma bubbles in the Southeast Asian region, *J. Geophys. Res. Space Physics*, 119, doi:10.1002/2013JA019570.

Imajo, S., K. Yumoto, T. Uozumi, H. Kawano, S. Abe, A. Ikeda, K. Koga, H. Matsumoto, T. Obara, R. Marshall, V.A. Akulichev, A. Mahrous, A. Liedloff and A. Yoshikawa, Statistical analysis of propagation delay of compressional Pi 2s between geosynchronous altitude and low latitudes, *J. Earth, Planets and Space*, 2014, 66:20 doi:10.1186/1880-5981-66-20.

Imajo, S., A. Yoshikawa, T. Uozumi, S. Ohtani 3, A. Nakamizo, R. Marshall, B. M. Shevtsov, V. A. Akulichev, U. Sukhbaatar, K. Yumoto, Characteristics of Pi 2 pulsations around the dawn and dusk terminator, *JPGU* 2014.

Imajo, S., A. Yoshikawa, T. Uozumi, S. Ohtani 3, A. Nakamizo, R. Marshall, B. M. Shevtsov, V. A. Akulichev, U. Sukhbaatar, K. Yumoto, Dayside ionospheric current oscillations associated with Pi 2 pulsations, *Asia-Oceania Geophysics Society AOGS* 2014, Hokkaido, Japan.

Lobzin, V.V., Iver H. Cairns and A. Zaslavsky, Automatic recognition of type III solar radio bursts in STEREO/WAVES data for onboard real-time and archived data processing, *Journal of Geophysical Research: Space Physics*, 119, pages 742–750, 2014, DOI: 10.1002/2013JA019008

Marshall, R.A., GIC observations, modeling and mitigation in the Australian power network, *GIC Workshop*, Cape Town, South Africa, 1-2 April 2014.

Wang K., Neudegg D., Yuile C., Thomson C., Patterson G., Marshall R., Terkildsen M. and Hyde M., The Space Weather Data Managed by IPS Radio and Space Services of Australia. ASSC – Australian Space Science Conference, Adelaide, September 2014.

Appendix D – External Oral Evidence

This appendix has been removed to reduce the size of document and is available upon request

Blank page