ESA Space Weather Programme

Alcatel contract

Space segment - Measurement and system requirements
WP 2200 and 2300 reports

Compiled by
Andrew Coates, Norma Crosby and Bob Bentley

Mullard Space Science Laboratory, University College London

ISSUE 2 – 29 November 2001

Table of Contents

1. INTRODUCTION

Space weather may be defined as the study of the causes and effects of electromagnetic and corpuscular radiation from space on the Earth and on humankind's technological systems. The main source of space weather events is the Sun and there are three principal timescales for effects to reach Earth:

1. Electromagnetic radiation, from the Sun itself and from solar flares, travels at the speed of light, taking just over 8 minutes to reach Earth.
2. Energetic (MeV) protons and electrons are relativistic and arrive within tens of minutes of release from the Sun
3. Disruptions in the solar wind, such as coronal mass ejections and high speed streams, arrive within 2-4 days if directed towards Earth and may have more or less effect on Earth's magnetosphere and humankind's technological assets depending on conditions.

In addition, galactic cosmic rays have a flux which peaks at ~hundreds of MeV per nucleon and the trajectories of these particles are affected by the heliospheric and the terrestrial magnetic fields. These particles can also have damaging effects as primary or secondary cosmic rays.

In this report we provide a brief introduction to the key parameters which must be monitored in a space weather programme and propose a set of instruments and space missions to provide the necessary monitoring.

Global space weather monitoring requires well-defined measurements and system requirements. In this report we identify the physical phenomena, which may pose threats to technological and biological systems, and define the parameters (observed and model-dependent) that are needed to predict these phenomena with the emphasis on space-based instruments. For each phenomenon we examine its importance in the current world-wide space weather field, how they may be observed, the need for space-based measurements, time coverage requirements, any applicable future planned missions (providing relevant observations) and the potential for small instrument development.

Furthermore a proposed strategy for pursuing the investigation of these phenomena will be offered. This includes summarising the necessary space-based instrumentation needed, while also identifying the system requirements necessary for each instrument. As a conclusion we propose a strategy of missions that could be envisaged for a European space weather programme.

In preparing this report we have built particularly on input from team members and from consultants, and in addition from the team reports: WP1100 'Benefits of a space weather programme', WP1300 & WP1400 'Space weather parameters required by the users and synthesis of user requirements', WP2100 'Space weather parameters', WP3120 'Ground-based observations', WP4400 'First Iteration'. The input to this report is a synthesis of the various pieces of information, where our objective is to define the space segment instruments required in detail and to suggest some mission implementations. The team and consortium input covering the physical phenomena and observations required has been placed in the appendix of this report.

Section 2 begins with an introduction to the physical phenomena that we have identified, emphasising their importance for the space weather application and the types of observations that are needed to characterise them. This is followed by Section 3, which introduces the instrumentation needed to perform the observations including system requirements. The final section recommends the types of space weather programmes that we conclude are most appropriate for Europe in the future.

2. PHYSICAL PHENOMENA AND OBSERVATIONS NEEDED

In some cases the science (physics and modelling) may not yet be "mature enough" for actually performing space weather forecasting and there is still work to be done to arrive at such a stage. As stated in *Koskinen and Pulkkinen* (1998), advances in physics understanding are required in various areas, basically on two fronts:

1.) As there are large voids in our knowledge of critical physics phenomena concerning the solar origins of space weather, the details of solar-wind magnetosphere interactions, or the particle acceleration in the magnetosphere, our physical models often give satisfactory answers to average and moderately disturbed conditions and not to the extreme 'space weather events'.

2.) This issue is related to the complexities in mathematical and numerical problems. Better and faster computers will help us in the future, but advances are also required in both mathematical and numerical aspects of space plasma physics.

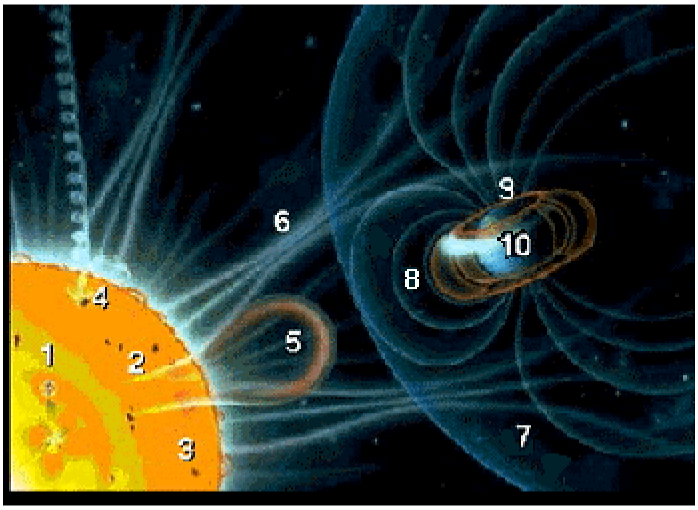
Furthermore plasma physics-based models of the solar-terrestrial systems are approximations to the actual physical environment and what may be sufficient for a magnetospheric physicist may not be precise enough for a operational space weather forecaster. This could be achieved having more experimental data to improve the models.

When monitoring space weather one needs to look at the individual physical phenomena that constitute the global Sun-Earth picture. Figure 1 is a schematic picture of the various parts of our local space environment where these phenomena are located.

As illustrated in Figure 2 the phenomena have a wide range of unwanted effects on both technological and biological systems. In fact particularly since space is relied on heavily in daily life one can say that everybody is in some way directly/indirectly influenced by our local space weather environment. Table 1 lists the physical phenomena that we have identified, partly taking into account information from WP2100 and keeping in mind user input from WP1300 & 1400, and the required observations necessary to describe them.

We have divided the table into five different regions of the space weather arena, respectively: Sun, Interplanetary Medium, Magnetosphere, Ionosphere and Thermosphere. The sub-sections that follow build on these five regions. The identified physical phenomena that we are interested in are placed in their corresponding region. For each physical phenomenon we explain their significance to the space weather application. Thereafter we present the types of observations that are required, so that one is able to obtain the physical parameters that describe the phenomenon.

The instrumentation required to provide the observations of the phenomena are summarised in Table 2. Table 2 lists the required space-based instruments necessary to observe the given space weather inducing phenomena that are defined in this section.



1. Solar Surface
2. Sunspots
3. Prominences
4. Solar Flares
5. Coronal Mass Ejections
6. Solar Wind
7. Magnetosphere
8. Radiation Belts
9. Polar Regions
10. Ionosphere/thermosphere

Figure 1: The Sun-Earth Connection. Image courtesy of NASA.
(http://www.windows.ucar/edu/spweather/spweather_4.html)

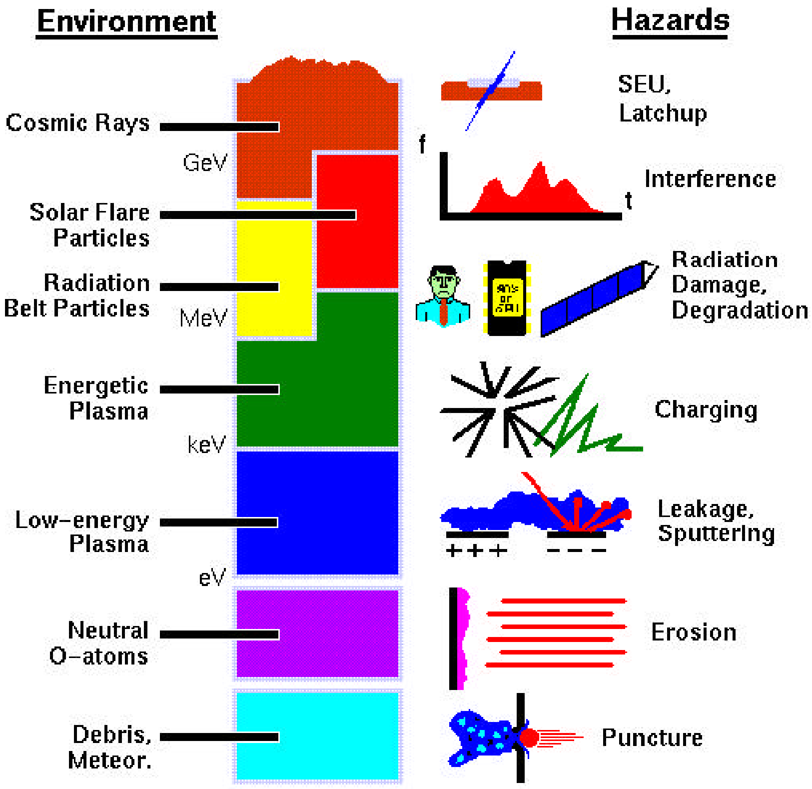


Figure 2: The Space Environment and its Hazardous Effects on Systems.
Image courtesy of ESA/ESTEC/TOS-EMA.
(http://www.estec.esa.nl/wmwww/wma/backgnd.html)

Table 1: Physical Phenomena, Required Observations and Users

	Phenomenon	**Observable**	**Users**
Sun	CME (prediction)	Solar magnetic fields Soft X-ray and H-a ? imaging	Satellite operators
	CME (onset and velocity)	EUV, soft X-ray and H-a imaging Visible light coronal imaging Radio (MHz-GHz imaging, ground-based) Particle and solar-wind parameters	Satellite operators
	Proton Flares	Soft X-ray flux and radio fluxes Particle fluxes Soft X-ray and EUV images Magnetic fields	Satellite operators, launchers humans in space, research
	Coronal Holes	X-ray and EUV images, radio	Spacecraft operators
	Solar constant	Flux intensity over wide-band	Climate - Humans on Earth
	CME with no coronal proxies	Radio (IPS and radio bursts) Particle and solar-wind parameters Hα, EUV	Satellite operators
Inter-planetary Medium	Solar wind parameters and disturbances	Solar wind particles (pressure, velocity) and magnetic field (mainly N-S component)s	Satellite operators, defence, power grids and pipelines
	Galactic and solar cosmic rays	Energetic particle spectrum	Civil aviation, human is space, research
	Irregularities in the electron density	In-situ electron measurements Thomson diffusion in white light	Storm predictions – Satellite operators
	Suprathermal electron beams and shock waves	In-situ electron measurements Radio emission (ground based)	Storm predictions – Satellite operators
	Large scale structure	Velocity and density projected on the sky (interplanetary scintillation, ground-based)	Satellite operators (GPS)
	Primary and secondary galactic cosmic rays	Flux and energy spectrum (Satellite, neutron monitor, air shower)	Aviation

Table 1 continued on next page

Table 1: Physical Phenomena, Required Observations and Users Cont.

	Phenomena		Observable	Users
Magneto-sphere	Particle and field conditions within the magnetosphere including configuration, substorms, particle acceleration		Particle flux (E = 100 MeV) Spectra of magnetospheric plasma (e^-, H^+; E = 100 keV) VLF waves Electric field Remote sensing (UV and ENA) Magnetic field and indices (ground based)	Satellite operators, defence, research and launch operators, power grids, pipelines
	Radiation belt conditions		Energetic particles	Satellite operators, defence, research and launch operators
Ionosphere	Auroral particle precipitatio		Spectra of auroral precipitations (e^-, H^+; E = 100 keV)	Satellite operators, defence, research
	Images of auroral ovals		UV, visible	Research, outreach
	Convection electric field		Electric field (from in-situ and ground based techniques)	Defence, research, telecommunications, power grids, pipelines
	Electron density	Variation with altitude	Electron density (in-situ a ground-based radars)	Defence, research, civil aviation
		TEC, foF2 and hmF2	TEC (GPS, ionosondes))	Defence, research, civil avaiation
Thermo-sphere	Neutral wind		Wind speed, density, temperature (interferometry, accelerometry)	Satellite operators, launch, defence
	Neutral density		Spectrometry	Satellite operators, research
	Neutral temperature		Interferometry	Satellite operators, research
Debris	Location of debris, interplanetary dust		In situ (hitchhikers) and ground based radars	Satellite operators, research

Table 1: Physical Phenomena and Required Observations

2.1 Sun

Until recently (e.g. Gosling, 1993) it was generally thought that solar flares were the most geo-effective solar phenomena. Today coronal mass ejections (CMEs) are considered the prime triggers for space weather hazards rather that flares. Below we will present different aspects in regard to CMEs: CME prediction, CME onset and velocity, and CME events which have few coronal proxies. Other areas of interest concerning regions of the Sun that have been identified include flares (without and without protons), coronal holes, the solar constant and the solar magnetic field. Each point is summarised below emphasising which physical property of the phenomenon one is interested in for space weather prediction and hence which parameter one wants observations for.

<u>CME Prediction</u> :

Solar magnetic field maps from both ground and space are used to determine the complexity of the magnetic topology, and the presence of large scale magnetic stresses greatly increases the probability of CME events. A future goal is to develop a diagnostic model to define the helicity threshold at which the structure is likely to disrupt.

Soft X-ray images are used with the magnetic maps as inputs to the magnetic field modelling, and are also used to provide proxies that warn of coronal field structures that might erupt. Such proxies include: field structures which overlay the neutral line in active regions, and quiet solar regions containing filaments; extended trans-equatorial loop structures that provide a diagnostic of the topologies that may result in large scale CMEs. The combined information from Soft X-ray images and magnetic maps will provide input to interplanetary CME propagation models that predict the orientation of the embedded magnetic field in the cloud as it interacts with the Earth's magnetosphere.

Shorter-term forecasts can be made from multiple wavelength Ha images. Several hours before a filament erupts, signatures appear in the velocity field as deduced from the spectral characteristics of the Ha line.

<u>CME onset</u> :

If the CME is flare related, sudden brightenings in soft X-ray, EUV and H-a are shortly followed by dimmings in the EUV (and occasionally soft X-rays) and shockwaves propagating across the disc in EUV, H-a and with radio signature.

If the CME involves an erupting filament, the onset is observed as rapid changes in the radial velocity in H-a. The structure also disappears from cooler lines and appears in hotter wavelengths as it is heated.

Just before a CME onset, structures observed in soft X-rays undergo structural changes. Magnetic reconnection forms larger loops which expand outward.

As a CME propagates outwards from the surface, it is seen in visible light (due to Thomson scattering) and its plane-of-sky velocity, density and structure can be determined.

When a CME is directed towards the Earth (or conversely, directly away from the Earth), it looks roughly like a "halo" surrounding the Sun. The Earth-directed "halo CMEs" then are those CMEs which are more likely to impact the Earth than those which are shot out at right angles to the Earth-Sun line. The Stereo mission will help in the understanding of the onset, structure and evolution of CMEs.

Radio bursts trace the destabilization of large scale magnetic structures and imaging at frequencies up to hundreds of MHz can show the outward motion of the CME.

CMEs (no coronal signatures) :

While a significant fraction of CMEs have a very clear interplanetary signature in the form of organised magnetic clouds, it is often the case that little or no emission has been seen in the Sun's atmosphere at the onset time of these events. It could be that there is emission that is not seen because of a lack of instrument sensitivity, or that the coronal signatures are not yet identified for these events. But, currently no warning is given of their possible arrival.

Proton Flares or solar proton events (SPEs):

At time of solar maximum, the number of flares observed increase dramatically. A subset of these, the most intense, produce relativistic particles which arrive at the Earth at timescales ranging from tens of minutes to a few hours after flare onset. These are hazardous to humans in aircraft or in manned spacecraft and to electrical equipment. The exact circumstances under which proton flares may occur are not clear, but it is important to try to recognize the structures that may produce such events.

The onset of flares in soft X-ray flux is concurrent with the increase in particle flux, but improved modelling based on imaging in soft X-rays and the EUV, and magnetic mapping will enable the forecaster to identify which active regions have the potential to produce proton flares, and when the likelihood of such flares is increasing.

From HXRBS on SMM, it has been suggested (Kiplinger, 1995) that the spectral index of the hard X-ray emission appears to harden during flare onset when the subsequent flare is a proton event. There are also some reports that in radio the ratio of 3cm to 8cm changes. These signatures are currently being investigated.

Less energetic proton emission occurs from large coronal post-flare structures that form after very large flares. The emission can last for tens of hours or even days. Although less hazardous to humans, they still present problems to spacecraft.

Coronal Holes :

Coronal holes are the source of the fast solar wind. The interaction between the slow and fast solar wind from low latitude and equatorial coronal holes leads to shock formation in the region of the ecliptic plane. Coronal holes are easily seen in images in soft X-rays and hotter lines at EUV wavelengths. Active regions which appear close to coronal holes are found to be more CME active, and tracing the location of the coronal holes may help the forecasting of CME events. These affect the upstream solar wind conditions at the Earth.

Solar Constant :

Long-term changes in the total solar irradiance occur over the solar cycle, and are also modulated on even longer timescales. This information has important implications for long-term changes in the terrestrial climate although it is not of immediate concern in a space weather programme.

Solar magnetic field

Recent results have highlighted the importance of long term variations in the solar magnetic field. The average field has increased over the last century or so. This has an effect on the heliosphere and on the numbers of cosmic ray particles reaching the Earth, which may in turn have an effect on cloud nucleation and climate. It is important therefore for a space weather programme to monitor this parameter.

2.1.1 Key phenomena, parameters and research issues

Key space weather related phenomena may be summarised as follows :

- CME onset
- CME propagation
- CME (few coronal proxies)
- Flares
- Flares with protons
- Coronal holes

Key parameters on the Sun for space weather are:

- Solar magnetic field as a proxy for solar activity (onset of flares and CMEs, quiet periods)
- EUV/UV spectral flux
- CME lift-off time and velocity to determine their arrival time at Earth
- Solar energetic particle flux
- H-α, EUV/UV and X-ray imaging (for forecasting CMEs, flares, proton events)
- Radio signatures of shocks in the corona and interplanetary medium

Major research issues are:

- Understand the initiation process of CMEs
- Predict CME lift-off time, speed and orientation
- Predict CME geoeffectiveness using CME initial conditions and ambient solar wind conditions
- Understand the initiation process of solar flares
- Predict solar flare onset time
- Predict geoeffectiveness of high speed solar wind streams

2.2 Interplanetary Medium

Solar Wind :

As the hot solar corona is not gravitationally bounded to the Sun, there is a flux of ionised matter that escapes continuously from the Sun. This solar wind consists largely of ionised hydrogen, contains a weak magnetic field frozen into the flow and is significantly influenced by solar activity. It has been well demonstrated by the ULYSSES spacecraft that two regimes of the solar wind exist (high speed and slow speed), at least at solar minimum. The slow wind (300 km/s) tends to be confined to a limited region with about 25^o North and South of the equator, while the high speed wind (700 km/s) comes from polar coronal holes. The flow is radial but on average the magnetic field shows a spiral pattern due to solar rotation. The interaction of high speed and slow speed solar winds leads to 3-D corotating interactive regions (CIRs) that have been detected in the outer heliosphere. In CIRs, the plasma and magnetic field are compressed, the plasma is heated up and pressure waves are produced. These pressure waves enhance the acceleration of the slow plasma ahead and the decelerating of the fast plasma behind. Due to enhanced field strength and rising wind speed within the compression region CIRs can cause geomagnetic storms. These are particularly intense if there is a component of the interplanetary field opposite to Earth's, i.e. southward, since reconnection enhances the coupling between the solar wind and the magnetosphere.

Upstream solar wind conditions are some of the most crucial parameters needed for a space weather programme. Solar wind parameters (velocity, density and temperature) and the interplanetary magnetic field, control both the shape of the magnetosphere and determine the details of the entire interaction. These are probably the most frequently used parameters in space weather forecasting and are currently being measured by the spacecraft ACE at L1 and, when orbital positions permit, from the spacecraft WIND nearer to the Earth. Missions to succeed ACE should be planned urgently.

Interplanetary Magnetic Clouds :

Interplanetary magnetic clouds are large magnetic flux ropes (> 0.2 AU wide), and are the interplanetary manifestation of CMEs. They can be easily observed by spacecraft such as ACE. As the cloud passes a monitoring point, the leading and trailing boundaries show a sudden change in plasma density and velocity. The cloud magnetic field usually shows a dramatic change in intensity and direction from the solar wind field, the degree of change depending on the orientation and intensity of the field within the cloud. The direction of motion of the cloud with respect to the radial vector to the Sun can also be important – space weather effects are less pronounced for clouds that are moving at an angle to the Sun-Earth line. One of the characteristics of CME magnetic clouds is that they include long durations of steady magnetic field orientations. If this direction is Southward, the solar wind connection to the Earth's magnetosphere is enhanced by reconnection. If in addition the solar wind velocity is high, which is frequently the case, the potential exists for significant particle injection and acceleration within the magnetosphere.

Interplanetary Shock :

Shock waves are formed if the speed of the faster plasma is higher than the characteristic wave speed in the surrounding plasma. They are particularly common at CMEs and CIRs. For example, at a CIR, at the leading edge a forward shock enhances the pressure, density and reduces the plasma velocity whereas at the trailing edge a reverse shock leads to a decrease of pressure, density and an increase of plasma velocity in the spacecraft frame. Changes in the magnetic field are also observed, but these depend on the precise details of the shock.

Fast CMEs produce interplanetary (IP) shocks which can cause sudden storm commencements on the Earth. The CME-related shocks also accelerate the solar energetic particles associated with major IP disturbances and with the consequent radiation hazards at Earth.

Cosmic Rays and Solar Energetic Particles :

There are two families of cosmic rays, known as galactic cosmic rays (GCRs) and anomalous cosmic rays (ACRs). In addition solar energetic particles (SEPs) and radiation belt particles may reach the lower atmosphere.

GCRs originate far outside our solar system and are the most typical cosmic rays. The present consensus is that Fermi acceleration by supernova shock-wave remnants is responsible for the production of cosmic rays in our galaxy and that subsequently they propagate in the galactic magnetic field. Their flux at the top of the Earth’s atmosphere is modulated by solar activity, by the structure of the solar wind magnetic field and (in polar regions) by the solar wind effects on the geomagnetic field. Minimum flux occurs at solar maximum as enhanced solar wind magnetic field shields the solar system from these particles.

ACRs are thought to originate as neutral interstellar gas that drifts into the heliosphere, whereafter it gets ionised by solar UV radiation. It is thereafter picked up by the solar wind and convected back to the outer heliosphere and is accelerated (e.g. by the solar wind termination shock). They then diffuse and drift into the heliosphere as cosmic rays.

SEPs were mentioned in Section 2.1. These are highly variable with time and latitude occurring more frequently near to solar maximum and it is easier for particles to penetrate at higher latitudes.

Radiation belt particles also reach the upper atmosphere at the polar horn regions and in the South Atlantic Anomaly (SAA).

This energetic particle environment is important for satellites as it may cause single event effects which are malfunctions in components such as random access memories, microprocessors, etc.. Also astronauts must be aware of these particles as they can knock electrons free from molecules that make up a cell. This disrupts the normal functioning of the cell. Furthermore secondary cosmic rays may have similar effects (technological and biological) on aviation. Onboard aircraft measurements are being conducted on European airlines during flight.

There is a need for better measurements and more coverage.

Heliocentric Potential :

The heliocentric potential (sometimes called modulation parameter) characterises, in units of MV, the variation with the solar cycle of cosmic ray intensity travelling arriving at the Earth's environment. It is deduced from measurements by neutron monitors of the secondary cosmic rays that reach the ground.

2.2.1 Key phenomena, parameters and research issues

Key space weather related phenomena may be summarised as follows :

- Corotating Interacting Regions (CIRs)
- Shocks
- Magnetic clouds
- Upstream plasma conditions
- Cosmic Ray Particles

Key parameters on the interplanetary medium for space weather are:

- Topology of the interplanetary magnetic field, in particular its north-south component, which controls the energy input of the solar wind into the magnetosphere
- Solar wind velocity which drives instabilities, and therefore particle acceleration, in the magnetosphere
- Solar wind dynamic pressure, which determines the pressure on the magnetospheric system and therefore the magnetopause position
- Solar and galactic energetic particle flux prior to interaction with magnetosphere
- Radio signatures of shocks in the corona and in the interplanetary medium

Major research issues are:

- Understanding the solar wind acceleration and heating process
- Predicting the solar wind conditions at Earth (north-south component of field, pressure)
- Relationship between CMEs and interplanetary CMEs (ICMEs).
- Understanding the evolution of plasma structures through the interplanetary medium

2.3 Magnetosphere

The existence of Earth's magnetic field is very important as it protects us from the solar wind and solar energetic- and cosmic ray- particles, though some of these particles can enter at high latitudes depending on their energy (rigidity). The pressure of the solar wind and the magnetic field it carries along modify the form of the Earth's magnetic field radically, by pushing it in on the dayside and creating a long tail (magnetotail) on the nightside.

The magnetopause is the boundary between the terrestrial and solar magnetic field and reconnection may occur at this boundary and in the tail. This process not only accelerates particles but also allows solar wind and magnetospheric field lines to be joined, allowing plasma from outside to leak in and vice versa. As the Earth is effectively a magnet in a moving plasma a cross-tail electric field is produced which drives magnetospheric convection. Nearer to the Earth the cold dense plasmasphere co-rotates with the Earth's atmosphere. The particle environment of the spacecraft is critically dependent on its position within the magnetosphere. Hot plasma and auroral electron beams may cause spacecraft charging while energetic particles may cause dielectric charging. In addition the Earth's magnetosphere affects the propagation of galactic and solar cosmic rays and radiation belt particles all of which may produce single-event-upsets in spacecraft electronics.

The radiation belts consist of high-energy electrons and ions formed by particle acceleration within the magnetosphere and by trapped cosmic rays. These spiral around the field, bounce between hemispheres along magnetic field lines and drift around the Earth at high altitudes. They are trapped in two main doughnut shaped zones – the Van Allen belts – Radiation belts. The inner belt is centred around 1.5 R_E and consists of a fairly stable population of protons (several 100 MeV). A well-known feature of the inner belt is the South Atlantic Anomaly where particles from the belts may strike the atmosphere due to the shift and tilt of the Earth's magnetic field dipole axis with respect to the Earth's rotation axis. The outer belt is centered around 4.0 R_E and is more dynamic than the inner belt on short-time scales. It consists mainly of energetic electrons (few MeV).

Post analysis of these regions requires monitoring. The prediction of the states of these environments requires modelling and also extrapolation of data for missing datapoints.

The ELF/VLF wave fields observed near the equator, in the radiation belts, control the precipitation of trapped particles. There is a need for better measurements for the determination of ELF/VLF wave models. Presently ELF/VLF wave data does not seem to enter as a standard input into the models used by the services to produce space weather data. Wave measurements also provide important information at magnetospheric boundaries.

Magnetospheric modelling is discussed in the WP2100 report.

Magnetic Fields (& Indices) :

The Earth's magnetic field is mainly described from measurements made at ground-based geomagnetic observatories and satellites in polar orbit. Higher altitude satellites are used to determine the highly variable magnetic field which departs significantly from dipolar form beyond a few Earth radii. The available data are used to derive models of the main magnetic field and of its secular variation close to the Earth.

Variations with time and space of the geomagnetic activity are described from recordings made at the geomagnetic observatories, and at networks of magnetic stations. Different magnetic indices (Kp, Ap, Dst, AE) are produced, with different time resolutions. They characterise different aspects of magnetic perturbation (magnetospheric compression, ring current particle injection, auroral particle precipitation and ionospheric currents).

2.3.1 Key phenomena, parameters and research issues

Key space weather related phenomena may be summarised as follows :

- Geomagnetic storms
- Substorms
- Radiation belt enhancements
- Enhanced low energy plasma
- Ring current changes

Key parameters on the magnetosphere for space weather are:

- Low energy (eV-keV) particle fluxes which determine spacecraft charging
- High energy (keV-MeV) particle fluxes (vs time and space) which may cause deep dielectric charging
- Magnetic field which determines particle trajectories

- Electromagnetic wave spectrum, which affects velocity space diffusion of the radiation belt particles
- Boundaries

Major research issues are:

- Understand coupling of the solar wind with the magnetosphere and the transport of particles
- Predict onset of substorms
- Understand the dynamics, acceleration and loss processes for radiation belt particles
- Predict radiation belt fluxes during storm and quiet times
- Understand coupling to the ionosphere

2.4 Ionosphere

The ionosphere is part of the upper atmosphere where the charged particle density becomes appreciable. The region starts at about 50 km altitude where free electrons occur in sufficiently density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. Solar X-rays and ultraviolet radiation and corpuscular radiation produce the major part of the ionisation. Particle precipitation from above causes excitation in the neutral and ionised species in this region, causing the aurora. The convection pattern in the magnetosphere also has its magnetic footprint in the auroral region, causing electric field convection patterns in this region.

Radio waves are broadcast in a number of bands, which each contain a range of frequencies and have different ways of travelling from point to point through the earth’s atmosphere. Because of the different paths that radio waves take through the ionosphere, each band is affected differently by space weather storms. Radio waves that reach the ionosphere may penetrate the ionospheric layer, be absorbed by the layer, be scattered in random directions by irregularities in the layer, or be reflected normally by the layer.

Navigation systems rely on latitude, longitude and altitude information in real-time, and basically two groups of navigation systems exist: terrestrial-based (Loran-C Radio Wave System and Omega System) and space-based (Global Positioning System). Both groups use radio wave propagation, which is affected by changes in ionospheric density (refraction), in the collision frequency (absorption) or by ionospheric irregularities (scintillation).

2.4.1 Key phenomena, parameters and research issues

Key space weather related phenomena may be summarised as follows:

- Ionospheric density changes
- Auroral oval shape & dynamics
- Convection electric field pattern
- Auroral precipitation

Key parameters for space weather are:

- Electron density variation with time, altitude, longitude and latitude
- Electric field

Major research issues are:

- Understand ionospheric response to geomagnetic storma and substorms

- Forecast the variability

2.5 Thermosphere

The thermosphere is a region above about 90 km in the Earth’s atmosphere where the neutral temperature increases with height. The thermosphere is affected directly by geomagnetic activity through the ionosphere, while the Sun directly affects it through UV and EUV global radiation. Both effects may cause significant variations in the neutral density, temperature, wind and composition. Following periods of enhanced magnetic activity, density increases lasting for days are observed. These variations have several consequences including increased drag on satellites, increased reentry of space debris and uncertainty in prediction of meteorite impacts.

The future TIMED (Thermosphere, Ionosphere and Mesosphere, Energetics and Dynamics) spacecraft will be the first mission to conduct a comprehensive global study of the Mesosphere and Lower Thermosphere/Ionosphere (MLTI) region. TIMED will help us gain a better understanding of the dynamics of this gateway region and its effects on communications, satellite tracking, spacecraft lifetimes, degradation of spacecraft materials and spacecraft reentering Earth’s atmosphere (http://tidi.engin.umich.edu).

2.5.1 Key phenomena, parameters and research issues

Key space weather related phenomena may be summarised as follows :

- Neutral atmosphere density changes (drag)

Key parameters for space weather are:

- Neutral gas density profile with altitude
- Neutral wind velocities

Major research issues are:

- Understand changes in neutral parameters, and effects of solar and magnetic activity
- Improve empirical models used in orbit analysis
- Forecast neutral density profiles

2.6 Space weather programme instrument requirements

In each region above we identified key parameters (see also WP 2100 and 4400) and we discussed the space weather phenomena which are important. In this section we summarise the key parameters in each region and the important phenomena. We use these to define a set of space instrumentation necessary to monitor the parameters (Table 2A) and phenomena (Table 2) in the top-down approach. Section 3 discusses the specific capabilities of the instrumentation.

Table 2A: Required space based instruments for monitoring key parameters

	Key parameters	Instruments (see Table 3)
Solar	Solar magnetic field	3
	EUV/UV spectral flux	1,2,6,8
	CME lift-off time and velocity	1,2,4,5
	Solar energetic particle flux	9
	X-ray, Hα, EUV, UV imaging	1,2,5
	Radio signatures of shocks	7
Interplanetary	IMF topology	13
	Solar wind velocity	10 or 11
	Solar wind dynamic pressure	10 or 11
	Energetic particle flux	9
	Radio signatures of shocks	7
Magnetosphere	eV-keV particles	11
	keV-MeV particles	12
	Magnetic field	13
	Electromagnetic wave spectrum	15
	Boundaries	11,13,14,15
Thermosphere	Neutral gas density profile with altitude	20,21
	Neutral wind velocities	19
Ionosphere	Electron density	18,17,25,24
	Electric field	16
	Convection electric field	16
	Auroral precipitation	18,22,23

Table 2: Required space-based instruments necessary to observe a given space weather inducing phenomenon

	Instrument	CME onset	CME propagation	CME (few coronal proxies)	Flares	Flares with protons	Coronal holes	Corotating Interacting Regions (CIRs)	Shocks	Magnetic clouds	Upstream plasma conditions	Geomagnetic storms	Substorms	Cosmic Ray Particles	Radiation belt enhancements	Enhanced low energy plasma	Ring current changes	Ionospheric density changes	Neutral atmosphere density changes (drag)	Auroral oval shape & dynamics	Convection pattern
1	Soft X-ray imager *	X	X		X	X	X			X											
2	EUV imager *	X	X		X	X	X			X											
3	Magnetograph *	X	X		X	X	X				X										
4	Coronagraph *		X							X											
5	H-α imager	X		X	X	X															
6	Soft X-ray & UV flux monitor *				X	X												X	X		
7	Radio spectrograph – a. High freq.		X	X	X	X		X	X	X											
	b. Low freq		X	X					X												
8	EUV spectrograph																	X	X		
9	Solar & galactic radiation monitor *					X								X							
10	Solar Wind monitor *		X	X			X	X	X	X	X	X	X		X						
11	Thermal plasma monitor *		X	X			X	X		X	X	X	X		X	X	X				
12	Mid energy particle monitor *		X	X						X		X	X		X		X				
13	Magnetometer *		X	X			X			X	X	X	X				X				
14	Waves – a. Magnetic								X			X	X		X						
	b. Electric								X												
15	Neutral particle imager												X				X				
16	E field antennae																	X			X
17	Sounder																	X			
18	Low energy plasma monitor															X		X			
19	Interferometer																		X		
20	Spectrometer																	X	X		
21	Accelerometer																		X		
22	UV imager																			X	
23	Visible imager																			X	
24	GPS receiver																		X		
25	Topside sounder																	X			

N.B.: The instruments marked with a (*) provide fundamental parameters which are used in space weather forecasting or monitoring at present. The other instruments are at present used for research but may ultimately be used operationally.

3. INSTRUMENTATION

This section describes in detail the instrumentation that we identified in Tables 2 and 2A. Section 3.1 gives an introduction to the space-based instruments. A brief summary to the Earth-based instruments is given in Section 3.2 and we refer to WP 3120 for more information about these ground-based instruments.

Table 3: Required instruments and their corresponding technical characteristics

	Instrument	**Platform**	**Description**
1	Soft X-ray imager *	Solar	Broad band, full Sun, 5” pixels, 1 minute, pair of filters
2	EUV imager *	Solar	Narrow band EUV (195 and 304 Å) , full Sun, 5” pixels, 2.5 min.
3	Magnetograph *	Solar	Full Sun, 2” pixels, 15 min. (average several images onboard)
4	Coronagraph *	Solar	1.5-30 Solar radii, 1024x1024 pixel CCD, 10 min. Two coronagraphs (inner and outer)
5	H-α imager	Solar	Selectable narrow bands around H-α line +/- 2 Å centre, full Sun, 2” pixels, 30 second
6	Soft X-ray & UV flux monitor *	Solar	Wide band flux monitors (SXR GOES-like), 1 minute
7	Radio spectrograph	Solar	a. 10 MHz-400 MHz (new development) b: 30 kHz-10 MHz (Wind heritage)
8	EUV spectrograph	Solar	Absolute EUV flux (full disc)
9	Solar and galactic radiation monitor *	Upstream	2-100 MeV ions, 2-20 MeV electrons, ≥500 MeV particles, 1 minute
10	Solar Wind monitor*	Upstream	Solar wind velocity and density, 1 minute
11	Thermal plasma monitor *	Upstream Magnetospheric	0-40 keV ions and electrons, 45° cone in solar wind, 4π in magnetosphere, 5° resolution upstream (ions), 45° elsewhere, 1 minute
12	Mid energy particle monitor *	Upstream Magnetospheric	40keV-2MeV ions and electrons, 4π, 45° resolution, 1 minute
13	Magnetometer *	Upstream Magnetospheric Ionospheric	0-±64, 0-±256 nT, 0-±65536 nT, 1 minute
14	Waves	Magnetospheric	a. 1 Hz-10 kHz, 3 magnetic antennae b. 1 Hz-100 kHz 1 electric antenna
15	Neutral particle imager	Magnetospheric	ENA
16	E field antennae	Ionospheric	3 orthogonal pairs if possible
17	Sounder	Ionospheric Magnetospheric	Excitation of plasma frequency
18	Low energy plasma monitor	Ionospheric	0-40 keV ions and electrons Langmuir probe and drift meter
19	Interferometer	Ionospheric	Fabry Perot
20	Mass spectrometer	Ionospheric	Ion mass and neutral atom
21	Accelerometer	Ionospheric	Drag and solar radiation pressure
22	UV imager	Magnetospheric Ionospheric	130-190 nm
23	Visible imager	Magnetospheric Ionospheric	Visible
24	GPS receiver	Ionosphere/thermosphere	Orbit position, TEC, tomography
25	Topside sounder	Ionosphere	Ionospheric density profile

3.1 Spaced-based Instrumentation

This sub-section deals with the instrumentation suggested for the space segment of a space weather programme. Table 3 lists the required instruments with their technical characteristics. A detailed technical description for each of the instruments follows. The instruments marked with a (*) provide fundamental parameters which are used in space weather forecasting or monitoring at present. The other instruments are at present used for research but may ultimately be used operationally for space weather purposes.

First we compare the capabilities of the proposed solar instruments with those on SOHO.

Table 3A: Comparison of proposed solar instruments with SOHO

Instrument	Comments
SXR Imager	No X-ray instruments on SOHO; Similar to design of GOES-SXI
EUV Imager	Similar design to SOHO-EIT; half spatial resolution, higher cadence, fewer channels
Coronagraph	Similar to SOHO-LASCO; comparable spatial and temporal resolutions
Magnetograph	Line-of-sight magnetograph: very similar to SOHO-MDI; higher cadence Vector magnetograph: never flown before, similar to one planned for the LWS SDO mission
H-Alpha Imager	Not flow previously

3.1.1 Soft X-ray Imager

A full-Sun imager needs to cover a field of view of at least 40’ by 40’. With a pixel size of ~5” this implies an image of 480 by 480 pixels. The most conveniently sized CCD is 512 x 512 pixels; if this was used in its entirety the field of view would be slightly larger and this would imply ~262K pixels per image. For a single image per minute, a standard 512 x 512 pixel image would require telemetry of 33 kbps (4.4 KB/s), assuming a 12-bit pixel is compressed to 8-bits, but without further compression.

Assuming that broad-band images are taken with a maximum of 2 different filters each minute, the bandwidth required for the SXR imager is 70 kbps, allowing some overhead. If more filters are needed, an option would be to repeat one of the wavelengths every minute, and alternate between the other wavelengths – this would keep the same telemetry requirements. Compressions could substantially reduce this, but we express the telemetry requirement without compression for the moment until the extent of the need for compression is known.

The soft X-ray imager is similar to the Yohkoh SXT instrument, but with a smaller selection of filters and nominally without the flare response capabilities of that instrument. The cadence suggested for the images is similar to that specified for the SXI instrument that will be flown on future GOES missions.

3.1.2 EUV Imager

Using the same argument regarding CCDs sizes as was discussed for the SXR imager, each EUV image would represent 35 kbps of telemetry. Assuming a maximum of narrow-band images at 2 wavelengths per 2.5 minutes, this amounts to 28 kbps.

The EUV imager is similar in specification to the SoHO EIT instrument, but with a smaller number of pixels and fewer filters; TRACE covers similar wavelengths but at a spatial resolution much higher than what is needed for space weather purposes. The minimum image cadence is determined by the need to monitor the waves observed to propagate across the solar surface after certain types of coronal events. Waves observed in the EUV to date have had velocities up to 300 km/s – any waves with velocities significantly greater than this could not be observed by EIT because its cadence is too low. To allow the EUV imager to monitor waves with higher velocities, and observe other features with short durations, we suggest a cadence of an image every 2.5 minutes (>4 times that of EIT), or perhaps greater.

3.1.3 Magnetograph

Because of the dominant role of magnetic fields in solar activity, their measurement plays an extremely important role. Magnetograms are made from measurements of a spectral line affected by Zeeman splitting. To construct an image of the photospheric magnetic field, a pair of polarised images is therefore needed. These can be processed and combined onboard, and can also be averaged over several minutes to improve statistics. With a spatial resolution similar to MDI FD mode (4", using 2" pixels), and a cadence of 15 minutes, this produces 9.5 kbps. A higher cadence would be possible within a reasonable telemetry allocation, although a lower cadence than the SXR and EUV imager should be adequate.

A much better set of measurements could be made with a vector magnetograph. This instrument would allow us to monitor the direction and strength of the field – changes in either could flag the onset of an event (flare or CME launch) significantly before evidence is seen on soft X-ray or EUV wavelengths. The main drawback of a vector magnetograph is its telemetry requirements – the instrument measures the Stokes parameters at all points in its field of view and produces around 20 times the volume data of a line-of-sight magnetograph. It is impractical to process the data onboard; any processing would not result in a net reduction of the data volume. However, with a cadence of 15-20 minutes, the volume produced by this type of magnetograph would be comparable to that produced by both the SXR and EUV imager. A vector magnetograph has never been flown before; the first will be flown on Solar-B. The design considered here is similar to one proposed for the Living With a Star (LWS) Solar Dynamic Observer (SDO).

3.1.4 Space-Based Coronagraph

Coronographs create artificial solar eclipses and allow one to study the outer solar corona. Space-based coronographs, such as LASCO on SoHO, provide a method of computing the velocity of the Earth-directed CMEs. Such coronagraphs can observe out to 30 solar radii, but require different techniques for the inner and outer corona. This will probably necessitate a double coronagraph, one internally and the other externally occulted. Also, exposure times of several minutes may be needed for the weaker material in the outer corona and this has implications for the image cadence and spacecraft pointing stability.

On SoHO, the image cadence is limited to 10 images per hour by the data compression implementation, which is done in software - this includes both EIT and LASCO images. Although a higher cadence would clearly benefit the EUV imager, it is not clear that a higher cadence is necessary for the coronagraph. Assuming a CCD similar to LASCO (1024 pixels square), and 6 images per hour, this yields a telemetry rate of ~50 kbps.

3.1.5 H-alpha Imager

H-alpha imaging provides information on activity in the solar chromosphere – they are made in a narrow waveband centred on a line at 6563 Å. When features become active, they develop upward and downward flows and are observed to shift rapidly in and out of the image. For example, coronal mass ejections are sometime preceded by activity in filaments.

The instrument needs to take a series of images spread over the H-alpha line centre, but perhaps biased towards the blue (e.g. +0.75, 0.0, -0.75, -1.50, -2.25 ?). Moreton waves are large-scale disturbances in the solar corona triggered by the onset of explosive events. The cadence of this imager is determined by whether it is necessary to observe Moreton waves. If this is needed, then since the waves can have velocities >1000 km/s, a cadence of 30 sec would allow several samples as the wave crossed the disk. Before compression, if the resolution were 2", with 5 wavelengths this would produce 1.4 Mbps and some compromise is therefore needed.

If it is not necessary to observe Moreton waves, a cadence of 2 minutes would be adequate to observe the filament rising as a flare starts. A resolution of 5" would be adequate to observe Morton waves, but a higher resolution might be needed to observe changes in filament structure. At this cadence, 5" pixels with 5 wavelengths, 90 kpbs would be needed.

Although it is possible to make magnetograph, coronagraph, and H-alpha measurements from the ground, space-borne instruments provide more continuous and higher quality observations (see section 3.2).

3.1.6 Soft X-Ray and UV Flux monitors

Broad-band measurements of the soft X-ray and UV flux give an overview of changes in solar activity.

The soft X-ray monitor is used to flag solar flares which can be a precursor of other effects. For several decades, the GOES spacecraft have carried this type of flux monitor - two GOES spacecraft are always in orbit giving a high degree of redundancy on this index.

The UV flux is known to affect the thermosphere. Increased flux causes the thermosphere to expand, increasing the drag on spacecraft and space debris and resulting in sudden changes of the orbital altitude of the objects. The UV flux is enhanced when there is an increased flaring rate, and can also be increased by the presence of a hot non-flaring active region on the solar disk. Currently no direct space-borne measurements of the UV flux are made.

3.1.7 Radio Spectrograph

The development of shocks in the solar corona and heliosphere can be monitored with a radio spectrograph. The shocks may be caused by the passage of CMEs, large particle events or electron beams.

A space-based radio-spectrograph would provide better temporal coverage than the conventional ground-based facilities. A frequency range of 30kHz-400MHz would cover the necessary atmospheric density regimes. The instrument is split into two technical packages. Package 7a (10 MHz-400 MHz) requires a large parabolic antenna (3.5x2.5m) and requires instrument development. This package can sense shocks near to the Sun starting in the low corona. Package 7b concentrates on lower frequencies (30 kHz-10 MHz) and is based on heritage from Wind. This package can sense shocks beyond a few solar radii.

To minimize man-made radio interference, the radio-spectrograph should be flown on a spacecraft located at the L1 Lagrangian point.

3.1.8 EUV Spectrograph

Measurement of EUV emission from the whole disc of the Sun, i.e. the solar constant at these wavelengths. This is an important parameter in the ionosphere/thermosphere energy balance. Heritage from UARS, TIMED and ISS.

3.1.9 Solar and galactic radiation monitor

The system must be flexible enough to work in different regimes: (e.g. 2-100 MeV, ions, 2-20 MeV, electrons and ≥ 500 MeV, galactic cosmic rays). The first two energy ranges suggested here are suitable for monitoring the solar component of cosmic rays. Ideally, higher energy particle monitors should be included (third range) to include galactic cosmic rays, these peak in intensity at approximately a few hundred MeV/nucleon. It may be possible to include a monitor based on heritage from Ulysses (COSPIN experiment) or via novel low-mass developments. Such particle monitors are useful for recording fluxes of particles which produce single event upsets in electronics. Measurement techniques include solid state detectors, scintillators and Cerenkov detectors.

Below are examples of existing monitors that provide heritage to the designing of ideal space weather solar/galactic monitors:

The Heliosphere Instrument for Spectra, Composition, and Anisotropy and Low Energies (HI-SCALE) is designed to make measurements of interplanetary ions and electrons on the Ulysses mission. The ions (E > 50 keV) and electrons (E > 30 keV) are identified uniquely and detected by five separate solid state detector telescopes.

GOES-8 proton fluxes are 5-minute averaged integral proton flux (protons/cm^2-s-sr) with energy thresholds of >=10, >=50, and >=100 MeV. SEC's proton event threshold is 10 protons/cm^2-s-sr at >=10 Mev.

GOES-8,10 electron fluxes are 5-minute averaged integral electron flux (electrons/cm^2-s-sr) with energies greater than or equal to 0.6 MeV and greater than or equal to 2 MeV at GOES-8 (W75) and GOES-10 (W135).

3.1.10 Solar wind monitor

Measurements of the solar wind density, velocity and temperature are crucial in any space weather programme. These parameters, together with the interplanetary magnetic field, determine the input parameters to the magnetosphere, namely the dynamic and thermal pressure of the solar wind. The measurements can be made either as part of the thermal plasma monitor (below) or via dedicated ion and electron monitors. The technique is electrostatic analysis. Heritage includes AMPTE, Giotto, ACE, Cassini, Cluster.

3.1.11 Thermal plasma monitor

A thermal plasma monitor is required to measure low energy particles in the magnetosphere. Such particles are thought to be the seed particles which are accelerated in the magnetosphere to provide some of the input into the ring current and radiation belts. In addition the technological reason for monitoring these particles is that they can cause surface charging on spacecraft surfaces. By measuring both ions and electrons it is possible to measure the spacecraft potential. Such a monitor can be adapted to measure the solar wind as well for a spacecraft which spends time outside the magnetosphere, by arranging a special sun-facing sector with finer angular and energy resolution (for ions) and perhaps reduced energy coverage (electrons). The main measurement technique is electrostatic analysis but to this, time of flight and/or solid state detection can be added. The instrument should be able to monitor 0-40 keV, ions and electrons, with 4p coverage. Heritage includes AMPTE, CRRES, Cluster, Cassini, Polar.

3.1.12 Mid energy particle monitor

A mid energy particle monitor acts as a monitor of the fluxes of particles which are thought to produce the most severe operational anomalies for spacecraft. So-called 'killer' electrons, with 1-2 MeV energies, cause deep dielectric charging in insulators and components on spacecraft. The main measurement techniques are solid state detectors and techniques involving radiation attenuation by matter. The instrument should be able to monitor 40 keV-2 MeV, ions and electrons, with 4p coverage. Heritage includes CRRES, Polar, Cluster, Goes and some Hitchhiker payloads (see Appendix A)

3.1.13 Magnetometer

A magnetometer is essential for in-situ measurements of the magnetic field both upstream and downstream of the magnetopause. Upstream, the North-South component of the IMF controls the amount of reconnection at the magnetopause and ultimately the efficiency of the coupling between the solar wind and the magnetosphere. Downstream, magnetic fields are important in helping to diagnose the structure and dynamics of the magnetosphere. The technique is the well-established fluxgate magnetometer. Heritage includes all magnetospheric spacecraft.

3.1.14 Waves

In-situ measurements of plasma waves are important in developing physical models of the radiation belt acceleration, in identifying plasma parameters such ad density and in understanding the process of particle acceleration in the magnetosphere. They can help in the identification of plasma boundaries. The techniques are: magnetic search coils (14a), sufficient to obtain power spectra, polarisation and propagation direction, and electric field antennae (14b), of interest for wave generation mechanisms. Heritage includes Cluster WEC and many other magnetospheric spacecraft.

3.1.15 Neutral particle imager

Energetic neutral atoms provide a novel remote sensing technique for the Earth’s magnetosphere. The technique depends on charge exchange between the ionised magnetospheric particles and neutral particles. Heritage is POLAR, IMAGE, Cassini and MARS EXPRESS.

3.1.16 DC E field antennae

Deployed in the ionosphere, these provide us with basic plasma properties namely the ionospheric electric field. Due to the lower Debye length in the ionosphere compared to the magnetosphere, the booms may be shorter and the instrument is distinct from the wave instrument. The technique uses E-field probes situated on booms protruding from the spacecraft. In practice the probes and booms can be part of the wave instrument if present. Heritage includes Cluster EFW.

3.1.17 Sounder

This is an active plasma experiment which transmits a short high frequency pulse of electromagnetic waves, from an electrode in contact with the plasma but concentric with the electric field boom. The received signal on the electric field probe determines the response of the plasma. This technique is used to find the plasma frequency directly, therefore giving the plasma electron density. Heritage includes the Cluster WHISPER instrument and Rosetta MIP.

3.1.18 Low energy plasma monitor

An ionospheric low energy plasma monitor would include particle counting instruments similar to but smaller than the thermal plasma monitor above. It would be used to study ambient plasmaspheric or ionospheric plasma populations as well as precipitating auroral particles. It may also include a Langmuir probe and a drift meter. The technique is electrostatic analysis. The heritage includes UARS and Cluster.

3.1.19 Interferometer

A Fabry Perot interferometer is included to determine the neutral temperature and velocity. Heritage includes UARS.

3.1.20 Spectrometer

The ion spectrometer will provide the ion velocity distribution over a chosen energy range and density range. Mass discrimination is included. Heritage Cluster, UARS.

3.1.21 Accelerometer

An accelerometer will make in-situ measurements of the effects of air drag and the solar radiation pressure on spacecraft orbits. Heritage: CHAMP.

3.1.22 UV imager

The UV imager will monitor the auroral oval in the 130-190 nm wavelength range, especially studying storm effects, auroral extent and dynamics.

3.1.23 Visible imager

The visible imager will monitor the auroral oval providing visible images, especially studying storm effects, auroral extent and dynamics.

3.1.24 GPS receiver

A GPS receiver will be used to monitor in-orbit position, thus allowing assessment of satellite drag.

3.1.25 Topside sounder

A topside sounder will be used to routinely measure ionospheric density profile from above.

3.1.26 Piggy-Back Instruments

For continuous monitoring, global coverage and cost-efficiency one may consider various piggy-back options, especially for radiation environment monitoring (a mid-energy particle monitor). Examples of existing monitors include:

1.) The Standard Radiation Environment Monitor (SREM) is a standard piece of equipment and useful for continuous monitoring of the radiation dose environment. The STRV 1c & STRV 1d spacecraft were launched on the 15 November 2000; the SREM was included onboard one of these spacecraft. It will also be included onboard the International Space Station. (http://www.estec.esa.nl/wmwww/wma/research/srem.html)

2.) The Compact Environmental Anomaly Sensor Space Radiation Alarm (CEASE) is a small, low power instrument that provides operators with fully processed, real time, in situ measurements and autonomously generated warnings of the space radiation environment threats. CEASE reports these threats to the host spacecraft (http://www.amptek.com/cease.html):

1.) Ionizing radiation dose and dose rates,
2.) Single event effects,
3.) Surface and deep dielectric charging.

3.) MSSL has started two studies funded by the satellite insurance industry, as part of the Tsunami initiative, to examine the effects of space weather on satellites. One of these studies involves the development of a "black box" detector to be carried by future commercial satellites. This will add much needed high-quality data to what are currently sparse records of the radiation environment near the Earth. (http://www.mssl.ucl.ac.uk/www_plasma/homepage.html)

Another possibility for potential piggy back instruments would be a low energy plasma monitor to study spacecraft surface charging effects. A full list of potential piggy.back instruments we have identified appears in Appendix A. Note that such instruments are useful for both post-event analysis and for model development.

3.2 Ground-based Instrumentation

Some of the solar monitoring instruments described in Section 3.1 can also be used to make observations of the Sun from the ground. These include the instruments that work at optical and radio wavelengths - EUV and X-ray wavelengths of course require space-based platforms. The ground-based solar observatories often make more comprehensive observations than are possible from space-based platforms (which are resource restricted), but can only be observed for a limited number of hours each day, and (at optical wavelengths) can also be affected by weather. To counter these problems an internationally coordinated programme of observations would be required. Optical instruments include coronagraphs, magnetographs and H-alpha patrol telescopes. Radio instruments include imaging at MHz and GHz and spectrographs.

Instruments	Comments
X-ray and EUV imager	Require space-based platform, atmosphere absorbs these wavelengths.
Coronagraph	Some measurements possible from the ground, but atmospheric scattering limits radial distance from solar disk that can be observed.
Magnetograph and H-alpha imager	Could be made from the ground, but continuous, reliable coverage would require an extensive network of ground-based observatories. Better coverage from space.

Several geophysical parameters can also be monitored. The effect of the geomagnetic storms are monitored using magnetometers at locations around the globe. Neutron monitors are used to monitor cosmic rays. There are several monitors in Europe and around the world. They are used to formulate the heliocentric potential, which gives an indication of the galactic cosmic ray flux expected at the Earth. We refer to WP 3120 for more information about these ground-based instruments.

As a footnote it should be mentioned that meteoroids and space debris may cause damage to space systems, and their orbit may be influenced by the solar cycle. Objects larger that about 10 cm in LEO and larger than 1 m in GEO are regularly tracked by radar or optical telescopes from ground. Particles with sizes lower than about 1 mm in diameter are too small to be detected by means of remote sensing and one must rely on in-situ measurements. This means that their presence in outer space can be inferred by their direct interaction with the surfaces of orbiting or interplanetary spacecraft. Measurements of this type can be divided into active detection of micro-particle impacts and passive collection on exposed surfaces preceding post-flight analysis of the retrieved spacecraft.

4. PROPOSED SPACE SEGMENT FOR EUROPEAN SPACE WEATHER

In this section we offer the system requirements (spacecraft resources) for the various instrumentation proposed for a space weather programme. The space segment for our purpose consists of the following: dedicated spacecraft, packages installed on commercial spacecraft (e.g. space environment monitors), and alternative solutions.

It should be mentioned that for mid-term and far-term programmes one should also consider innovative technologies for spacecraft orbits/techniques (e.g. ion propulsion development) and shielding concepts. The same applies for instrumentation, building on either already existing design concepts or developing totally new technical design concepts.

Our study includes looking at the pros and cons of different spacecraft locations. We conclude by including a suggested mission strategy for a European space weather programme that we divide into three parts: 1.) Autonomous space weather programme 2.) Complementing other world-wide space weather programmes 3.) Instrument piggy-back ride possibilities.

4.1 System requirements

We propose building on existing instruments that provide the fundamental parameters that are used in space weather forecasting or monitoring at the moment. To complement these observations we also consider instrumentation that are at present used solely for research purposes. For each instrument the expected mass, power usage, telemetry rate and cost is listed in Table 4. These have been estimated comparing with instruments that are already available.

It should be noted that for some cases mass and power figures could be reduced if the processing electronics were shared between instruments. However, great care is needed when designing the instruments and their electronics to ensure that they continue to function when subjected to intense radiation. Several existing missions in LEO (e.g TRACE) have problems making images in parts of their orbit because they do not have adequate screening against the particles in the radiation belts. Outside of the magnetosphere (e.g. at the Lagrangian point L1) both SoHO and ACE are badly affected at the time of intense solar proton events - ACE was unable to monitor several of the parameters key to space weather modelling at these times and it is essential that future missions are not compromised in this way.

Since the cadence and resolution of the imaging instruments needed for space weather observations often match those of previously defined instruments used to assess resource requirements, the telemetry requirements have been calculated. This has been done on the basis of the parameters given in the table; data compression has not been assumed, but a loss-less compression could easily reduce data volumes by a factor 3. Clearly there is a need for robust compression schemes to survive the possible data corruption during an intense particle event.

Spacecraft pointing capabilities fall into distinct categories:

1. For the solar monitoring instruments, since they are mostly full-Sun imagers with fields of view ~ 40’, pointing accuracy should be of order a few arc minutes with drift rates be small enough that image is not blurred due to motion of the spacecraft during the exposure. Aspect monitors need to be of sufficient resolution so that the actual pointing can be determined later. Typical drift rate in x and y should be <1 arcsec/sec; <5 arcsec/min; <30 arcsec/hour. In the roll axis (z) <20 arcsec/sec.
2. Auroral imagers. Requirement ~ 0.1 degrees.

3. All the in-situ monitors have much less stringent pointing requirements. Usually, one degree alignment and knowledge is sufficient.

In general, particle detectors are better suited to spinning platforms due to the need to measure particles from all directions, while imagers require three-axis stabilisation. Another system point is that spacecraft with magnetometers tend to require magnetic cleanliness programmes, and for spacecraft which measure low energy particles, special care is necessary in the electrostatic design to avoid differential charging which affects the measurements.

In determining representative mass, power and telemetry estimates for the solar instruments, the sources under ‘solar missions’ in the reference list were used. For the magnetospheric and ionospheric instruments representative numbers are used based on heritage from previous missions including ACE, CLUSTER, CRRES, Polar, AMPTE, IMAGE, Cassini, GIOTTO and others

	Instrument	Mass (kg)	Power (W)	Telemetry (kbps)	Cost (MEuro)	Status	Main references	Size (cm)	3 axis/Spin
1	Soft X-ray imager	25	20	70	15	1	Yohkoh, GOES SXI	30x15x140	3
2	EUV imager	28	20	28	15	2	SOHO, TRACE, SO	30x15x140	3
3	Magnetograph	26	25	9.5*	15	2	Solar B, SDO, SO	30x40x120	3
4	Coronagraph	18 – 25	25	50	15	2	SOHO, STEREO	20x20x50	3
5	H-α imager	18	20	120	15	4	Similar instruments	20x20x50	3
6	Soft X-ray & UV flux monitor	5	5	0.2	7	1	GOES, UARS	11x11x22	3
7	Radio spectrograph A high freq.	12	6	0.5	15	4	None	Antenna 3.5x2.5m+elec	3
	Radio spectrograph B low freq.	2	0.8	0.8	3	1	Wind, SO	5m boom+10x10x10	3/S
8	EUV spectrograph	5	5	1	5	3	UARS, TIMED	11x11x22	3
9	Solar and galactic radiation monitor	6	8	0.1	10	2	GOES, Ulysses	20x20x20	3/S
10	Solar Wind monitor	6	5	2	5	2	ACE, AMPTE, Giotto, Cassini, Cluster	20x20x20	S/3
11	Thermal plasma monitor	6	8	2	5	2	AMPTE, CRRES, Cluster, Cassini	20x20x20	S/3
12	Mid energy particle monitor	2	4	2	5	2	CRRES, Polar, Cluster, GOES, Hitchhikers	15x15x15	S/3
13	Magnetometer	1	2	0.2	3	1	Cluster, Rosetta	20x10x5 (elec) 4x4x4 (2 sensors on boom)	S/3
14	Waves A magnetic	1.3	1.2	2	2	1	Cluster, SO	20x10x5 (elec) + booms	S/3
	Waves B electric	8	0.6	2	5	1	Demeter	TBD	
15	Neutral particle imager	3	3	2	3	2	Mars Express, STORMS, IMAGE	15x15x15	3
16	E field antennae	17.5	3.1	1.5	6	1	Cluster	20x10x5 (electronics) plus booms	S/3
17	Sounder	1.2	2	0.3	2	1	Rosetta	TBD	S/3
18	Low energy plasma monitor	2	4	1	5	2	UARS, Cluster, Rosetta	15x15x15	S/3
19	Interferometer	42	19	1	10	3	UARS, TIMED	4 tel. 20x12x12, int. 40x15x15 + elec	3
20	Mass spectrometer	2.7	7.4	1	10	3	Cluster, UARS	15x15x15	S/3
21	Accelerometer	0.5	1	1	0.5	2	CHAMP, Huygens	5x5x5	3
22	UV imager	20	10	10	10	2	Polar, IMAGE	80x50x30	3
23	Visible imager	29	10	10	10	2	Polar, IMAGE	60x60x25	3
24	GPS receiver	8.5	12	0.1	1	2	SAC-C, CHAMP,JASON-1	20x20x10 + antennae	3/S

Table 4: System requirements for the various instruments (preliminary)

In the Table, under status, we indicate the maturity of instruments' 'industrial maturity'. The codes are: 1=off the shelf, 2=to be adapted from existing designs, 3=need further development, but technology exists, 4=need for technological development, 5=feasibility to be proven. Cost column includes manpower and development where required. * assumes data compression; raw rate up to 200 kbps

4.2 Pros and Cons of Different Spacecraft Locations

Three well-known spacecraft locations are studied for solar monitoring spacecraft: Low Earth Orbit, High Earth Orbit incl. Geo-synchronous, and the first Lagrangian point L1. In addition we discuss the options of upstream monitoring spacecraft in orbits up or downstream of the Lagrangian point L1, and solar measurements ahead of, or behind the Earth in its orbit.

For magnetospheric monitoring, the additional orbit possibilities are medium Earth orbit (MEO), geostationary transfer orbit (GTO), elliptical and polar orbits.

For ionospheric monitoring Low-Earth orbit is ideal.

Each orbit has its own benefits and problems and these are discussed below. We touch briefly on the problems of operating spacecraft in deep space, but there are also difficulties associated with managing a large number of spacecraft close to the Earth. The ground segment costs and requirements related to this, as well as many other system issues, are covered in WP2400.

4.2.1 Low Earth Orbit (LEO)

Although the simplest to launch, spacecraft in LEO provide only intermittent coverage of solar parameters. A spacecraft in a high-inclination, sun-synchronous orbit will in principle provide coverage for weeks or months at a time, provided that the design includes proper screening against the radiation belts. This type of orbit is ideal for ionospheric in-situ monitoring.

The Yohkoh and TRACE spacecraft are in LEO; TRACE is in a sun-synchronous orbit. Yohkoh provides full-Sun soft X-ray images from the SXT instrument; TRACE provides EUV and UV images of a medium-sized (8’) field of view. Yohkoh and TRACE are both nearing the end of their operational lifetime.

Past missions to the ionosphere include UARS and in future TIMED is planned, SAMPEX, the Solar Anomalous and Magnetospheric Particle Explorer, is also in this orbit.

4.2.2 High Earth Orbit (HEO, incl. Geo-synchronous)

A spacecraft placed in HEO can maintain continuous coverage of the Sun and does not suffer the telemetry bandwidth problems related to L1. In geo-synchronous orbit, a spacecraft suffers infrequent eclipses of short duration that can affect a programme of continuous observations. One solution is to have two closely spaced spacecraft so that one is always out of eclipse, but both can be served from the same ground-station.

A series of GOES spacecraft operated by NOAA have for several decades monitored the solar soft X-ray flux and energetic particle densities from geo-synchronous orbits. NOAA always keeps two spacecraft active - they are positioned over the US with approximate longitudes of 75° and 135° W. The GOES spacecraft will shortly also carry a Soft X-ray Imager (SXI) – five such payloads are currently planned and it is anticipated that this will be extended. As such, the need for ESA to provide a soft X-ray imager is reduced.

NOAA is currently testing a hard X-ray spectrometer (HXRS) on a technology satellite – this is being used to monitor the evolution of the hard X-ray spectrum during a flare. Whether such an instrument will be carried as part of the regular GOES payload is to be assessed.

At the moment, full-Sun images in the EUV are provided by EIT on SoHO (located at L1). Similarly, SoHO also provides coronagraph images to a range of solar radii (R_S), and full-Sun magnetograms. These measurements could just as easily be made from a platform in a geosynchronous orbit.

Geosynchronous orbit is usually in the Earth's outer radiation belt zone and usually inside the magnetopause except during periods of enhanced solar wind dynamic pressure. In addition most of the world-wide commercial spacecraft are in this orbit. Therefore it offers a useful orbit for in-situ monitoring of potentially damaging spacecraft surface charging or deep dielectric charging conditions.

4.2.3 Elliptical (Highly Eccentric Orbit)

This type of orbit, from a few hundred km at perigee to several Earth radii at apogee, permits observation of conditions as a function of altitude. The orbital period depends on the semi major axis of the orbit.

This type of orbit is ideal for many magnetospheric studies.

4.2.4 The Sun-Earth Lagrangian point, L1

Spacecraft located at L1 provide continuous coverage of the Sun and Earthward moving solar wind, however the bandwidth of the telemetry stream is by default more restricted than in a near-Earth orbit. For early warning of the key in-situ parameters of the plasma cloud of an Earth-directed CME (e.g. the orientation of the magnetic field) and for general solar wind conditions including dynamic pressure and for radiospectrograph measurements, a location at L1 is essential; it is not quite so necessary for other solar measurements (e.g. imaging at various wavelength, and flux monitoring).

Two spacecraft measuring solar wind parameters are currently located in halo orbits at L1: SoHO (the Solar and Heliospheric Observatory) and ACE (the Advanced Composition Explorer). It is essential that the space weather related components of these observatories be replaced in an organised way in order to ensure coverage of these parameters.

4.2.5 Up and Downstream of Lagrangian point L1

For mid-term and far-term programmes, the possibility of placing a spacecraft up or downstream of L1 through the use of innovative technologies (such as solar sails or ion propulsion) should be considered. Solar sails have been suggested for several missions in the solar system - in this application, the radiation pressure provides the force needed to counter the extra orbital velocity inside of L1, thus allowing the spacecraft to station-keep with the Earth. However, the size of the sail, and difficulty in making the in-situ measurements in the presence of the sail, probably make this technology unsuitable for a space weather programme. Ion propulsion is currently being validated by both ESA and NASA (SMART1 and DEEP-SPACE1). This technology has been adopted in our recommendations whereever some form of long-term propulsion is needed.

It is possible, although technologically challenging, to move a spacecraft upstream of L1 using solar sail or ion propulsion. A location upstream of L1 is particularly advantageous for the in-situ measurements related to the passage of plasma clouds related to CMEs - the closer the spacecraft is to the Sun, the earlier the warning that a geo-effective CME is on its way towards the Earth. For fast moving CMEs, the additional warning afforded by moving upstream would ensure that there is still adequate time to assess and respond to the threat of geo-effective CMEs. The upstream location suffers the same telemetry bandwidth problems of other "deep space" missions and is more restricted than near-Earth orbits, but spacecraft primarily designed for in-situ measurements do not require a lot of telemetry and this restriction should not be a problem.

However, moving a spacecraft downstream of L1 requires a force that necessitates some form of propulsion. If ion propulsion is used, a spacecraft could be placed in a stable location, downstream of L1 (in the Earth’s magnetopause). The conditions of the magnetopause dictate the nature of the solar wind / Earth interaction.

4.2.6 Ahead of, or Behind the Earth

Spacecraft placed ahead of, or behind the Earth in its orbit provide a stereoscopic view of the Sun. Stereo imaging by coronagraphs is particularly useful for providing a better view of Earth directed CMEs. These locations suffer the same telemetry bandwidth problems of other “deep space” missions in that the bandwidth is less than in near-Earth orbits, but such missions should be considered because of the view they afford.

The STEREO mission planned by NASA for 2004/05 uses two identical spacecraft placed in slowly drifting helio-centric orbits.

4.2.7 Medium Earth Orbit

Constellations such as Galileo, GPS and ICO use this type of orbit, which is intermediate in altitude between LEO and GTO, consequently it is an important orbit for monitoring. In addition, the orbit is located at the heart of the radiation belts making spacecraft particularly susceptible. While we are not proposing a dedicated mission in this region, we suggest the use of piggy back payloads on planned commercial spacecraft as a monitor of conditions which would be useful for the analysis of specific anomalies and for the development of models.

4.2.8 Geostationary Transfer Orbit (GTO)

This orbit is a few hundred km at perigee and 36,600 km altitude at apogee, with an orbital period just over 10 hours. It is generally used as a transfer orbit for commercial spacecraft bound for geosynchronous orbit. However the orbit provides an unique vantage point for measurements of the altitude dependence of the Earth’s radiation belts. It is a harsh radiation environment but provides good coverage of the inner and outer radiation belts.

4.2.9 Polar Orbit

An eccentric polar orbit, with perigee a few hundred km and apogee a few Earth radii, provides the third dimension for coverage of the magnetosphere. The cusp area in particular allows particles to enter the Earth's magnetic field and precipitate into the aurora. This orbit also provides the ideal vantage point for auroral imaging.

4.3 Suggested Mission Strategy (Possible Payloads)

Here we present ideas for conceptual payloads. We divide our mission strategy into three sections. In the first section, the global set of space weather measurements and instruments discussed above are used to define a programme that is complete in itself. If ESA wanted to cover all aspects of space weather using its own sources (an autonomous European space weather programme), this section defines what is required. In the second section we examine what measurements are already available from existing sources and suggest how an ESA programme might complement other already existing world-wide programmes preventing redundancy of efforts. One could say that the ultimate future space weather programme would be a world-wide collaboration between the various international efforts. The final section shows how a space weather programme could be extended using piggy-back instruments on other planned spacecraft (ESA, NASA, …) and also onboard the ISS. All options should be studied in the system level studies by Industry.

4.3.1 An Autonomous European Space Weather Programme

The space weather space segment is divided into three parts as a function of the observations required in the Sun-Earth scenario; they are 'Solar/upstream measurements', 'Magnetospheric measurements', and 'Ionospheric measurements'. When reading the following we recommend that the reader refers to Tables 5A, 5B and 5C, so as to obtain a global view of our suggested mission strategies (possible payloads).

4.3.1.1 Solar and upstream monitoring spacecraft

OPTION 1:

Solar and Upstream monitoring

In order to make continuous measurements of the Sun and of upstream plasma conditions ahead of the Earth's magnetosphere, the best single spacecraft solution is a 3 axis stabilised L1 spacecraft. This platform would carry the solar instruments (1-8 in the tables above), the particle instruments (9-12), and a magnetometer (13). This payload would provide all the solar and upstream plasma parameters required. Some modification may be needed to particle instruments to operate on a non-spinning spacecraft which may affect resources.

In the Table this is split into two platforms, due to the different pointing and stabilisation requirements for solar and in-situ instruments. However, this could be combined onto a single pointed platform.

OPTION 2:

This option requires both solar and plasma monitoring spacecraft.

Solar monitoring

The solar segment would consist either of two 3-axis stabilised spacecraft in near-Earth sun-synchronous orbits or two (to avoid eclipses which would be present) in geosynchronous orbit.

This would keep L1 operational costs down and better match bandwidth requirements of the solar segment imaging instruments. Two spacecraft would be ideally needed in the case of Sun-synchronous to provide continuous coverage and to provide a degree of redundancy. Whether the payloads (instruments 1-6, 8) of the two spacecraft should be identical requires further study. It would seem beneficial to have the core imaging instruments on both spacecraft, with perhaps less essential instruments shared between the payloads. This option is less suitable for radio spectrographs (instrument 7) as it leads to a limitation in the low frequency range. It may be possible to achieve the requirements of continuous operations with a single Sun-synchronous spacecraft in the dawn-dusk plane.

The need for stereo imaging by the coronagraphs should be studied, perhaps using a single additional spacecraft 10 degrees ahead of, or behind, the Earth's orbit.

Upstream plasma monitoring based on already existing spacecraft technology

Strategies building on already existing spacecraft technology for upstream plasma monitoring would carry instruments 9-13.

a.) Strategy 1 would require placing one spinning spacecraft positioned at L1. This would require a much smaller spacecraft than a combined solar and plasma mission and would have less demanding pointing requirements.

b.) A second possible strategy for plasma monitoring would be to place three spinning spacecraft, in a high circular Earth orbit similar to IMP-8 where at least one of the spacecraft would be in the solar wind at any time.

Plasma upstream monitoring based on new spacecraft technology

Strategies requiring new technologies (using ion propulsion) for plasma upstream monitoring, would carry a minimum payload to save mass, namely the basic plasma instruments 10 and 13.

a.) One strategy would be to position one spinning spacecraft upstream from L1 to give a longer warning time for upstream parameters.

b.) The other strategy would be to position the spacecraft downstream, nearer the magnetopause giving more relevant upstream conditions.

Scientific preference:

Our preferred option from the above possibilities is a single L1 monitor (OPTION 1), because this gives the best overall performance for both solar and upstream measurements. The split option, 1A and 1B, is also a strong possibility here. In particular, the 1B platform could accommodate the in-situ upstream instruments on a spinning spacecraft while the solar instruments could be located on a 3-axis stabilised closer to the Earth (with the exception of the radio experiment where accommodation on the 1B platform could be studied).

It may be however that costs will dictate the selection of our second choice, which would be two geosynchronous 3 axis stabilised solar monitoring spacecraft plus a spinning plasma only monitor at L1.

4.3.1.2 Magnetospheric measurements

OPTION 1:

There is a very strong case for at least one, and preferably at least three (apogees equally spaced in local time), equatorial spinning satellites in GTO with a payload consisting of instruments 11,12,13 and 14 above. We may also wish to include instruments to monitor the aurora (22, 23), although the spatial resolution possible from GTO may be too poor, and to do neutral particle imaging (15), although this techniques, used on IMAGE, is perhaps not yet sufficiently operational for use in a space weather programme. Even with instruments 11-14 alone, these well-instrumented spacecraft will monitor the particles involved in surface and deep dielectric charging as well as magnetic fields and waves. The measurements are crucial for improving models and interpretation of data/models.

OPTION 2:

We propose a single geo-synchronous spinning spacecraft including instruments 11 and 12, but ideally instrumented in the same way as OPTION 1 (instruments 11-15, 22-23), to monitor conditions over Europe near Europe's telecommunications satellites.

OPTION 3:

We also propose a multi-satellite constellation of 30-50 spinning spacecraft instrumented with only instruments 11, 12 and 13. This will provide a real-time dynamic view of the state of the magnetosphere at all times. Due to orbital considerations and the coverage required to track space weather fronts as they propagate through the magnetosphere a large number of spacecraft us required to avoid undersampling. Such a mission was proposed to ESA as SWARM (Space Weather Advanced Research Mission) in 1999.

A representative constellation mission could include the following deployment of spacecraft and orbits:

Local time	Apogee Re	Perigee Re	Inclination deg	Spacecraft per orbit
0000	20	2.5	0	6
0600	20	2.5	0	6
1200	20	2.5	0	6
1800	20	2.5	0	6
0000	15	2.5	90	6
0000	8	2	63.4	2

OPTION 4:

Arguably the most urgent measurements in the Earth's magnetosphere for space weather purposes are multi-spacecraft measurements of energetic particles, i.e. those which cause deep dielectric charging, using the mid energy monitor (instrument 12 in the Tables). If possible, but as a lower priority we would suggest, also carrying a thermal plasma monitor (instrument 11), which can monitor spacecraft surface charging. It is suggested that additional measurements are achieved by placing hitchhiker payloads on as many commercial satellites as possible. There is a very strong need for these measurements as present models of the energetic particle environment are based on extremely sparse data. Suitable low Earth orbit hitchhiker payloads would also allow mapping and monitoring of features such as the South Atlantic Anomaly and polar horns.

Scientific preference:
We suggest OPTIONS 1,2 and 4 as a minimum, but the programme will be significantly enhanced by selecting OPTION 3 as well. Option 1 affords good coverage of the radiation belt at all altitudes, option 2 gives excellent environment information close to Europe's main commercial satellite platforms and option 4 gives good coverage throughout the magnetosphere and on actual satellite buses. Option 3 gives good coverage in a methodical manner and allows the tracking of space weather fronts through the magnetosphere. All options contribute to monitoring and model development.

4.3.1.3 Ionospheric and thermospheric measurements

OPTION 1:

We propose to fly 3 pairs of 3-axis stabilised spacecraft and another over the pole. Two different local time meridians are sampled by the first pair. On the equatorial and 75 degree inclination pairs, one spacecraft is on the dayside while the other is on the nightside. Another spacecraft monitors the northern auroral oval and polar cap. In this way, there is a global and permanent coverage of the Earth. The details of the orbits and the recommended onboard equipment are the following:

Orbit 1

One pair of spacecraft are placed in sun synchronous orbit with a 97.8° inclination and a delay of 6 hours between the one spacecraft and the other, namely 9 / 21 LT and 15 / 3 LT. Their altitude should be about 600 km.

The payload should include electric field antennae (16), a low energy plasma monitor (18), a neutral mass spectrometer (20), a GPS receiver (24), a topside sounder (25) and a solar and galactic cosmic ray monitor (9). The rationale for the latter is monitoring relevant to aviation and space flight.

Orbit 2:

1 pair of spacecraft (2 spacecraft) is placed in 75 degree inclination orbit with an altitude of around 600 km.

The payload is the same as for Orbit 1, except there are no electric field antennae (16) and an interferometer is added (19).

Orbit 3

1 pair of spacecraft in equatorial orbit. The payload includes an interferometer (19), a neutral mass spectrometer (20), a GPS receiver (24) and a topside sounder (25).

Orbit 4

1 spacecraft is placed in highly eccentric orbit with perigee around 600 km and apogee around 3 Earth Radii over the Northern polar region. This orbit allows monitoring of the auroral zone 5 hours of the 6 required for an orbit.

The payload includes a UV Imager (22) and a visible imager (23).

Scientific preference:

The medium scale requirement is for the sun-synchronous satellites only. While not providing continuous coverage this would be adequate for many requirements.

Table 5A: Suggested mission strategy (possible payload)

	Option	Strategy	No. of Space-craft	Orbit	Possible payload
Solar and Upstream Measurements	1A	SOLAR MONITORING	1	L1	1. Soft X-ray imager 2. EUV imager 3. Magnetograph 4. Coronograph 5. H-a imager 6. Soft X-ray & UV flux monitor 7. Radio spectrograph A 8. EUV spectrograph
	1B	UPSTREAM MONITORING	1	L1	9. Solar and galactic radiation monitor 10. Solar wind monitor 11.Thermal plasma monitor 12. Mid-energy particle monitor 13. Magnetometer
	2	A - SOLAR MONITORING	2	2 in Near-Earth Sun-synchronous orbit OR 2 in Geo-synchronous orbit	1. Soft X-ray imager 2. EUV imager 3. Magnetograph 4. Coronograph 5. H-a imager 6. Soft X-ray & UV flux monitor 8. EUV spectrograph
		B - PLASMA MONITORING	1	1 spacecraft at L1	9. Solar and galactic radiation monitor 10. Solar wind monitor 11.Thermal plasma monitor 12. Mid-energy particle monitor 13. Magnetometer 7. Radiospectrograph (B only if resources limited)
			3	3 spacecraft in High Circular Orbit (may replace 1 spacecraft downstream of L1)	
			1	1 spacecraft upstream of L1	10. Solar wind monitor 13. Magnetometer
			1	1 spacecraft downstream of L1	

Table 5B: Suggested mission strategy (possible payloads)

	Option	Strategy	No. of spacecraft	Orbit	Possible payload
Magnetospheric Measurements	1	RADIATION BELT MONITORING	1-3	1-3 equatorial spacecraft in GTO (At least 1, = 3 preferable)	11.Thermal plasma monitor 12. Mid-energy particle monitor 13. Magnetometer 14. Waves (A only if resources limited)
	2	OUTER RADIATION BELT MONITORING NEAR EUROPEAN ASSETS	1	1 geo-synchronous spacecraft over Europe	11.Thermal plasma monitor 12. Mid-energy particle monitor
	3	PLASMA MONITORING	30-50	Multi-satellite constellation of small satelittes (SWARM)	11. Thermal plasma monitor 12. Mid-energy particle monitor 13. Magnetometer
	4	PIGGY-BACK INSTRUMENTS	As many as possible	Geo-synchronous, Medium Earth Orbit, and Low Earth Orbit	[11. Thermal plasma monitor] 12. Mid-energy particle monitor [9. Solar and galactic radiation monitor]

Table 5C: Suggested mission strategy (possible payloads)

	Option	Strategy	No. of spacecraft	Orbit	Possible payload
Ionospheric Measurements	1	DAYSIDE/ NIGHTSIDE MONITORING	2	Sun-synchronous orbit (SSO), 97.8° inclination, 600 km altitude 3-15h and 9-21h	16. E-field antennae 18. Low energy plasma monitor 20. Neutral mass spectrometer 24. GPS receiver 25. Topside sounder 9. Solar and galactic radiation monitor
		DAYSIDE/ NIGHTSIDE MONITORING	2	Equatorial Orbit, 600 km altitude	19. Interferometer 20. Neutral mass spectrometer 24. GPS receiver 25. Topside sounder
		DAYSIDE/ NIGHTSIDE MONITORING	2	75° inclination 600 km altitude	18. Low energy plasma monitor 19. Interferometer 20. Neutral mass spectrometer 24. GPS receiver 25. Topside sounder 9. Solar and galactic radiation monitor
		NORTHERN AURORAL & POLAR CAP MONITORING	1	Highly Eccentric Orbit, perigee around 600 km, apogee around 3 Earth radii	22. UV imager 23. Visible imager

4.3.2 Complementing other Space Weather Programmes

A complementary space weather programme is arguably the most cost effective option for ESA. Since organisations such as NOAA and other space agencies already operate, or have plans to operate a number of missions related to space weather, ESA should perhaps only be duplicating instruments where they are considered vital to obtain a particular set of measurements, or where they have particular value in combination with other instruments. (Another reason why instruments might be included is because they are strategically important; such reasoning is however considered to be beyond the scope of this study.)

The solar monitors carried on the GOES spacecraft (operated by NOAA) are such a case. Soft X-ray flux monitors have been flown on GOES spacecraft for several decades; they are used as a standard measure of solar flare activity. NOAA will shortly fly a Soft X-ray Imager (SXI) - this will be the first of a series and is designed to provide images similar to the Yohkoh-SXT. Since NOAA tries to follow a strategy that ensures that two GOES spacecraft are always operational, it is therefore probably unnecessary to include these monitors in an ESA programme. NOAA are currently testing a Hard X-ray Spectrometer (HXRS) that was launched as a piggy-back instrument on spacecraft operated by the US Department of Energy. They are trying to determine the efficiency of monitoring the Sun in hard X-rays for predicting energetic proton storms. Depending on the outcome of this study, such instruments might also be flown on future GOES spacecraft. ESA should closely monitor the progress of this study.

Currently SOHO provides EUV and coronagraph imaging, and some in-situ solar wind plasma parameters, and ACE measures a comprehensive range of in-situ parameters. Both make observations at a much higher resolution (and in some cases a higher cadence) than is required for space weather forecasting, although ACE does include a low-bandwidth real-time channel specifically designed for the purpose. However, both missions were launched primarily as scientific observatories and are not part of an ongoing series of observations. As such, the data they provide probably will not be available five years from now. The observations are now used widely in space weather forecasting and ESA should provide at least one set of instruments that covers the spece weather relevant subset of these observables.

The STEREO mission planned by NASA for 2004/05 uses two identical spacecraft placed in slowly drifting helio-centric orbits and will provide a stereoscopic view of Earth directed CMEs. Currently, only one pair of spacecraft are planned and as they drift further around the orbit their usefulness will be decreased.

In magnetospheric physics NASA has planned a magnetospheric multi-scale mission five spacecraft to study small-scale phenomenon and possibly a constellation mission. IMAGE is currently operating and TWINS will launch soon.

As part of its "Living with a Star" (LWS) programme, NASA is planning a fleet of spacecraft that should be in place by the time of the next solar maximum in 2011, with launches from 2008. The LWS programme is proposed as a space weather science focussed, and application driven research programme. It will permit a comprehensive study of the cause-and-effect relationship between events at the Sun and their effects in geospace that influence life on Earth and technological systems. There are two groups of missions:

(a) Solar dynamics elements (Solar Dynamics Observatory (SDO) and Sentinels) that observe the Sun and track disturbances originating from there.

(b) Geospace dynamics elements (Radiation Belt Mappers (RBM) and Ionospheric Mappers (IM)) consisting of constellations of small satellites located in key regions around the Earth to measure downstream effects.

SDO and Sentinels will carry EUV imagers, along with many other instruments. Details of the missions are still tentative, but if the programme is realised in its entirety, the spacecraft will perform a comprehensive set of measurements.

The US Triana mission will also carry instrumentation to make in-situ measurements. Triana's Plasma-Mag instrument suite is an advanced, smaller version of the ACE instrumentation. Real-time data will be relayed to NOAA to support space weather forecasting, as it is with ACE. The Triana spacecraft will be 90 degrees out of phase with the ACE spacecraft in a halo orbit around L1 – this is designed to improve the coverage of the observations close to the Sun-Earth line. The mission will ensure some continuity of space weather data beyond the designed lifetime of ACE.

4.3.3 Piggy-Back Payloads

The parts of a space weather programme that could benefit in particular from flying piggy-back instruments on other spacecraft are:

- monitoring of energetic particle fluxes
- mapping the radiation belts

Piggy-back payloads are also a useful way of demonstrating new instruments before they are included on space weather applications spacecraft. Examples of payloads are those listed in Section 3.1.25 and Appendix A.

Acknowledgements

Team members Peter Cargill, Monique Pick, Francois Lefeuvre, Jean Lilensten, Chantal Lathuillere, Thierry Dudok de Wit, Frank Jansen and Olivier Pansart, and consultants Louise Harra, Lidia van Driel-Gesztelyi, Alan Aylward, Lili Cander, Luc Dame contributed to this report.

References

Gosling J., 1993, J. Geophy. Res., 98, 18, 937
Kiplinger,1995, Astroph. J. 453, 973
Koskinen H. and Pulkkinen T., 1998, SPEE-EP310-TN-1.2 "State of the art of space modelling and proposed ESA strategy"

'solar missions'
The Yohkoh Mission: 1991, Solar Physics, vol. 136
The SOHO Mission: 1995, Solar Physics, vol. 162
TRACE "Investigation and Technical Plan": 1994, Lockheed Document LMSC P017270P-1
GOES-SXI: 1998, Lockheed Martin documents on GOES-SXI N-O
NASA AO for STEREO: 1999, NASA document AO 99-OSS-01
Web pages related to STEREO instruments (http://sd-www.jhuapl.edu/STEREO)
Solar Orbiter, Assessment Study Report: 2000, ESA document ESA-SCI(2000)6

Appendix A – ‘Piggy back’ monitors

Table of Contents

1. INTRODUCTION

For continuous space environment monitoring, global coverage and cost-efficiency, one may consider placing small standard detectors onboard spacecraft; better known as “piggy-back options”. In-orbit monitors of the space environment are important for Space Weather monitoring, especially because they provide real-time measurements of input parameters for models.

This document gives an overview of existing “piggy-back” monitors and some that are in development. Topics include monitors for the magnetospheric, solar and space debris environments. This document also illustrates various missions that have as payload ‘piggy-back’ monitors. A summary of the main instrument characteristics (weight, power, telemetry, etc.) are listed in the tables in the appendix.

2. MAGNETOSPHERIC SPACE ENVIRONMENT MONITORS

2.1 ESA Space Flight Instrumentation

2.1.1 Radiation Environment Monitor (REM)

The REM detector consists of two, totally depleted silicon diodes, solid state detectors, both with a thickness of 300 mm. Measuring the differential linear energy transfer (LET) of charged particles, the detector electronics measures the energy deposit and increments one of 16 counters. The accumulation time of the data is over a period of typically 100 seconds and is stored as a 16-bin histogram.

Both detectors are covered by a spherical dome of 3 mm Al. The first detector, called the ‘e-detector’, sees protons as well as electrons and has a surface area of 50 mm². The second detector, called ‘p-detector’, has a larger surface area (150 mm²) and an additional layer of 0.75 mm Ta shielding that reduces the penetration for electrons in the relevant energy range (2-10 MeV) by approximately a factor of 200. This makes this detector better at monitoring protons (energy range 35-300 MeV). Due to the variation of the energy loss of protons in silicon in this energy range the incident energy of the protons is measured, whereas the incident energy of the detected electrons is only poorly determined.

REM was aboard the STRV-1b microsatellite of DERA (UK) during June 1994 through mid-1998 (Geostationary Transfer Orbit) and on the Russian Mir Space Station from September 1994 through 1996 (Low-Earth Orbit).

References:

1. <http://www.estec.esa.nl/wmwww/wma/rem/>
2. <http://www1.psi.ch/www_lap_hn/astr_rem/REM_intrument.html>
3. TREND (Trapped Radiation Environment Model Development), ESA/TOS-EMA Contract No. 11711/95/NL/JG-CCN, Technical Note 1A, D. Heynderickx, July 1998
4. “REM Instrument”, P. Buhler et al., *Nucl. Instr. and Meth. In Phys. Res. A.*, **386**, 825, 1996

2.1.2 Standard Radiation Environment Monitor (SREM)

The Standard Radiation Environment Monitor (SREM) is a standard piece of equipment and useful for continuous monitoring of the radiation dose environment. It is designed under ESA, and is a follow-on of the REM instrument. SREM measures electrons (>0.5 MeV), protons (>10 MeV), and heavy ions qualitatively. The weight of the device is 2.5 kg, power consumption 2.6 W, and the volume approximately 2 liters.

The STRV 1c & STRV 1d spacecraft were launched on the 15 November 2000; the SREM was included onboard one of these spacecraft. It will also be included onboard the International Space Station. It is also part of the Columbus Radiation Environment and Effects Package (CREEP) – see Section 5.

References:

1. <http://www.estec.esa.nl/wmwww/wma/srem/index.html>
2. < http://www.estec.esa.nl/wmwww/wma/research/srem.html >
3. <http://pc1582.psi.ch:80/SREM/>.

2.2 AMPTEK Spaceflight Instrumentation

2.2.1 Compact Environmental Anomaly Sensor Space Radiation Alarm (CEASE)

CEASE is a small, low power instrument that provides operators with fully processed, real time, in situ measurements and autonomously generated warnings of the space radiation environment threats. The threats that are reported to the host spacecraft by CEASE are as follows:

- Ionizing radiation dose and dose rates
- Single event effects
- Surface and deep dielectric charging.

A summary of the CEASE properties are listed in Table 1.

Properties	CEASE I	CEASE II
Size	4.0 x 4.0 x 3.2 "	4.0 x 5.1 x 3.2 "
Mass	1.0 kg	1.3 kg
Power*	1.5 Watts	1.7 Watts
Standard Interface	RS422 or MIL-STD-1553B	RS422 or MIL-STD-1553B
Telemetry (minimum)	10 bytes per 60 sec	10 bytes per 60 sec
Diagnostic Sensors	Lightly Shielded Dosimeter Heavily Shielded Dosimeter SEE Detector Particle Telescope	Lightly Shielded Dosimeter Heavily Shielded Dosimeter SEE Detector Particle Telescope Electrostatic Analyzer
*Power requirements can vary for non-standard interfaces. Power ratings for RS422 interface.		

Table 1: Summary of CEASE Properties

References:
1. <http://www.amptek.com/cease.html>
2. Dichter, B.K, et. al., “Compact Environmental Anomaly Sensor (CEASE): A Novel Spacecraft Instrument for In-Situ Measurement of Environmental Conditions”, IEEE Trans. Nucl. Sci., Vol 45, No. 6, p. 2758, December 1998.

2.2.2 Digital Ion Drift Meter (DIDM)

The DIDM instruments are designed to measure the velocity vectors of ambient ions at a spacecraft's location, including also ion density and temperature. Furthermore the electric field strength can be obtained via the relationship between electric field, ion drift velocity and the magnetic field provided by an on-board magnetometer. The DIDM-1000 series is comprised of two sensors mounted directly into the electronics housing. The mechanical specifications of DIDM are listed in Table 2.

Size	6"x5"x4.5" (150mmx128mmx112mm)
Weight	5 lbs (2.3 kg)
Power	5 Watts from a 28 Volt supply

Table 2. Mechanical specifications of DIDM

References:
1. <http://www.amptek.com/didm.html>

2.2.3 Electrostatic Analyzer Detector (ESA)

The two Electrostatic Analyser Detector models (ESA-200 and ESA-500) are designed for satellite and space systems use. They detect and analyse electrons and ions, and provide information on the angular distribution of the incoming particles. Both instruments permit a broad energy passband that may be customised with respect to absolute sensitivity, sweep rates, and data format. A typical configuration measures one second intervals of electrons and ions from 30 eV to 30 keV over an 8° x 2° (ESA-200) or 8°x 90° (ESA-500) viewing angle. The mechanical specifications of the two ESA detectors are listed in Table 3.

	ESA-200	ESA-500
Small Size	5"x5"x6" 127x127x152mm^3	6"x6"x9" 152x152x230mm^3
Lightweight	6 lbs. (2.7 kg)	7 lbs. (3.2 kg)
Low Power	0.5 Watts from a 28 VDC supply	1.5 Watts from a 28 VDC supply

Table 3. Mechanical specifications of ESA-200 and ESA-500

References:
1. <http://www.amptek.com/esa.html>

2.3 Los Alamos National Laboratory (LANL) Geosynchronous Energetic Particle and Magnetospheric Plasma Analyzer Data

Over 10 satellites so far, sponsored by the Department of Energy USA, have provided continuous geosynchronous energetic particle data acquisition from 1976 to the present. The instruments that have been performing the observations are the Charged Particle Analyzer (CPA) and the Synchronous Orbit Particle Analyzer (SOPA) - See Sections 2.3.1 and 2.3.2.

Furthermore the LANL Magnetospheric Plasma Analyzer (MPA) geosynchronous plasma instrument is presented in Section 2.3.3.

References:

1. <http://leadbelly.lanl.gov/lanl_ep_data/lanl_ep.html>
2. <http://leadbelly.lanl.gov/lanl_ep_data/information/general.html>
3. <http://leadbelly.lanl.gov/lanl_ep_data/information/hardware.html>

2.3.1 Charged Particle Analyzer (CPA)

The CPA instrument was flown on satellites launched from 1976 to 1987 (last operation was in 1995). These satellites are in geosynchronous orbit which has a nominal altitude of 6.6 Re (42,000 km), geographic latitude of 0 degrees, and a fixed (but arbitrary) longitude. The actual latitude, longitude, and altitude can vary somewhat.

The CPA experiment consists of four detectors including the LoE (low energy electron), HiE (high energy electron), LoP (low energy proton) and HiP (high energy proton). It performs the following measurements:

- Measures electrons from 30 keV to 2 MeV in 12 energy channels
- Measures protons from 75 keV to 200 MeV in 26 energy channels

References:

1. <http://leadbelly.lanl.gov/lanl_ep_data/information/general.html>
2. P.R. Higbie, R.D. Belian and D.N. Baker, “High-Resolution Energetic Particle Measurements at 6.6 Re: 1 Electron Micropulsations”, J. Geophys. Res., 88, 4851, 1978
3. D.N. Baker, W. Aiello, J.R. Asbridge, R.D. Belian, P.R. Higbie, R.W. Klebesadel, J.G. Laros and E.R. Tech, “Los Alamos Energetic Particle Sensor Systems at Geostationary Orbit”, AIAA 85-0243

2.3.2 Synchronous Orbit Particle Analyzer (SOPA)

The SOPA instrument has flown on satellites launched beginning in 1989 and these satellites are in geosynchronous orbit, geographic latitude of 0 degrees, and a fixed (but arbitrary) longitude. The actual latitude, longitude, and altitude can vary somewhat. Besides measuring electrons and protons, heavy ions are also recorded:

- Measures electrons from 50 keV to 26 MeV in 16 energy channels
- Measures protons from 50 keV to >50 MeV in 15 energy channels
- Measures heavy ions in 10 channels, 7 mass groups, at energies >0.5 MeV

The instrument consists of three solid state detector telescopes that accept particles from three different directions relative to the spacecraft spin axis.

References:

1. <http://leadbelly.lanl.gov/lanl_ep_data/information/general.html>
2. R.D. Belian, G.R. Gisler, T. Cayton a,d R. Christensen, “High-Z Energetic Particles at Geostationary Orbit During the Great Solar Proton Event Series of October 1989”, J. Geophys. Res., 97,16,897, 1992

2.3.3 Magnetospheric Plasma Analyzer (MPA)

The MPA instruments were designed and built to measure the three-dimensional plasma electron and ion distributions, with energies between ~1 eV/q and ~ 40 keV/q, at geosynchronous orbit. It is a unique system using a single electrostatic analyser coupled to a single array of channel electron multipliers that makes this possible. By changing the polarity of the plate voltage and channel electron multiplier bias, the ion and electron distributions are measured alternately.

The MPA has a low weight of 3.6 kg and a power usage of 3.5 Watts.

References:

1. <http://nis-www.lanl.gov/nis-projects/mpa/mpa_inst.shtml>
2. D.J. McComas, S.J. Bame, B.L. Barraclough, J.R. Doart, R.C. Elphic, J.T. Gosling, M.B. Moldwin, K.R. Moore and M.F. Thomsen, “Magnetospheric Plasma Analyzer: Initial Three-Spacecraft Observations from Geosynchronous Orbit”, Journal of Geophysical Research, 98, A8, 13,453, August 1, 1993
3. S.J. Bame, D.J. McComas, M.F. Thomsen, B.L. Barraclough, R.C. Elphic, J.P. Glore and J.T. Gosling, “Magnetospheric Plasma Analyzer for Spacecraft with Constrained Resources”, Rev. Sci. Instrum., 64, 4, April 1993

2.4 Mullard Space Science Laboratory (MSSL) Black-boxes

2.4.1 High-Energy

MSSL is being funded by the satellite insurance industry, as part of the Tsunami initiative, to examine the effects of space weather on satellites. One of the studies involves the development of a “black box” detector to be carried by future commercial satellites as a piggy-back payload. This will add much needed high-quality data to what are currently sparse records of the radiation environment near the Earth.

This “black-box detector” will measure electrons in the 300 keV to 3 MeV energy range, thus concentrating on the energy-range relevant in the study of deep di-electric charging. A prototype of this detector has been developed with a mass of 0.5 kg, a power usage of 2 Watts and a telemetry rate of 100 bits/s.

References:
1. <http://www.mssl.ucl.ac.uk/www_plasma/homepage.html>
2. <http://www.mssl.ucl.ac.uk/news>

2.4.2 Low-Energy

MSSL is also involved in the development of a low-energy plasma monitor in the 0 to 30 keV range. This energy range is ideal for studying spacecraft surface charging effects. A prototype has also been developed and this detector is also intended to be carried by future commercial satellites as a piggy-back payload. It has a mass of 0.8 kg, a power usage of 2 Watts and a telemetry rate of 100 bits/s.

References:
1. <http://www.mssl.ucl.ac.uk/www_plasma/homepage.html>

2.5 Iridium Magnetometer

The Ithaco series of magnetometers have been designed specifically for use on spacecraft where mass, size and power requirements need to be minimized in both two- and three-axis configurations. Ithaco's production of the IM Series Magnetometers (see table 4) exceeds 175 units with the largest single production order to support IRIDIUM®.

INSTRUMENT	NUMBER OF AXES	ENERGY RANGE	MASS	POWER
Iridium Magnetometer IM-102	Two orthogonal	+/- 600 mG	< 220 g	<50 mW (0 mG) <100 mW (600 mG)
Iridium Magnetometer IN-103	Three orthogonal	+/- 600 mG	< 227 g	<0.8 mW (0 mG) <1.0 mW (600 mG)
Iridium Magnetometer IM-203	Three orthogonal	+/- 1000 mG	< 635 g	<1.4 mW (0 mG) < 1.7 mW (600 mG)

Table 4. The IM Series Magnetometers

Iridium is a constellation of 72 Low Earth Orbit satellites. The company provided global satellite telephone services until it filed for bankruptcy last year. A new company, Iridium Satellite LLC, has taken over the satellites and will keep them operating for at least the next few years. Each satellite has a magnetometer, which measures the Earth's magnetic field. These magnetometers provide continuous vector measurements of the Earth's magnetic field as the spacecraft orbits Earth. The magnetometer variations can be interpreted to show geospace dynamics, i.e. changes in shape due to solar effects.

References:

1. <http://www.crcss.csiro.au/spin/spin89/spin8907.html>
2. <http://www.ithaco.com/TorqRods.html>
3. <http://www.ithaco.com/Magnetometers.html>

2.6 Gorizont 91/2 (ADIPE)

The Gorizont satellites are a series of telecommunication satellites in geostationary orbit and started operating on November 25th, 1991. In addition to their main payload, these satellites also carried instruments to monitor the space environment.

ADIPE is the spectrometric and dosimetric instrument group of instruments on the Gorizont satellites produced by the Scientific Production Association of Applied Mechanics (NPO-PM) in Krasnoyarsk. The instrument package consists of a faraday cup, a cylindrical electrostatic analyser, solid state detectors, gas discharge counters, Cherenkov counters and gas proportional counters. The main data rate is 128s.

References:

1. Rodgers, D. J., Evaluation of Russian Spacecraft Charging Data, Chapter 6 in Final Report On Rider 2, Estec Contract No. 7989/88/NL/PB(SC), 1994.

2. <http://www.spenvis.oma.be/spenvis/help/models/chargingdata/chargingdatamain.html>
3. <http://www.spenvis.oma.be/spenvis/help/models/chargingdata/adipe/adipemain.html>

2.7 ICARE/COMRAD

This is a CNES/Alcatel initiative which has flown on XMM and will fly on Stentor. The measurement range for electrons is 50 keV-6 MeV, protons 8 –30 MeV, heavy ions 1-100 MeV/(mg/cm2)

3. SOLAR MONITORS

3.1 Solar X-ray Imager (SXI)

The SXI provides full-disk X-ray images of the Sun in several wavelength bands from 0.6 to 6 nm. SXI measures the X-ray flux of the Sun in a 512 x 512 grid, these million+ pieces of information are then combined to make a single image of the Sun in X-rays. The power requirements are 57 Watts and the total mass of SXI is 14.76 kg telescope and 7.9 kg electronics.

The geosynchronous orbit of the GOES satellite provides nearly continuous viewing of the Sun, and two SXI in operation gives complete coverage.

In the summer of 2001, NOAA began to monitor the structure of the solar atmosphere via the Solar X-ray Imager (SXI) onboard its GOES satellites.

References:
1. <http://www.sel.noaa.gov/sxi/>
2. <http://www.sel.noaa.gov/sxi/sxi_doc/SXI_SPIE.html>

4. SPACE DEBRIS MONITORS

Knowledge on the meteoroid and space debris environment is required for a reliable spacecraft risk assessment and for the design of protective shielding. Radar or optical telescopes from the ground can detect particles larger than a few cm in diameter. Information on the sub-millimeter environment is only possible by retrieving spacecraft (< 600 km) or in other cases by in-situ monitors in orbit to obtain information about impacting fluxes, their seasonal variations and long term evolution.

4.1 DEBris In orbit Evaluator (DEBIE)

DEBIE is under development and will be a standard meteoroid and space debris in-situ monitor which will actively monitor sub-millimeter sized particles which impact its surface. It consists of a Data Processing Unit with up to four Sensor Units and the detecting area of a sensor unit is 10 cm x 10 cm per sensor. The power consumption is less than 4.0 W with four Sensor Units and the weight is 3.0 kg with four Sensor Units.

The standard in-situ impact detector DEBIE will fly on ESA's PROBA spacecraft, scheduled for launch later in 2001. A second DEBIE could be placed on the International Space Station as external payload.

References:
1. <http://www.estec.esa.nl/wmwww/WMA/research/debie/debie_web.html>
2. <http://www.esa.int/est/prod/prod0431.htm>

4.2 Geostationary Orbit Impact Detector (GORID)

On 26 September 1996 the Russian Express-2 telecommunications spacecraft was launched into geostationary orbit (GEO). The GORID Cosmic Dust/Space Debris detector was included as a piggyback instrument. The instrument consists of a plasma type detector and associated electronics and is essentially identical to the Dust detectors flying on the Ulysses and Galileo spacecraft. Its mass is 3.8 kg and it has a power usage of 2.2 W and a telemetry rate of 8 bits/s. Data are down-linked every 10 days and sent via e-mail to ESTEC

References:
1. http://www.estec.esa.nl/wmwww/WMA/research/gorid/gorid_web.html

5. COLUMBUS RADIATION ENVIRONMENT AND EFFECTS PACKAGE (CREEP)

CREEP is an experiment proposed to ESA in response to the Announcement of Opportunity for externally mounted payloads during the early International Space Station (ISS) utilisation period.

The CREEP experiments have been chosen to provide complementary, high-quality data on various particle species over a wide energy range. In addition, directional particle flux information will also be available. The effects of the space radiation environment on a number of critical electronics components will additionally be studied. In its initial configuration, CREEP will contain the following sub-units:

- Standard Radiation Environment Monitor (SREM) – see Section 2.1.2
- CREAX - The instrument is optimised for cosmic ray detection, although protons and electrons are also detected, and can provide directional information. CREAX weighs 2.4 kg, has a power consumption of 3-5 W, and a volume of about 2 litres.
- SPICA - The instrument measures electrons (>0.1 MeV), protons (>4 MeV), and heavy ions (1-100 MeV/mg/cm2) with a high spectral resolution. The weight of SPICA is 3 kg, power consumption is 6-7 Watts, and it has a volume of 4 litres.
- Proton and Dose-Depth Monitors (PM and DDM) - The PM is designed for proton-induced Single Event Upset (SEU) detection from protons > 30 MeV. The DDM measures total ionising radiation doses behind four different thicknesses of aluminum representing spacecraft shielding. The mass of the PM is 0.3 kg, its power consumption is 0.4W, and its volume ~ 0.3 litres. The mass of the DDM is 0.5 kg, its power consumption is 0.9 W and its volume ~ 0.4 litres.
- Columbus Technology Test-Bed (CTTB) – The CTTB is intended to carry a number of experiments ranging from Commercial Off-The-Shelf digital and analogue components to photonics components.

References:
1. <http://www.estec.esa.nl/wmwww/WMA/creep/index.html>

6. STRV-PAYLOAD

STRV-1a
Atomic Oxygen Experiment, Battery Recharge, Cold Ion Detector, Cosmic Ray & Dosimetry Monitor, Langmuir Probe, Radiation Dose Rate Sensor, Surface Charge Detector and the Xenon Plasma Charge Neutraliser

- Of particular interest here is the Cold Ion Detector (CID). In addition to measuring the plasmaspheric ions for which it was designed, it was sensitive to penetrating electrons >750 keV, providing an effective monitor of their intensity. Cross-calibration with REM on 1b showed excellent results.

STRV-1b
Cryocooler/Vibration Suppression Experiment, Infrared Detectors, Neural Network Microprocessors, Radiation Environment Monitor, Single Event Upset & Radiation Monitor and the Solar Cell Technology Experiment.

- Radiation Environment Monitor (REM)

STRV-1c and STRV-1b

Radiation Experiments:

- The Cosmic Rays and Dosimetry Experiment, Ministry of Defence and DERA
- The Surface Charge Experiment, DERA
- The Standard Radiation Environment Monitor (SREM), ESA
- The Compact Environmental Anomaly Sensor (CEASE), U.S. Air Force
- The Proton Monitor, Defence Research Establishment, Canada
- The Depth Dose Monitor, Defence Research Establishment, Canada

Other Scientific Experiments:

- Atomic Oxygen Experiment on STRV-1c, Southampton University
- Micrometeoroid and Dust Detector, Open University and ESA
- Changes in the Ionosphere Measurements when the Satellite is near Perigee on STRV-1d, U.S. Air Force / Naval Research Laboratory

References:

1. <http://www.ras.org.uk/press/pn00-18.htm>

7. GOES-PAYLOAD

NOAA operates a series of meteorology observing satellites known as Geosynchronous Operational Environmental Satellites (GOES). Besides providing us with the local weather broadcast, GOES also monitors space weather via its onboard Space Environment Monitor (SEM) system. Until 2001, NOAA monitored three prominent space weather parameters: energetic particles (EPS), magnetic field (MAG) and the total X-ray output of the Sun (XRS). In the summer of 2001, NOAA also began to monitor the structure of the solar atmosphere via the Solar X-ray Imager (SXI), see Section 4. The payload of GOES-10 is listed below.

GOES-10 Characteristics
Launch date: April 25, 1997

Sensors:

- Imager
- Sounder
- Space Environment Monitor (SEM)
- Data Collection System (DCS)
- Search and Rescue (SAR) Transponder

References:
1. < http://www.ngdc.noaa.gov/stp/CDROM/goesCD.html >
2. < http://www.oso.noaa.gov/goes/index.htm > - click on ‘GOES Satellite System’.
3. < http://www.ngdc.noaa.gov/stp/GOES/goes_mission.htm>

8. POES -PAYLOAD

Complementing the GOES satellites are polar-orbiting satellites. The POES system includes the Advanced Very High Resolution Radiometer (AVHRR) and the Tiros Operational Vertical Sounder (TOVS).

The Second Generation Space Environment Monitor (SEM-2) began operations with the launch of NOAA-15 and is comprised of two detectors: 1.) Total Energy Detector (TED) and 2.) Medium Energy Proton and Electron Detector (MEPED)

- TED provides the data used to determine the level of auroral activity. It monitors the electron fluxes carried into the atmosphere by electrons and positive ions over the energy range between 50 and 20,000 eV.
- MEPED includes four solid-state detector telescopes, two to measure the intensity of electrons between 30 and 1000 keV and two to measure the intensity of protons (positive ions) between 30 and 6900 keV, as well as solid-state “dome” detectors that measure the intensities of protons between 16 MeV and 275 MeV.

The payload of NOAA-15 is listed below.

NOAA-15 Characteristics
Launch date: May 13, 1998

Sensors:

- Advanced Very High Resolution Radiometer (AVHRR/3)
- Advanced Microwave Sounding Unit-A (AMSU-A)
- Advanced Microwave Sounding Unit-B (AMSU-B)
- High Resolution Infrared Radiation Sounder (HIRS/3)
- Space Environment Monitor (SEM/2)
- Search and Rescue (SAR) Repeater and Processor
- Data Collection System (DCS/2)

References:

1. < http://www.sel.noaa.gov/pmap/PoesSem.html >
2. < http://www.oso.noaa.gov/poes/index.htm >

9. DATA BASE OF LOW ALTITUDE SPACE RADIATION ENVIRONMENT (DB LASRE)

The DB LASRE contains experimental data about energetic electrons (E >40 keV) and energetic protons (E >0.5 MeV) observed on the near Earth's satellites at altitudes less than 1000 Km and was developed at the D.V. Skobeltsyn Institute of Nuclear Physics of M.V. Lomonosov Moscow State University. The observations cover the period from 1979 to present time (two solar cycles). High inclined orbits of some satellites and large sensitivity of some detectors allow observations of both trapped particles and particle fluxes under the radiation belts including the polar cap regions. Missions that have provided this data include:

- Intercosmos-19 – The SINP MSU instrument package onboard Intercosmos-19 measures energetic electrons with energy >40 keV in 6 energy ranges and energetic protons with energy >0.9 MeV. Data is available from March to August 1979
- Cosmos-1686 – The instrument package ELECTRON-4 (developed in SINP MSU) onboard Cosmos-1686 permits to measure energetic electrons with energy >40 keV in 6 energy ranges and protons with energy >0.9 MeV in 3 energy ranges. Data is available from February to December 1986.
- CORONAS-I – CORONAS-I carries the SCR (Solar Cosmic Rays) instrument package created at the D.V. Skobeltsin Institute of Nuclear Physics Moscow State University (SINP MSU). The SCR package onboard CORONAS-I measures energetic electrons with energy >0.5 MeV and energetic protons from ~1 MeV to hundreds of MeV and nuclei (He to O). The SCR combines some of the most sensitive energetic particle sensors (MCR, SONG) ever flown in space and consists of three instruments (data availability: March 1994 to April 1995):
    1.) MCR (Monitor of Cosmic Rays)
    2.) SONG (Solar Neutron and Gamma-Quantum)
    3.) SCR-3 (Solar Cosmic Rays-3).
- MIR Station – There were two space experiments by SINP MSU onboard the MIR Station (Riabina and GRIF). Riabina included two instruments inside the Kvant-2 module: gas-discharge counter (gdc) (diameter 1cm and length 7.5 cm) and scintillating crystal NaI(Tl) (diameter 1.6 cm and height 3 cm).

References:
1. http://dec1.npi.msu.su/english/data/lasre/index.html

Table – piggy back monitors

TABLE
PIGGY-BACK MONITORS 1

INSTRUMENT	MEASURED PARAMETER	ENERGY RANGE	MASS	POWER	TELEMETRY
REM	- Electrons - Protons	- 1 MeV - 25 MeV	1.8 kg	< 5 W	
SREM	- Electrons - Protons	- 0.3 to 6 MeV - 8 to 300 MeV	< 2.5 kg	< 2 W	
CEASE I	Radiation dose Radiation dose rate Electron flux	$50 < E < 250$ keV $E > 250$ keV	1.0 kg	1.5 W*	10 bytes/60 s
CEASE II	Radiation dose Radiation dose rate Electron flux	$50 < E < 250$ keV $E > 250$ keV	1.3 kg	1.7 W*	10 bytes per 60 s
DIDM	Ions	Velocity vector Density Temperature	5 lbs (2.3 kg)	5 W from a 28 V supply	
ESA-200	Electrons Ions (angular distribution) 8° x 2° viewing angle	30 eV to 30 KeV	6 lbs. (2.7 kg)	0.5 W from a 28 VDC supply	
ESA-500	Electrons Ions (angular distribution) 8° x 90° viewing angle	30 eV to 30 KeV	7 lbs. (3.2 kg)	1.5 Watts from a 28 VDC supply	

(*) Power requirements can vary for non-standard interfaces.

TABLE
PIGGY-BACK MONITORS 2

INSTRUMENT	MEASURED PARAMETER	ENERGY RANGE	MASS	POWER	TELEMETRY
CPA	- Electrons - Protons	- 30 keV to 2 MeV - 75 keV to 200 MeV			
SOPA	- Electrons - Protons - Heavier Ions	- 50 keV to 26 MeV - 50 keV to >50 MeV - >0.5 MeV			
MPA	Plasma Electron and Ion Distributions	E/q ~ 1 eV/q to 40 keV/q	3.6 kg	3.5 W	
MSSL HE	electrons	300 keV-3 MeV	0.5 kg	2 W	100 bits/s
MSSL LE	electrons	0-30 keV	0.8 kg	2 W	100 bits/s
ICARE/COMRAD	Electrons, protons, heavy ions	50keV-6MeV (e), 8-30 MeV (i), 1-100 MeV (heavy)	2.4	7	
Iridium Magnetometer IM-102	Earth's Magnetic field	+/- 600 mG	< 220 g	<50 mW (0 mG) <100 mW (600 mG)	
Iridium Magnetometer IN-103	Earth's Magnetic field	+/- 600 mG	< 227 g	<0.8 mW (0 mG) <1.0 mW (600 mG)	
Iridium Magnetometer IM-203	Earth's Magnetic field	+/- 1000 mG	< 635 g	<1.4 mW (0 mG) < 1.7 mW (600 mG)	
Gorizont 91/2 (ADIPE)					
SXI	X-ray	0.6-6 nm (0.2-2 keV)	14.76 kg telescope 7.9 kg electronics	57 W	

TABLE
PIGGY-BACK MONITORS 3

INSTRUMENT	MEASURED PARAMETER	ENERGY RANGE	MASS	POWER	TELEMETRY
DEBIE	small-size (sub-millimeter) meteoroid & space debris		3.0 kg with four Sensor Units	less than 4.0 W with four Sensor Units	
GORID	submicron to millimetre size meteoroid & space debris		3.8 kg	2.2 W	8 bits/s