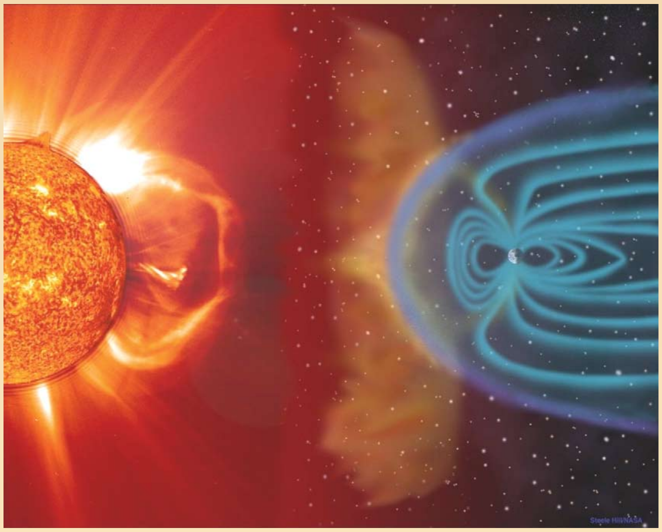
WMO Space Programme



THE POTENTIAL ROLE OF WMO IN SPACE WEATHER

A REPORT ON THE POTENTIAL SCOPE, COST AND BENEFIT OF A WMO ACTIVITY IN SUPPORT OF INTERNATIONAL COORDINATION OF SPACE WEATHER SERVICES, PREPARED FOR THE SIXTIETH EXECUTIVE COUNCIL

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World Meteorological Organization
Weather • Climate • Water

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EXECUTIVE SUMMARY

In May 2007, the fifteenth World Meteorological Congress requested the WMO Space Programme office to *"consider activities in the area of Space Weather, since it had a direct impact on meteorological satellite operations".* This was further discussed in January 2008 by the eighth session of Consultative Meetings on High-level Policy on Satellite Matters (CM-8). The present report was prepared in response to CM-8 who had recommended preparing a report on scope, cost and benefit of a potential WMO involvement in Space Weather for discussion at the sixtieth WMO Executive Council (EC-LX).

Space Weather is highly relevant to WMO activities, primarily because it has a strong impact on environmental satellites, which are key components of the Global Observing System (GOS), and on radio-communications, which are operational components of the WMO Information System (WIS). Furthermore, considering that Space Weather affects important economic activities such as aviation, spacecraft operations, satellite positioning and energy distribution, which involve major users of meteorological services, there is a potential for synergy between the emerging operational activities in the area of Space Weather and current WMO activities regarding meteorological services delivery. Such a synergy could mainly occur in the sharing of space- and ground-based observing platforms, in the delivery of routine information through the WMO Information System, in the issuance of Space Weather warnings within a multi-hazard approach, and in interactions with operational users in general.

Several WMO Members have placed Space Weather activities under the authority of their National Meteorological or Hydrological Services and are encouraging WMO to engage in this field, in partnership with relevant international organizations. The main international coordination mechanism for Space Weather is currently the International Space Environment Service (ISES). As Space Weather is evolving from research to operational services the ISES has expressed interest for cooperating with WMO, considering that the WMO framework would be appropriate to enhance international cooperation on operational aspects of Space Weather. It is noted that no United Nations organization is currently responsible for international coordination in Space Weather.

Examples taken from aviation, space operations, Global Satellite Navigation Systems, and Electric power grid management indicate how Space Weather warnings enable substantial reduction of economic losses due to Space Weather events. It is anticipated that a modest investment in coordination activities under the auspices of WMO could significantly expand these benefits, for the interest of all WMO Members.

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1 BACKGROUND

The present report addresses the possible scope, cost and benefit of initiating a WMO activity in the area of Space Weather. The expression Space Weather is used to designate processes occurring on the Sun, in the magnetosphere, ionosphere and thermosphere, which have the potential to affect the near-Earth environment. These processes occurring mainly outside of the atmosphere are not meteorological phenomena, and thus haven't so far been considered within the mandate of WMO. However, because of their importance and possible synergy with activities under WMO's responsibility, the issue of a possible WMO involvement needs to be reassessed.

The Fifteenth World Meteorological Congress requested the WMO Space Programme to consider the possible scope of Space Weather activities. Bilateral contacts held in 2007 with several WMO Members involved in Space Weather have suggested that WMO could provide an appropriate framework to support global cooperation in this area. This idea was reinforced by contacts made early 2008 with representatives of the International Space Environment Service (ISES). It is also consistent with the growing importance given to Space Situational Awareness by the space operational community and discussions being held on this subject within the United Nations Committee on Peaceful Use of Outer Space (COPUOS).

The Eighth session of Consultative Meetings on High-level Policy on Satellite Matters (CM-8), held in January 2008, widely supported the view that Space Weather events were of major importance and that the developments occurred in that area in recent years had reached a stage where Space Weather observation and forecasting activities were providing operational benefit to a growing number of applications. It was emphasized that such phenomena affecting the Earth-Sun system should best be addressed at global scale, and were anticipated to play a significant role in the climate system.

The session acknowledged that international coordination was necessary to support these activities and ensure that all countries could benefit of the observations and warnings of relevance to them. It was furthermore acknowledged that no United Nations body was currently providing technical coordination in that area, and WMO was deemed to be the most appropriate organization for that, because of its experience in operational coordination and of the potential synergy with core WMO activities. The session noted WMO's unique technical capability to distribute global advisories through the WMO Information System (WIS), similar to what has been done for volcanic ash and tsunami warnings.

CM-8 recommended proceeding stepwise, recognizing the complexity of this new field of activity. Caution was necessary regarding the implications on staff resources, being aware that in the context of Zero Nominal Growth Budgets the Secretariat had no margin in this respect.

CM-8 thus requested the Space Programme Office to prepare a proposal to be submitted to the Executive Council highlighting the cost and benefit of WMO involvement in Space Weather. The President of CBS suggested that a Rapporteur be appointed as a matter of urgency, in order to present a report to the next session of CBS on this matter. The report would review existing activities on Space Weather among the NMHSs and would identify in more detail the possible tasks where a contribution of WMO would be beneficial.

The present report intends to respond to the request from CM-8.

2 INTRODUCTION TO SPACE WEATHER

2.1 Definition

Space Weather encompasses the conditions on the Sun, the solar wind, the magnetosphere, the ionosphere, and the neutral atmosphere that can influence the performance and reliability of space-borne and ground-based technological systems and endanger human life or health.

2.2 Type of phenomena

Space Weather has both eruptive and quiescent aspects. The eruptive component, which occurs generally in phase with the sunspot cycle, consists of solar flares, coronal mass ejections and solar energetic particles. Nearer Earth these eruptive events cause: ionospheric storms, which disrupt GPS/GNSS and communications; magnetic storms that induce damaging currents in power grids; and radiation storms that affect the health and safety of passengers and aircrews.

The quiescent component includes the increase in solar luminescence with the sunspot cycle – a contributor to global warming – and the elevated flux of galactic cosmic rays which are anti-correlated with the sunspot cycle. More galactic cosmic rays cause heightened radiation for satellites, manned spaceflight, and trans-polar aviation.

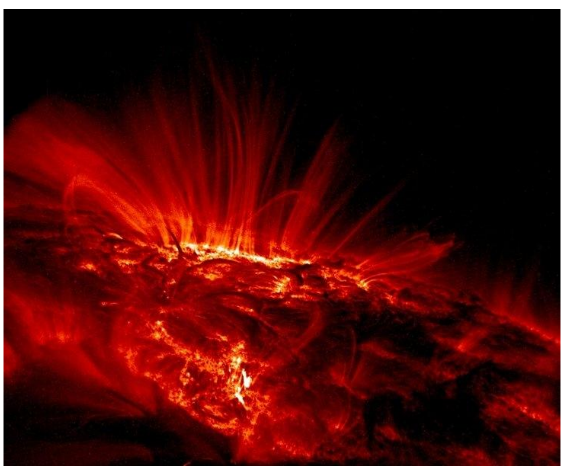

Figure 1: Solar eruption observed by the NASA TRACE satellite. Initiation of space weather activity at the Sun.

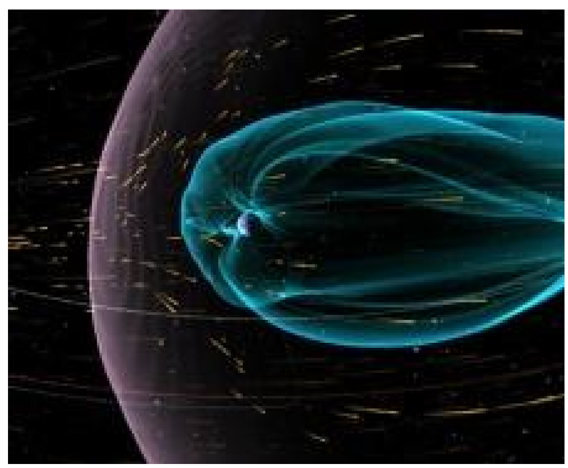

Figure 2: Illustration of the Earth embedded within its own magnetic field, with charged particles – the solar wind – flowing around it.

Space Weather generically spans the fields of solar physics, plasma physics, and stellar astronomy. Nearer Earth it includes study – and modelling – of the neutral atmosphere as well as the regimes of the ionosphere and the magnetosphere.

2.3 Socio-economic impact

The socio-economic impact of Space Weather is great and continues to grow. Our society's vulnerability is increasing, which primarily results from the expanded reliance on satellite technologies, radio-communications – particularly for trans-polar commercial airlines – and large surface-based electric power networks. A number of operational activity areas thus require a better ability to provide global Space Weather support.

One example is the Global Navigation Satellite Systems (GNSS) that enable every country to develop positioning, location, and timing services for their own constituency. The largest error source for GNSS is imposed by Space Weather. Another activity that has become particularly concerned with Space Weather is that of the commercial airlines. In the past ten years, the routes over the North Pole have become very desirable and profitable for air carriers. As that polar region serves as a focus for the charged particles that originate in solar eruptions, Space Weather is a crucial component into the operational modes of the airlines. Manned space flight operations – humans flying to low-earth orbit and beyond- are an emerging application area. On the Earth's surface, variations in the magnetic field generate two types of problems for energy-related infrastructures: induced currents in electric power grids and corrosion of pipe-lines. Users' demand for knowledge of Space Weather conditions that impact their operations is increasingly more demanding and ubiquitous. By some estimates, each of the aforementioned user areas may experience economic impacts well in excess of 200 million US dollars per year.

In addition, the effect of solar events on the climate of our planet is recognized and requires particular attention in the context of global climate change and its high societal impact. The significance of their contribution to global warming is still uncertain; it is a subject of keen scientific inquiry. However, Space Weather data clearly show that the Sun is not constant in its output. There is evidence of variability of the solar constant and of the quantity of solar energetic particles near Earth as a function of the solar cycle. Both of these parameters increase as the Sun produces more magnetic flux and, as a result, eruptive Space Weather.

2.4 History of Space Weather activities

The recognition of Space Weather had its early beginnings in the 1850s, when an eruption from the Sun was observed to cause a subsequent geomagnetic storm. As technologies developed – telegraph, electric power, deep sea cables – impacts were seen that were consequences of Space Weather.

A first initiative for global coordination was taken in 1928 with the initiation of regular forecasts of radio conditions by the International Union of Radio Science (URSI). Cooperation was enhanced during the International Geophysical Year in 1957-1958 with the establishment of a calendar of "world days" for coordinated observations, and with the setting up of a series of Regional Warning Centres (RWC) and a World Warning Agency. These initiatives were combined in 1962 and, in 1996, they were renamed the International Space Environment Service (ISES).

In the World War II era, as radar was being deployed operationally, an awareness of backscatter and clutter, especially at high latitudes, showed the impact of space weather. Space weather continues to affect modern radars, causing a need for operators to be advised of space weather activity.

More recently, the ambitions of satellite operations and human spaceflight, plus the emergence of satellite navigation and the expansion of commercial airline routes, all played into the burgeoning need for Space Weather services.

2.5 Emerging operational applications

While Space Weather is still an area of active scientific research, the community has reached a stage of overall knowledge and modelling capability that provides firm ground for the development of operational services in response to these emerging needs. The table below lists three general types of space weather events: radio blackouts, radiation storms, and geomagnetic storms. The three columns show the typical transit time for the phenomenon to impact Earth (note that for radio blackouts, the photons travel at the speed of light, so no precursor can transmit the information more rapidly), the current predictive capability and the envisioned improvement with more sophisticated physics-based numerical models.

	Transit Time from the Sun	Current Predictive Capability	Potential for Improvement with Better Models
Radio Blackout	8 minutes *(no forerunner)*	Poor	Fair
Radiation Storm	30 minutes – 1 day	Fair	Good
Geomagnetic Storm	20 hours – 4 days	Good	Good

A number of countries are not only regularly providing reports of recorded Space Weather phenomena but have also initiated the issuance of regular Space Weather forecast bulletins and of specific warnings for acute events. The USA has developed a three-component Space Weather hazard scale (used in the above table) which helps quantifying the severity of the event and providing guidance to the users (Annexes 1, 2 and 3). At a different scale, predictions are also generated for the whole solar cycle (Annex 4).

3 RELEVANCE OF SPACE WEATHER TO WMO ACTIVITY AND MISSION

3.1 Space Weather relevance to the observing function

Space Weather is directly relevant to the observing function, and there is a two-fold relationship between space-based observations and Space Weather: on one hand, meteorological satellites are subject to damages and disturbances caused by Space Weather events, and, on the other hand, because these satellites are exposed to such events, they are well positioned to contribute to Space Weather observations.

3.1.1 Space Weather affecting meteorological satellites

Environmental satellites are now the main source of observations in support of weather forecasting and global climate monitoring. Efforts are made to maintain operational and long-term continuity of operation through in-orbit redundancy and contingency plans. However there remains always a risk of in-orbit failure of a sub-system which can have either a limited impact, if only affecting one instrument, or a catastrophic impact when affecting for instance the main communication system or the power feed.

Space Weather is the primary cause of in-orbit failure, which can be of multiple form:

- Differential charging and discharge, or Single Event Upsets causing temporary anomalies or permanent damage to onboard computers and instrumentation;
- Total Dose effect which causes aging of electronic hardware and progressively decreases solar panel efficiency;
- Expansion of the upper layer of the atmosphere causing increased drag on low-orbiting spacecraft which then require additional manoeuvres;
- Magnetic disturbances on orientation systems;
- Interference on communications.

It is thus essential to monitor and predict hazardous conditions in order to allow putting some subsystems in safe mode, when this is possible, for instance by suspending some operations and shielding the most vulnerable elements.

3.1.2 Existing contribution of meteorological satellites to SW in situ observations

While space environment observations are essential for safe satellite operations, part of these observations are collected aboard the satellite itself. Indeed, Space Weather sensors are regularly included in the payload of environmental satellites and provide "in-situ" measurements of the outer space radiation, magnetic field and particle flow. Annex 5 indicates a list of such space environment sensors flying aboard past, present or future operational meteorological satellites.

3.1.3 Common use of GNSS signals for Space Weather and meteorological observations

Space-based radio-occultation sounders are increasingly used and have the potential to become a major source of data to retrieve vertical profiles of atmospheric temperature and humidity, particularly for the high troposphere and the stratosphere. This technique is based on the alteration of radio signals emitted by Global Navigation Satellite Systems (GNSS) such as the Global Positioning System (GPS) when propagating across atmospheric layers of varying refractive indexes between the source, located on a GNSS spacecraft, and the receiver, located on a meteorological spacecraft. It can be noted that such radio-occultation measurements are not only providing useful sounding data for meteorology and climate, but also measuring the Total Electron Content and the electron density profile.

3.1.4 Ground-based observations

Similarly, ground-based GNSS receivers are measuring the propagation delay of GNSS signals from satellite to ground; hence they allow inferring the total precipitable water, for meteorological purpose, as well as the ionospheric electron density above the receiver, for Space Weather purpose.

Incidentally, Space Weather conditions have an influence on the noise level of radar measurements and they should be taken into account when using the Sun as a calibration target for meteorological radars. Solar flare activity also affects pointing angle calibrations.

3.1.5 Scope for integrating Space Weather and meteorological observation

In the context and logic of the WMO Integration of Global Observing Systems (WIGOS), there is particular scope for considering Space Weather observations in conjunction with meteorological observations, having regard to the possibility of sharing observation platforms, either space-based or ground-based, and given the impact of Space Weather events on meteorological satellites, which are a cornerstone of operational meteorological observations.

3.2 Space Weather relevance to the delivery of meteorological services

Space Weather and meteorological services are two aspects of environmental information that are jointly needed in support of safety and sustainability of several major socio-economic activities.

3.2.1 Aviation

Space Weather alerts, warnings, and watches are being increasingly integrated into the normal operations of commercial airlines. The process was accelerated by the increasingly popular trans-polar routes – primarily northern hemisphere – flown by many carriers. These routes offer the advantage of avoiding prevailing head winds as well as being on the great circle route for many destinations. Primary effects of Space Weather events on such flights are expected in the Communication/Navigation/Surveillance systems, which increasingly rely on space-based global position systems (GPS, Glonass, Galileo). Furthermore, some debate has taken place on potential ill-effects to the health of passengers and crew of trans-polar flights, in particular during pregnancy.

The International Civil Aviation Organization (ICAO) would be the international body with the remit to define requirements for Space Weather warnings to aviation, possibly through relevant amendments to its Annex 3 - Meteorological Service for International Air Navigation.

The relevance of better integrating Space Weather with terrestrial weather information is now under the purview of the International Airways Volcanic Watch Operations Group of ICAO, and, on a regional basis, of the NextGen Air Traffic System project in the United States. Integration is expected to improve efficiency of the end-to-end warning process through relying on established procedures and communication tools, as is already the case for volcanic ash warnings, and contribute to aeronautical safety.

3.2.2 Spacecraft operations

It may be recalled that meteorological support is provided to satellite operators for launch operations and for the optimal exploitation of visible or infrared Earth-observation satellites with respect to cloudiness. Meteorological information is also a key element for the operational planning of manned spacecraft re-entry and landing. Integration of Space Weather warnings could be beneficial since Space Weather similarly affects all phases of spacecraft operations, from launch to on-orbit deployment. Space Weather alerts are used for "go/no go" decisions for launch vehicles with known susceptibilities to single event upsets in non-radiation hardened navigation units. While on-orbit, various procedures regarding computer commands, dumping momentum, and other housekeeping-type activities may be forestalled by inclement Space Weather. Space Weather events are posing recognized threats to astronauts. The graceful integration of Space Weather information with meteorological data would be an advantage for spacecraft operators in their operational planning.

3.2.3 Electricity supply networks

Electric power distribution grids are intertwined and interdependent. Space Weather causes unwanted induced currents to flow within the grid, ultimately causing transformer malfunction in the worst case, and resulting in total blackouts when multiple units fail in quick succession. Procedures to keep power grids resilient and, at the same time, appropriately responsive to the needs of consumers in very hot or very cold weather, is a goal for the electric power industry. This can be compared with the meteorological support currently provided to energy suppliers for the optimal exploitation and sustainability of their network, which encompasses multiple aspects such as medium-range and short-range temperature forecasting for anticipating heating user demand, nowcasting for lighting demand over large cities, or early warning of stormy and icing conditions for maintenance pre-alerts. It is anticipated that integration of Space Weather warnings could serve the overall efficiency of the end-to-end warning process and thus be beneficial to operators and end-users.

3.2.4 Global Navigation Satellite Systems (GNSS)

Space Weather imposes the largest errors for the vast majority of satellite navigation applications. In addition to aviation mentioned above, road traffic management, agriculture, and tourism are but a few examples of GNSS-based services. The expansion of several GPs-like systems will further broaden the customer basis of these services. There are emerging services integrating meteorological information with precise satellite location services, and there is a potential for considerable development of such services in particular for road traffic management, agriculture and tourism which are important customers of meteorological information. It may be appropriate for meteorological service providers to consider the effects of Space Weather on the accuracy and reliability of these location services in order to control the quality of the overall service. The seamless combination of space and terrestrial weather information may benefit to all.

3.2.5 Human health

While air quality is a subject of growing importance for WMO, and includes the issue of UV radiation level warnings, the potential effect of geomagnetic storms on human health might be considered as a logical extension of this activity, if the importance of such an effect is confirmed, still being a matter of investigation. At present, notwithstanding the risk for astronauts and the potential concern for trans-polar aircraft passengers and crew as mentioned above, there is no evidence that Space Weather events have significant impact on human health at the Earth's surface.

3.2.6 Scope for integrated services

The list of applications above is not limitative. These are examples of major activities where the delivery of Space Weather information is potentially very important for the benefit of public safety and economic activity. In each of these areas, meteorological information provided under WMO auspices currently plays, or is expected to play, a major role as well towards the same or similar end-user communities.

It is thus worth evaluating whether a useful synergy could be generated from combining these two types of information in integrated environmental services. There are several paths for such integration:

- Integrating access to information from the user viewpoint (one-stop shop)
- Sharing communication infrastructure from the provider viewpoint (WIS)
- Sharing communication procedures in routine and emergency mode
- Ensuring adequate visibility
- Benefiting of established relation with end-user community

3.3 Space Weather and radio-communications

Space Weather events dramatically affect the quality of radio-communications in certain areas, like severe (meteorological) weather. In some cases Space Weather can blackout radio communications for days at a time. It can thus affect the efficiency of operational meteorological data exchange, as well as the dissemination of meteorological information to remote users (e.g. ships, aircraft). An irony is that Space Weather conditions can also allow enhanced radio communications at times, and thus be taken advantage of for heightened data dissemination and exchange. Space Weather information, together with meteorological information on heavy precipitation for instance, can thus be of key importance to radio-telecommunications operators for optimizing the real-time exploitation of operational telecommunication systems, which can entail decisions such as adapting the power of ground or space-based emitters, activating additional transponders, or modifying the emission pattern of a space-based antenna.

3.4 Scientific and technical cooperation

Space Weather services are increasingly available around the world. ISES, in its affiliation with ICSU, has enabled a sharing of models and research results, but to a limited partner base. A formal inclusion into the WMO would enable a broader visibility for Space Weather activities, inviting the research community to partake in the requisite scientific dialogue for the transition of research to operations.

3.5 Current involvement of NMHS of WMO Members in Space Weather

The maturity of Space Weather forecasts and warnings, combined with the needs of professional user communities, such as airlines, spacecraft operators, power grids, GPS/GNSS has been a driving force leading several countries to placing their Space Weather services with the remit of their NMHS. To-date, this is the case of Australia, China, Finland the Russian Federation and the United States of America. These affiliations offer a prospect for integrating meteorological and Space Weather input together and optimizing the delivery of operational environmental services to users.

4 CURRENT INTERNATIONAL COORDINATION MECHANISMS

4.1 ISES

The mission of the International Space Environment Service (ISES) is to encourage and facilitate near-real-time international monitoring and prediction of the space environment by the rapid exchange of space environment information, standardization of observations and data reduction methodology, uniform publication of observations and statistics. ISES promotes the application of standardized space environment products and services to assist users in reducing the impact of Space Weather on activities of human interest.

ISES is a permanent service of the Federations of Astronomical and Geophysical Data Analysis Services (FAGS) of the International Council for Science (ICSU), under the auspices of the International Union of Radio Science (URSI) in association with the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). ISES was called IUWDS (International URSIgram and World Days Service) until 1996. ISES currently consists of thirteen member nations (Australia, Belgium, Canada, China, Czech Republic, France, India, Japan, Poland, Russian Federation, Sweden, South-Africa and the United States of America) soon to be fourteen with the forthcoming inclusion of Brazil.

ISES Members' Regional Warning Centres (RWC) are the official government forecast centres for Space Weather in the member countries and are linked to government agencies. For example, in Canada the Space Weather forecast operations are combined with the seismic alerting system in the Canadian Hazards Information Service operated by the federal department of Natural Resources. In some other countries, the RWC is linked to the NMHS.

4.2 United Nations

The United Nations Office of Outer Space Affairs, Committee on the Peaceful Uses of Outer Space (UN COPUOS), has initiated activities related to Space Weather, but in a limited sense. Their focus is on harmonization of the satellite navigation systems (GPS, Glonass, Galileo, Compass), and the errors imposed on each of these systems by Space Weather are a prime concern. A global plan for compatibility, interoperability, and error mitigation is the purview of the UNCOPUOS. Another subject under consideration by UN COPUOS is the awareness of the environment in which spacecraft are operating, including Space Weather phenomena and the presence of orbital debris, in order to support diagnosis and handling of spacecraft anomalies. Informal discussions are starting with a view of addressing such issues on the agenda of UN COPUOS as of 2009.

4.3 Regional initiatives

A cooperation framework in Europe was set up from 2002 to 2007 under the aegis of the European Union and named "COST Action 724" to develop the basis for monitoring, modelling and predicting Space Weather. It involved 27 organizations from 23 different European countries with strong participation of the European Space Agency (ESA).

More recently, ESA has proposed international cooperation on "Space Situational Awareness" aiming to exchange information among satellite operators about natural or man-made phenomena affecting the environment of satellites. The possible involvement of WMO in Space Weather was encouraged by ESA in this context.

4.4 Conclusion on coordination mechanisms

The exiting entities or initiatives – ISES, UN COPUOS, ESA – are well-intended and each address part of the Space Weather issues; however, these separate initiatives do not provide a framework for global coordination of the full range of Space Weather services. The transition process from scientific discovery to modelling, product development and ultimately, operational implementation, would benefit from the structure and organizational knowledge available in WMO. The current organizations now providing Space Weather services would each benefit from leadership being provided by WMO. This leadership should however not duplicate the existing initiatives mentioned above but appropriately link with them and leverage their work for the benefit of the global community.

5 POTENTIAL SCOPE OF WMO'S ROLE

WMO could act as a facilitator of international coordination on the following aspects:

5.1 Ensuring comparability of measurements

Space Weather suffers in comparison to terrestrial weather in that the data available for real-time products and services are extremely sparse, although the volume over which Space Weather acts, starting 93 million miles away at the Sun, is very great. There is thus a need to combine observing efforts of the various partners and to ensure efficient sharing of observations. Consequently, it is critical that the measurements that are available be of high quality and in a form that is standardized for all member service providers. Increasingly, the most important measurements are made by satellites, and these platforms must carry the appropriately specified instrument suites that provide the basis from which real-time services can flow, which requires detailed planning, long-term ahead. Harmonizing generic specifications of space-based instruments would improve inter-comparability of measurements and thus increase their usefulness.

5.2 Support to data distribution

The data acquired to support Space Weather services must be palatable to all users globally. A standard agreed upon format is a necessary ingredient. Currently most Space Weather agencies subscribe to the data formats of the ISES. As these data types increase, given the needs of member states, a mechanism to broker the appropriate formats is a requirement.

In light of current developments of the WMO Information System (WIS) and of the striving for interoperability within the WIS and the Global Earth Observation system of Systems (GEOSS) it seems appropriate to consider the WIS as the vehicle for Space Weather data exchange and to ensure that Space Weather data are properly identified in catalogues and described by metadata in accordance with WIS agreed standards, which will be the key for interoperability and wide access.

5.3 Harmonizing service delivery

The nature of Space Weather services is that these shall be applicable to the needs of each specific country in spite of the fact that the impacts are much broader -- similar to the synoptic scale for terrestrial weather. Space Weather effects are global in many ways, i.e., polar airline usage, and the need for harmonization and coordination is clear. Actions taken by member states are, by necessity, often interdependent. The WMO provides a venue and forum for the necessary discussions and debates.

Of particular value would be the adoption of standardized concepts and procedures for the issuance of warnings, as well as for the verification of their accuracy. In light of current progress of the multi-hazard warning approach that is currently supported by WMO, it is anticipated that combining Space Weather warnings with meteorological or other environmental warnings could be beneficial for the visibility of the warning and the reliability of its transmission, i.e. ensuring that it reaches its target in due time.

5.4 Outreach and user interaction

The WMO has a leadership role in working with all users, from the most knowledgeable and professionally specialized, to the general public, ensuring that the information contained in Space Weather products is passed efficiently to the end users. The WMO gives both a legitimacy and trademark to the output of the service providers.

Through its relevant Technical Commissions, it has a mechanism to interact with users, to raise their awareness on the availability of data and services, to monitor the use and impact of the information delivered, and to collect feed-back.

5.5 Relevance to the WMO Expected Results and Programmes

Support to Space Weather was not foreseen in the WMO Strategic Plan but has the potential to contribute to several Expected Results, and in particular to the following:

- E.R. 4: Integration of WMO observing systems
- E.R. 6: Enhanced capabilities of Members in multi-hazard early warning and disaster prevention ad preparedness
- E.R. 7: Enhanced capabilities of Members to provide and use weather, climate and water and environmental applications and services

It would also expand the scope and user basis of the WIS, which is relevant to E.R. 5: Development and implementation of the WMO Information System.

A potential new activity in this field would be primarily related to the WMO Space Programme, with links to other relevant programmes, in particular the Aeronautical Meteorology Programme and the Disaster Risk Reduction Programme.

6 COST AND BENEFIT

6.1 Proposed methodology to evaluate cost and benefit

Analysis of cost and benefit is in the context of the impacts of Space Weather on the end users. Illustrations of benefits for some highly visible and globally significant users are put forward. From these examples, a quantitative measure of the larger benefit can be made with a multiplier based on the frequency of the events and the rate of growth of the individual enterprise.

6.2 Quantitative elements on the socio-economic impact of Space Weather

- Commercial aviation

Polar route usage by commercial airlines has grown markedly in the past ten years. United Airlines flew 12 polar flights in 1999; in 2007, United flew 1,832 polar flights. This rate of increase is typical for the entire industry. NavCanada estimated traffic increasing from 5,308 cross-polar movements in 2006 to 7,291 in 2007, an increase of 37%.

During the October 2003 outbreak of Space Weather, United estimated its cost to be greater than 100,000 US dollars per divergence for every flight that was re-routed due to the increase in radiation to the passengers and aircrew, and the outage of communications. Six flights were rerouted by United Airlines alone. The potential benefit of coordinated and timely Space Weather predictions is to save these costs to the airlines, easily totalling more than two million US dollars per year for one airline. Currently there are ten airlines flying polar routes: United, Continental, Air China, Cathay Pacific, Singapore, Air Canada, Northwest, Thai, American, and Korean. Emirates expects to begin polar flights in late 2008. Asiana, Japan, and All Nippon have expressed their intent to begin polar operations in the near future. Due to geography, most of the polar traffic is in the Northern Hemisphere. However, in the Southern Hemisphere, similar issues apply for Space Weather effects. Qantas has an active Space Weather interest, peaked by their high latitude route between Sydney and Cape Town.

- Geophysical exploration

Hubbert (1956) proposed a model for world oil production. His estimate and others show the time of maximum output to be the years around 2000-2010. Consequently this puts pressure on geophysical exploration to locate new sources of crude oil. Exploration companies rely heavily on GPS/GNSS satellite systems for the precise positioning required for drilling activities. Estimates for the cost of lost work and the necessity to resurvey the area, for small operations, i.e., North Slope of Alaska, are on the order of 10 thousand US dollars a day, to up to more than 100 thousand US dollars a day for large offshore geophysical drilling operations.

- Space operations

Space Weather affects space vehicle launches, on-orbit activities, and for manned spaceflight, sorties outside the protection afforded by their host vehicle. Arianespace estimates that a 48-hour warning of solar radiation storms for their launch operations would save 2.5 million US dollars a year. During the October 2003 Space Weather storms, the NASA Goddard Space Flight Center Space Science Mission Operations Team estimated that 80% of all deep space and near-Earth missions experienced impacts, and that 40% of the missions either turned off or took protective actions to safeguard their instruments. In spite of measures taken as a result of Space Weather forecasts and warnings, some satellites failed. The JAXA ADEOS-2 satellite was lost, at a cost of 70 billion yen, approximately 640 million US dollars. Manned spaceflight flight directors had the International Space Station Expedition 8 crew relocate to the aft portion of the Zvedza Service Module, for protection against harmful radiation during the 2003 storm. The benefits of better, more coordinated Space Weather services could reap a huge economic benefit as well as better protection of the health and safety of humans in space.

- Electrical power grids

Geomagnetic storms are one strong type of Space Weather. Electrical power grids are adversely affected by the unwanted induced current from a rapidly changing – storm driven -- external magnetic field. These effects are most pronounced at high latitudes, and at locations where the underlying geology does not readily allow the induced currents to go to ground. Some incidents where better, more useful Space Weather services would be a benefit are typified by what occurred in 2003. The power grid in the south of Sweden including the city of Malmo, failed, causing 50,000 people to be blacked out for one half hour. Another geomagnetic storm, in March 1989, caused the Hydro-Quebec power grid to unexpectedly fail, leaving 6 million in the dark for 9 hours. Costs associated with these blackouts exceeded 10 million US dollars.

The incidents described above are to give a sense of impacts to a sample of representative users during the more severe Space Weather occurrences in recent times. These extreme events occur on the order of 5-10 times per solar cycle, although geomagnetic storms that impact geophysical exploration and electric power grids occur 10 to 100 times per solar cycle. A solar cycle is, on average, eleven years. Therefore the benefit – in most cases the benefit is the partial savings realized from minimizing the loss – can be estimated by a multiplicative and additive function of the estimates provided earlier in this document. For example, if the cost of a power grid failure is 10 million US dollars and the Space Weather event that could cause this failure occurs 20 times in an eleven-year solar cycle, the potential for savings in this area during a cycle is 200 million US dollars.

Benefits to WMO members would be accrued through the increased visibility and the opportunity for education provided by WMO, allowing affected users to be made aware of these issues and of the availability of high-quality monitoring, forecasting and warning information. Furthermore, through WMO the full science and modelling communities can be brought to bear on the improvement of Space Weather services. Data and products will be improved through quality controlled, standardized collection processes. Through the global communication infrastructure of WMO, those data will be made reliably and quickly available to all governments and interested users.

6.3 Expected cost, resources needed

In the first instance, in light of the current experiences of ISES and of the Space Programme office, it is assumed that significant benefit can already be achieved through a small coordination unit whose primary tasks would be to collect and maintain information, to convene and support harmonization meetings and workshops, to publicize the outcome of these meetings and to monitor the progress in implementing actions and recommendations. It is expected that two persons would provide the critical mass to initiate such activity, if they can rely on the working environment of a larger unit.

In financial terms this would represent expenditure of the order of two millions Swiss francs per four-year period, for two professional salaries with associated operating expenses and travel budget for coordination. Additional amounts would be needed if this coordination unit were requested, for instance, to sponsor international travel of meetings participants.

It is clear that such resources are presently not available within WMO Secretariat budget, and cannot be distracted from meteorological, hydrological and climatological activities that are the core mission of WMO. However, it is envisaged that the expected benefit of improved Space Weather coordination may be attractive enough to justify the secondment of the necessary personnel and the provision of the necessary financial resources by interested organizations, either among providers of Space Weather services, or among major end-users.

The establishment of an Aircraft Meteorological Data Relay (AMDAR) Technical Coordinator within the WMO Secretariat totally funded by the AMDAR Trust Fund is but one example of how a user community has taken advantage of the WMO infrastructure to meet the needs of a user community. Secondments by Space Weather user communities to WMO could be another example to the betterment of WMO Members in meeting their mandates and increasing the visibility and national importance.

6.4 Global nature of benefits

The expansion of the ISES Regional Warning Centres network illustrates how the awareness on, and the importance of Space Weather has been rapidly spreading from the most technologically advanced countries to emerging countries (India, South-Africa, Brazil). This trend is expected to continue further and involve developing countries as they will expand their use of satellite telecommunications. While developing countries are suffering from poor ground-based telecommunication infrastructure, space-based telecommunications may offer the most cost-efficient and rapidly deployable solutions allowing them to bridge the gap to parity with more advanced countries, and to access specific applications such as telemedicine and GNSS-assisted cartography. In this context, Space Weather issues should become increasingly significant for developing countries. Thus, it is anticipated that the benefits of Space Weather will spread to all categories of WMO Members in a near future.

7 CONCLUSIONS

In summary, it is considered that the growing concerns raised by the impact of Space Weather events on major activities, the pressing need for enhanced international coordination, and the direct relevance to some core functions and Expected Results of WMO make the case to consider WMO involvement in this new and challenging field, as suggested by several key players. It is furthermore expected that there is scope for synergy with core activities of WMO through integration of certain activities, namely observation, communication and service delivery, and emergency warnings.

It is noted that no United Nations organization is currently in charge of this domain as a whole although UN COPUOS is considering some aspects of it and ISES has initiated some coordination; appropriate relationships should be established with these organizations addressing Space Weather or neighbouring fields, in order to avoid any duplication and leverage each other's work.

While no resources are presently available to support such an activity within WMO Secretariat, it is anticipated that external resources could be mobilized to initiate coordination activity at a level enabling significant achievements and benefits. Subject to further analysis of the possible tasks, required resources, and partnership opportunities, such activity, if agreed in principle, could be implemented in the context of the Observation and Information Systems Department, more precisely within the Space Programme Office, in close collaboration with the Weather and Disaster Risk Reduction Services Department, in particular the Aeronautical Meteorology Programme Office.

It is suggested to investigate possibilities to initiate such an activity on a pilot mode in the short term if external resources can be made available, and to task the Commission for Basic Systems (CBS) and Commission for Aeronautical Meteorology, in close cooperation with ISES and with the relevant working groups of ICAO such as the International Airways Volcanic Watch Operations Group (IAVWOPS-G), to review the detailed objectives, possible implementation arrangements and timeline for a longer term involvement of WMO in that area for the benefit of the global community.

REFERENCES AND LINKS

Hubbert, K. King, (1956) "Nuclear Energy and the Fossil Fuels" Presented before the Spring Meeting of the Southern District Division of Production, American Petroleum Institute, San Antonio, Texas, March 8, 1956. Publication No. 95. Houston: Shell Development Company, Exploration and Production Research Division, 1956.

International Space Environment Service (ISES) web site, giving access to many relevant web sites: http://www.ises-spaceweather.org/

ACKNOWLEDGEMENTS

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ANNEX 1

NOAA Space Weather Scale for Geomagnetic Storms

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	**Extreme**	**Power systems:** : widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp = 8, including a 9-	100 per cycle (60 days per cycle)

G 3	**Strong**	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** weak power grid fluctuations can occur. **Spacecraft operations:** minor impact on satellite operations possible. **Other systems:** migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp = 5	1700 per cycle (900 days per cycle)

* The K-index used to generate these messages are derived in real-time from the Boulder NOAA Magnetometer. The Boulder K-index, in most cases, approximates the Planetary Kp-index referenced in the NOAA Space Weather Scales. The Planetary Kp-index is not available in real-time.
** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (Tips on Viewing the Aurora)

ANNEX 2

NOAA Space Weather Scale for Solar Radiation Storms

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Solar Radiation Storms			Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
S 5	**Extreme**	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Other systems:** complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	**Severe**	**Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Other systems:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle

S 3	**Strong**	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Other systems:** degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	**Moderate**	**Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** **Satellite operations:** infrequent single-event upsets possible. **Other systems:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	**Minor**	**Biological:** none. **Satellite operations:** none. **Other systems:** minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2}. Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

ANNEX 3

NOAA Space Weather Scale for Radio Blackouts

Category		Effect	Physical measure	Average Frequency (1 cycle=11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	**Extreme**	**HF Radio:** Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2 x 10^{-3})	Less than 1 per cycle
R 4	**Severe**	**HF Radio:** : HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	**Strong**	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	**Moderate**	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5 x 10^{-5})	350 per cycle (300 days per cycle)
R 1	**Minor**	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered. ** Other frequencies may also be affected by these conditions.

ISES SOLAR CYCLE SUNSPOT NUMBER PROGRESSION
Data through 31 March 2008

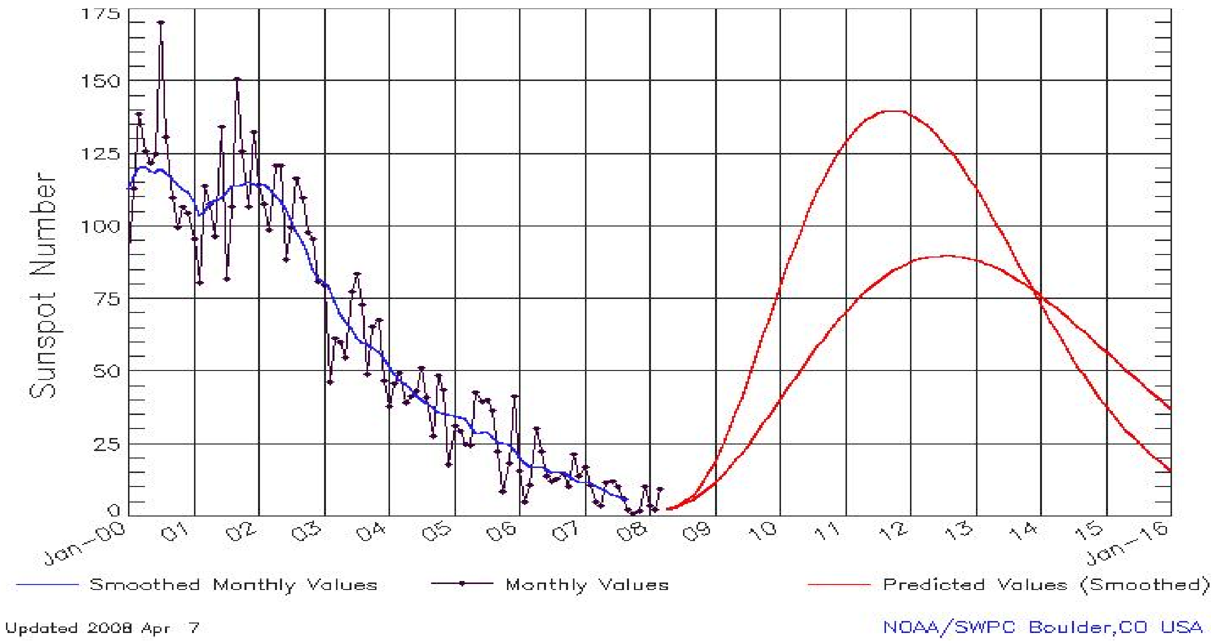

Figure 3. A plot of the just ended Solar Cycle 23, and the two predictions of the coming Solar Cycle 24. Predictions are divided at this point, with dramatically different consequences of one as opposed to the other. The scientific community is struggling with this dilemma as space weather users are asking for guidance as they plan for potential impacts to their systems and operations.

ANNEX 5

SOME SPACE WEATHER INSTRUMENTS ABOARD PAST, PRESENT AND FUTURE SATELLITES OF THE GLOBAL OBSERVING SYSTEM

Agency	Satellite	Sensor	Description
CMA	FY-1	SEM	Space Environment Monitor, for high-energy protons, electrons, heavy particles
	FY-2	SEM	Idem + solar X-ray monitor
	FY-3	SEM	Idem + solar X-ray monitor
	FY-4	SEM	Idem + solar X-ray imager
EUMETSAT	Metop	GRAS	GNSS Receiver Atmospheric Sounder (primarily used for atmospheric sounding)
NASA	UARS	PEM	Particle Environment Monitor
		PEM (AXIS)	X-Ray sensor
		PEM (HEPS)	High-energy particles sensor
		PEM (MEPS)	Medium/Low-energy particles sensor
		PEM (VMAG)	Magnetic field sensor
NOAA	POES	SEM	Space Environment Monitor
		SEM (TED)	Total Energy Detector
		SEM (MEPED)	Medium Energy Proton-Electron Detector
	GOES	SEM	Space Environment Monitor
		SEM (Magnetom.)	Magnetometer
		SEM (EPS)	Energetic Particles Sensor (low-energy)
		SEM (HEPAD)	High-Energy Proton & Alpha Detector
		SEM (XRS)	X-Ray Sensor
		SXI	Solar X-ray Imager (on GOES-12 onwards)
	GOES-R series	SEISS	Space Environment In-Situ Suite
		SUV	Solar UV Imager
		EXIS	Extreme UV and X-ray Irradiance Sensors
NOAA (IPO)	NPOESS	SESS	Auroral characteristics, geomagnetic field, electron density profile, total electron content
		GPSOS	GPS Occultation Sensor *(Now cancelled)*
Roshydromet	Meteor-3M	KGI-4C	High-energy electrons & protons
		MSGI-MKA	Low-energy electrons % protons
	Meteor-M	GGAK-M	Radiation and magnetic sensors
	Elektro-L	GGKAK-E (HMS)	Heliogeophysical Measurements System