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WP610. Project Implementation Plan

Project Implementation Plan and Final Report

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1 Preface

1.1 Document change record

Issue	Date	Notes/remarks
0.4	24 Aug 2001	Outline of implementation plan for internal discussion
0.9	14 Nov 2001	First complete draft for internal review
1.0	23-Nov-2001	First formal issue

1.2 Purpose of the document

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This document presents a plan to implement a European space weather programme based on the requirements and design ideas developed during a study under ESA contract 14069/99/NL/SB. As envisaged in [PROPOSAL], the document also forms the final report from that study; it therefore includes a substantive review of the foundation work within this study (on which the implementation plan is based).

1.3 Definitions, acronyms and abbreviations

ACE	Advanced Composition Explorer (NASA spacecraft)
AE	Auroral Electrojet (index of geomagnetic activity at high latitudes)
AKR	Auroral Kilometric Radiation (radio emission produced by auroral electron precipitation)
ALIS	Auroral Large Imaging System (http://alis.irf.se/alis/)
Ap	Planetary index of geomagnetic activity at mid-latitudes
BIRA	Belgian Institute for Space Aeronomy
B-field	Magnetic field
BNSC	British National Space Centre
CARI	Civil Aeromedical Research Institute
CCSDS	Consultative Committee for Space Data Standards
CDAW	Co-ordinated Data Analysis Workshops
CDAWlib	Library of IDL-based tools developed by NASA for use with CDF files - compliant with IACG standards
CD-ROM	Compact Disc - Read-Only Media
CELIAS	Charge, Element, and Isotope Analysis System
CHAMP	CHAllenging Microsatellite Payload
CME	Coronal Mass Ejection
CNES	Centre National d'Etudes Spatiales
CORBA	Common Object Request Broker Architecture
CREME	Cosmic Ray Effects on Micro-Electronics
CSMR	Consolidated System Measurement Requirement
CTIP	Coupled Thermosphere Ionosphere Plasmasphere model
dB/dt	Rate of change of magnetic field

DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt
DSN	Deep Space Network (NASA ground station network)
Dst	Index of equatorial geomagnetic activity due to ring current in magnetosphere
ECMWF	European Centre for Medium-range Weather Forecasting
EIT	Extreme ultraviolet Imaging Telescope
ERNE	Energetic and Relativistic Nuclei and Electron experiment on (SOHO)
ESA	European Space Agency
ESOC	European Space Operations Centre (Darmstadt)
ESF	European Science Foundation
EUMETSAT	European organisation for the exploitation of METeorological SATellites
EUV	Extreme ultra-violet
foF2	Critical frequency of the F2 layer in the Earth's ionosphere. Similarly foE and foF1 for the critical frequencies of the E and F1 layers.
FMI	Finnish Meteorological Institute
FTP	File Transfer Protocol
F10.7	Index of solar radio emission at 10.7cm wavelength. Also called the Penticton index.
GEANT	GEometry ANd Tracking
GCR	Galactic cosmic rays
GEO	Geosynchronous orbit
GIC	Ground induced current
GIM	Global Ionospheric Maps
GNSS	Global Navigation Satellite System
GNU	Gnu’s Not Unix
GPS	Global Positioning System
GTO	Geosynchronous Transfer Orbit
GUMICS	Grand Unified Ionosphere-Magnetosphere Coupling Simulation
HLA	High level architecture
HF	High frequency (radio)
HTML	HyperText Markup Language
HTTP	Hypertext Transfer Protocol
IACG	Inter-Agency Consultative Group
IDES	Integrated Debris Evolution Suite
IDL	Interactive Data Language - programming environment with rich set of mathematical and graphical functions (sold by Kodak/RSI)
IMF	Interplanetary magnetic field
INTERMAGNET	International Real-time Magnetic observatory Network, http://www.gsrg.nmh.ac.uk/intermagnet/
IPS	Interplanetary scintillation
IRF	Swedish Institute of Space Physics
IRI	International Reference Ionosphere
ITU	International Telecommunications Union
ITU-R	ITU recommendation
JOSO	Joint Organization for Solar Observations, http://joso.oat.ts.astro.it/
JPL	Jet Propulsion Laboratory
keV	kilo-electron-volt (unit of energy)

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Kp	Planetary index of geomagnetic activity at mid-latitudes. Same as Ap but Kp is presented on a logarithmic scale while Ap is presented on a linear scale.
L	L value or McIlwain parameter. It is a way of labelling and ordering particle trajectories in the magnetosphere - based on the adiabatic invariants of charged particle motion in a magnetic field
LASCO	Large Angle and Spectrometric Coronagraph
LEO	Low Earth orbit
L1	Lagrangian point 1 (1500000 km sunward of Earth)
MASTER	Meteoroid And Space debris Terrestrial Environment Reference model
MeV	mega-electron-volt (unit of energy)
MSFM	Magnetospheric Specification and Forecast Model
MSIS	Model of atmospheric composition, density and temperature based on Mass Spectrometer (MS) and Incoherent Scatter (IS) radar measurements
MSSL	Mullard Space Science Laboratory
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
Ne	Number density (of a plasma)
Nsw	Number density of the solar wind
NWRA	North West Research Associates
ONERA-DESP	Office National d'Etudes et de Recherches Aérospatiales, Département Environnement Spatial
PEO	Polar Earth orbit
PIM	Parameterized Ionospheric Model
POES	Polar Operational Environmental Satellite
PRISM	Parameterized Real-time Ionospheric Specification Model
RAID	Redundant Array of Identical Disks
RAL	Rutherford Appleton Laboratory
RF	Radio frequency
S/c	Spacecraft
SCR	Solar Cosmic Rays
SEPE	Solar energetic particle event
SFE	Service Functional Element
SFR	Service Functional Requirement
SIP	Service Implementation Proposal
SMR	System Measurement Requirement
SMS	Short Message Service
SMTP	Simple Message Transfer Protocol
SOHO	Solar and Heliospheric Observatory
SPE	Solar proton event
SSN	Sunspot number
SSWG	Solar System Working Group (ESA)
STP	Solar Terrestrial Physics
SuperDARN	Super Dual Auroral Radar Network
SUR	Service User Requirement
SWS	Space Weather Service
TBD	To be done
TEC	Total electron content

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TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics (NASA spacecraft)
UCL	University College London
UK	United Kingdom
URL	Uniform Resource Locator
US	United States
UV	Ultra-violet
Vsw	Velocity of the solar wind
WBMOD	WideBand MODel
W3C	World-Wide Web Consortium
XMM	X-ray Multi-Mirror

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1.4 Important Documents

We list here the various documents used as source material for this report. These include both hardcopy and web sources. For convenience we divide this list into two sections:

- The reports generated by this study
- Other documents

Documents may be referenced in the text and this is indicated by a series of characters enclosed in square brackets, e.g. [ITT].

1.4.1 Reports from this study

BENEFITS	ESWPS-DER-TN-0001, Benefits of a European Space Weather Programme
PROTYPING	ESWS-BIR-TN-0001, Space Weather Prototype System
EFFECTS	ESWS-FMI-RP-0001, Space Weather Effects Catalogue
G_INTERFACE	ESWS-RAL-TN-0002, Interface between spacecraft ground segment and space weather service
INST_DEF	ESWS-RAL-TN-0001, A definition of instruments needed for space weather measurements
MA	Space Weather Market Analysis: Summary Report for the ESA Space Weather Working Team
CASE_STUDIES	ESWS-FMI-WP433, Testing user scenarios with space weather events
RATIONALE	ESWS-FMI-RP-0002, Rationale for a European Space Weather Programme
ROADMAP	ESWS-RAL-RP-0003, Roadmap for European co-ordination in space weather
SC_INTERFACE	ESWS-RAL-TN-0004, Ground segment interface with space-based space weather measurements
SPACE_SEG	Space Weather – Space Segment Options
SRD	ESWP-DER-SR-0001, System Requirements Definition
SW_SERVICE	ESWS-RAL-TN-0003, Space Weather Service
SWR_CAT	ESWS-RAL-RP-0001 Catalogue of European Space Weather Resources

These reports from our study will be publicly available once they have been completed. You can download them as PDF files from our web site at http://www.wdc.rl.ac.uk/SWstudy.

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1.4.2 Other documents

APACHE	http://httpd.apache.org/
CARI	http://www.cami.jccbi.gov/aam-600/610/600Radio.html
CCSDS	Consultative Committee for Space Data Systems, http://www.ccsds.org/
CHAMP1	A. Wehrenpfenig N. Jakowski, and J. Wickert, A dynamically configurable system for operational processing of space weather data. *Phys. Chem Earth (C)* **26**, 601-604, 2001
CHAMP2	N. Jakowski, S. Heise, A. Wehrenpfenig and S. Schlüter, TEC Monitoring by GPS - a possible contribution to space weather monitoring. *Phys. Chem Earth (C)* **26**, 609-613, 2001
CORBA	http://www.omg.com/gettingstarted/corbafaq.htm
COSTELLO	http://sec.noaa.gov/rpc/costello/index.html
CREME	http://crsp3.nrl.navy.mil/creme96/cm/refs.htm
CTIP	http://alpha.apg.ph.ucl.ac.uk/Docs/ctip index.htm
EISCAT	European Incoherent Scatter radar, http://seldon.eiscat.uit.no/instrumentation.html
GEANT	http://wwwinfo.cern.ch/asd/geant4/geant4.html
GIM	http://iono.jpl.nasa.gov/gim.html
GUMICS	http://www.geo.fmi.fi/~pjanhune/gumics3/
HLA	High Level Architecture, http://www.dmso.mil/index.php?page=64/
IDES	Integrated Debris Evolution Suite, TBD
INAG	Ionosonde Network Advisory Group, http://www.ips.gov.au/INAG/
INTERMAGNET	The International Real-time Magnetic observatory Network, http://www.gsrg.nmh.ac.uk/intermagnet/
IPS1	R.A. Harrison, M.A. Hapgood, V. Moore and E.A. Lucek, (1992) "An Interplanetary Scintillation activity index", *Ann. Geophysicae* **10**, 519-526.
IPS2	Mike Hapgood and Elizabeth Lucek, (1999) "Interplanetary Scintillation and Space Weather Monitoring", *Proceeding of the Workshop on Space Weather* - held at ESTEC, 11-13 November 1998, **ESA WPP-155**, 487-490.
IRI	http://nssdc.gsfc.nasa.gov/space/model/ionos/iri.html.
ITU-R	International Telecommunications Union. *ITU-R Methods of basic MUF, operational MUF and ray-path predictio*n, Recommendation P.1240 (05/97) edition, May 1997.
JINI	http://www.javacommerce.com/tutorial/jini
JOSO	Joint Organisation for Solar Observations, http://joso.oat.ts.astro.it/
JPL91	Feynman,J., Spitale,G., Wang,J. And Gabriel,S. (1993) Interplanetary proton fluence model: JPL 1991, *J.Geophys.Res.* **98**, 13281-13294.
LUND	http://www.irfl.lu.se/HeliosHome/spacew2.html.
LUND2	F Boberg, P Wintoft, and H Lundstedt. Real time Kp predictions from solar wind data using neural networks. *Physics and Chemistry of Earth, Part* C, 25(4):275–280, 2000.
LUND3	http://sol.irfl.lu.se/~fredrikb/Kp/

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MASTER	H Klinkrad, J Bendisch, H Sdunnus, P Wegener, and R Westerkamp. An introduction to the 1997 ESA MASTER model. In *Proceedings of the Second European Conference on Space Debri*s, volume ESA SP-393, pages 217–224, May 1997.
METATECH	Applied Power Solutions division and Geomagnetic Storm Forecasting services, http://www.metatechcorp.com/aps/apsmain.html
METEOR	P Jenniskens. Meteor stream activity. *Astronomy and Astrophysic*s, 287:990–1013, 1994.
MODELS	http://www.expi.net/space/tools.html
PIM	R E Daniell, L D Brown, D M Anderson, and M W Fox. Parametrized Ionospheric Model: A global ionospheric parametrization based on first principle models. *Radio Scienc*e, 30(5):1499–1510, Sep-Oct 1995.
POES	http://www.sel.noaa.gov/pmap/index.html
PRISM	http://www1.primushost.com/~cpibos/ Computational Physics, Inc., vendor of PRISM.
PROPOSAL	RAL/RRS/116/99. Study for an ESA Space Weather programme. Proposal in Response to ESA ITT AO/1-3533/99/NL/SB. 28 October 1999
SALAMMBO	S Bourdarie, D Boscher, M Blank, and J A Sauvaud. A physical 4D radiation belt model including a time dependent magnetic field. *Advances in Space Researc*h, 25(12):2303–2306, 2000.
SHEA	M A Shea and D F Smart. . In *18th International Comsic Ray Conference*, *Conference Paper*s, volume 3, page 415, 1983.
STØRMER	C Stormer. . *Z. Astrophys*., 1:237, 1930.
SDARN	Super Dual Auroral Radar Network (SuperDARN), http://superdarn.jhuapl.edu/
SWARM	SWARM : A Fleet of Microsatellites to Explore the Magnetosphere, http://sprg.ssl.berkeley.edu/ConstellationClassMissions/Schwartz.pdf
SWAVES	STEREO SWAVES instrument, http://www-lep.gsfc.nasa.gov/swaves/swaves.html
THEMIS	Télescope Héliographique pour l'Étude du Magnétisme et des Instabilités Solaires, http://www.themis.iac.es/
TSYG	http://nssdc.gsfc.nasa.gov/space/model/magnetos/tsygan.html
TTP	ESA Technology Transfer Programme, http://www.esa.int/ttp/
WBMOD1	E J Fremouw and J A Secan. Modeling and scientific application of scintillation results. *Radio Scienc*e, 19:687–694, 1984.
WBMOD2	http://www.nwra-az.com/ionoscint/wbmod.html

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2 Executive summary

This is the Final Report from ESA Contract No. 14069/99/NL/SB to study the requirements for, and implementation of, a European space weather programme. The study has followed a systems approach as follows. We first reviewed the current state of scientific knowledge about space weather processes and discussed the potential benefits of a space weather programme. We also surveyed organisations that are affected by space weather to establish an initial set of requirements for services of potential use to them. We then analysed these user requirements to identify the modelling processes that can generate space weather products for these users together with the measurements that are required as inputs to those modelling processes. This established a set of system measurement requirements that specifies the measurement capabilities required in the proposed space weather programme. We then discussed options for implementation of those requirements through an appropriate combination of ground-based and space-based sensors. Finally we discussed the infrastructure required to support those sensors, to collect data from them and to generate and disseminate the required products. In following the above logic, we established and maintained traceability back to the system and user requirements. Thus it will be straightforward to find the implementation issues that are affected by any change in the requirements.

This systems approach has been strongly guided by our understanding of the basic science underlying space weather (i.e. solar-terrestrial physics). It is this scientific understanding that allows us to relate user requirements (e.g. for prediction of ionospheric conditions) to other space weather data (e.g. changes in the heliospheric magnetic field upstream of the Earth). The systems approach then allows us to consolidate measurement requirements so that we can see how certain measurements address many user requirements.

The survey of user needs also showed that there is significant user demand, and willingness to pay for, for specific and well-targeted space weather services. However, that demand is focussed on the provision of services that interpret space weather measurements to generate products that can be used without specialist knowledge of space weather. There are significant opportunities here for niche developments by industry, government laboratories and academia. In contrast, we find that end users do not require direct access to space weather measurements and are not willing to pay for collection of, or access to, such data. They regard that as a public sector function as it is for other environmental measurements, e.g. meteorological data. An important issue that follows from this view is that there is no user demand for an overarching space weather service. Integration of services can only be justified when it improves the delivery of services to all the users affected, e.g. where implementation as an integrated service yields technical or financial advantages.

The result of the study is a proposal to establish a space weather programme that collects data on relevant space weather parameters through a combination of space-based and ground-based sensors and processes these to deliver products required by users. The space element has been analysed quite extensively. We have looked at options to obtain the required measurements by three routes: (a) taking data from existing and planned missions, (b) placing space weather instruments as hitch-hiker payloads on other missions, and (c) establishing a number of dedicated missions to make space weather measurements. We find that opportunities to use existing and planned space missions as data sources will be very limited, especially if we restrict this to European missions. The availability of data will be much enhanced if we consider use of hitch-hiker payloads and dedicated missions. Hitch-hiker payloads are suited to measurements in geosynchronous orbit (e.g. radiation belt monitors) and perhaps in low Earth orbit (e.g. auroral imagery, debris monitors). In contrast

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dedicated missions are suited to measurements that require unusual orbits such as L1 (e.g. for monitoring the heliospheric medium upstream of Earth) and orbits off the Earth-Sun line (e.g. for monitoring Earth-directed solar ejecta). In addition, dedicated missions can provide a convenient platform for space weather measurements with less critical orbit requirements (e.g. flying a solar proton monitor on an L1 mission). Thus the costs of dedicated missions can be spread over a greater range of measurements and thus increase the data return from investment in such missions.

An important and generic result of the study is that the architectures of space weather missions (both hitch-hiker payloads and dedicated missions) will be driven by the need to return telemetry in near-real-time so that it can be processed in time to produce useful space weather products. This will drive space weather missions in a very different way to science missions (where delayed downlink is usually acceptable as a way of reducing costs).

Another important result is that, contrary to our expectations at the start of the study, the costs of implementing hitch-hiker and dedicated missions are broadly similar. Thus we suggest that the space segment of any future space weather programme is likely to involve a mixture of dedicated missions and hitch-hiker payloads. We present an initial ranking of the priorities for both classes of missions and provide a methodology for assessing how to match a mixture of the classes to the available level of funding.

We also show that ground-based sensors are an important part of any space weather programme. Many relevant measurements can be made on the ground and are usually much cheaper to build and operate than are space-based measurements. There is already an extensive base of ground-based measurements across Europe. But these are fragmented across local, national and pan-European programmes and are often at risk of cuts as a result of that fragmentation. There is an urgent need for better co-ordination to demonstrate the value of European ground-based measurements and thus to persuade funding agencies to slow down, and perhaps reverse, the trend to cut these activities. We note that some new ground-based techniques have great potential for the future and warrant funding of development activities, e.g. use of HF backscatter radars to monitor the high-latitude ionosphere as a proxy for magnetospheric dynamics, use of interplanetary scintillation to monitor the propagation of heliospheric disturbances away from the Sun.

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We have developed a plan for the organisation and implementation of a European space weather programme. This includes the following organisational structures:

- A Network for Ground-based space weather measurements. This would be an advocacy group to co-ordinate and promote ground-based measurements as discussed above.
- A Space Weather Research Group. This would act as an advocacy group to encourage and help the scientific community to address key science topics relevant to space weather.
- An Space Weather Outreach Centre funded by ESA, but operated by a contractor, to promote understanding of space weather issues among a number of key target groups including end users, decision makers and technical commentators. This is a key proposal; the survey of user needs showed that there is a clear need to improve that understanding across Europe.
- A Space Weather Development Group within ESA to encourage the development and use of space weather activities both within the Agency and across Europe. The group's remit should include advice to European groups wishing to set up space weather services, the promotion of standards for use by service and data providers, the development of a prototype space weather service and a prototype space segment for space weather measurements.

Finally, we identify a set of options to allow the phased implementation of these structures, and their programme of work, according to the available funding.

3 Scope and structure

In section 4 we describe the context in which this study was carried out. We identify the teams involved in the study and then provide an overview of the logic that the study has followed. This is important as it emphasises the systems approach that has been fundamental to our work.

In section 5 we review the key results from the earlier phases of our study. In particular, we review:

- The state of scientific knowledge. We discuss what space weather services can be supported on the basis of current knowledge and also where research is required to provide good services in other areas.
- The case for a space weather programme. We review the likely benefits of a programme and the market perception of the value of those benefits. We also use the response to the market survey to draw conclusions about funding of various aspects of space weather services and to argue that better outreach activities are required to raise user awareness of space weather issues.
- Requirements. We review the requirements analysis carried out within this study and present the user requirements that have been established in order to specify the user products to be provided by a space weather programme. Most of these user products must be derived from monitoring of various space weather parameters. Thus we also present the system measurement requirements derived from those user requirements – these specify the parameters to be monitored.
- Data infrastructure. We review the instruments required to satisfy the system measurement requirements and identify cases in which these should be space-based and in which they should be ground-based. We then review the options for implementing instruments in these two domains.
- Data handling. We review the data handling system required to process the above measurements and convert them into space weather products. This is separated into two parts. The central part is a space weather service, which ingests calibrated parameters from all sources (space- and ground-based), uses them to generate space weather products and then disseminates those products to users. In addition we review the ground systems that are required to operate space-based instruments and to convert their raw telemetry into calibrated parameters.

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In section 6 we discuss European needs with respect to space weather. These needs cover a number of distinct areas that have emerged from our study, namely:

- Space weather outreach
- Maintenance of current space weather assets
- Encouraging development of space weather services
- Developing new and better data sources (in particular, new space measurements)
- The need for additional scientific research

We discuss each of these areas in detail. We outline the European needs in each area and discuss how to meet those - with particular emphasis on the organisational approach appropriate to each area. Note that we have treated each area independently in order to draw out its key aspects but have also identified areas of synergy between the different areas.

In section 7 we consolidate the ideas developed in section 6 to provide a single co-ordinated plan. In particular, we identify where a combined organisational approach is appropriate and stress where it is important that distinctions are maintained. We also develop a strawman schedule for the proposed programme. This includes options for different rates of expenditure.

Finally in the Appendix we present a discussion of the overall costs and risks of a space weather programme. This forms an integral part of the Final Report.

3.1 Acknowledgements

I would like to thank my many colleagues who have contributed to this study – in particular Daniel Boscher, Steven Eckersley, Manuel Grande, Richard Harrison, Daniel Heynderickx, Hannu Koskinen, Michel Kruglanksi, Lesley Murphy, Risto Pirjola, Tuija Pulkkinen, David Rodgers, Manola Romero, Martyn Snelling, Richard Stamper and Emma Taylor.

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4 Background

ESA has funded two parallel studies on a European Space Weather programme. These studies are charged to investigate the benefits of, and need for, such a programme – and then to establish the possible content and organisation of that programme. This document is the final report on one of the two studies – namely that carried out by a consortium of six groups led by RAL:

- Rutherford Appleton Laboratory, Chilton, Oxfordshire,UK (RAL)
- QinetiQ, (formerly Defence Evaluation and Research Agency) at Farnbrough and Malvern, UK
- Astrium, Stevenage, UK
- Finnish Meteorological Institute (FMI), Helsinki, Finland
- Office National d'Etudes et de Recherches Aérospatiales, Département Environnement Spatial, France (ONERA-DESP), Toulouse, France
- Belgian Institute for Space Aeronomy (BIRA), Brussels, Belgium

4.1 Overview of Study Logic

An important aspect of the study is the use of a systems approach. This is illustrated by the study logic shown in Figure 1 below. The early part of the study established requirements for a space weather system (see left hand side of Figure 1) and then used these to build up a specification of the content of that system (rest of Figure 1). Throughout this process we maintain traceability from each step to the next. Thus it will be straightforward to adapt the study results in response to changes at any point in the study logic.

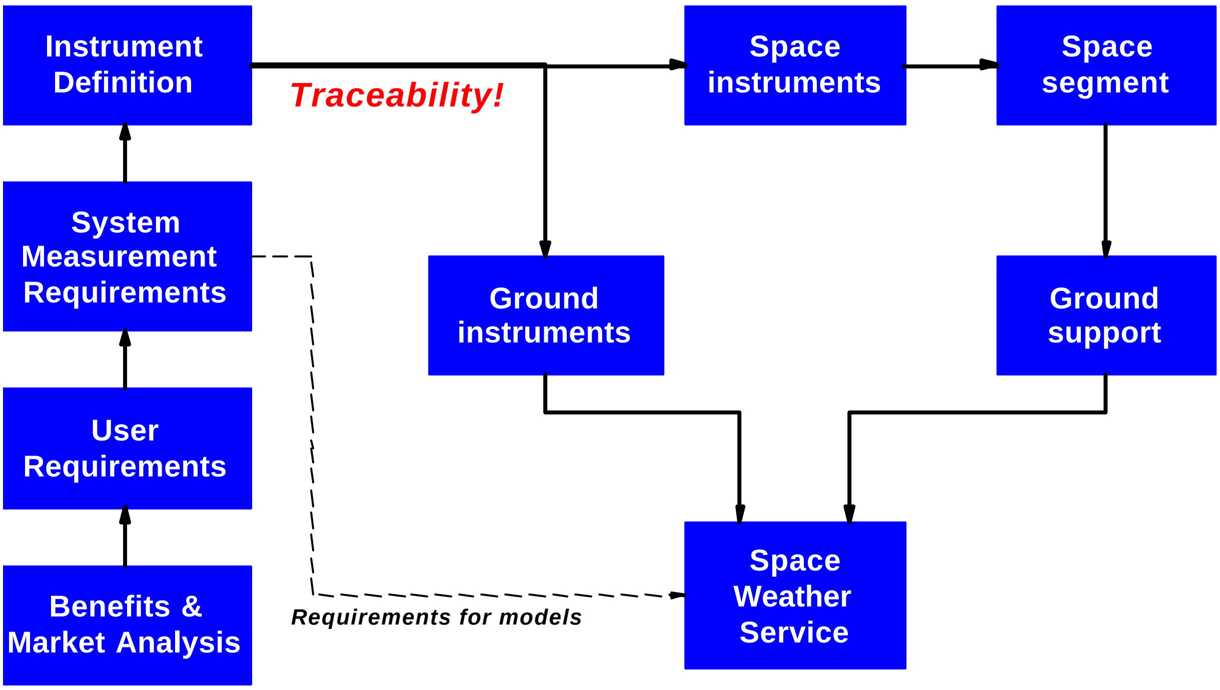

Figure 1. Simplified study logic. This logic is underpinned by our scientific knowledge of space weather

The study started with an analysis of our existing knowledge of space weather (known as the "Detailed Rationale" in the terminology of the study contract). This provided a summary of the existing scientific knowledge that can applied to space weather activities; it also identified important areas for further scientific work – both in terms of basic research and in development of the scientific models needed for space weather applications. The results of this work package provide an essential underpinning for the rest of the study. For this reason the detailed rationale is not shown in Figure 1. Its influence is pervasive throughout the study and cannot easily be represented in this diagram.

The requirements analysis then started by identifying the potential benefits of a space weather programme - and by interviewing potential users in order to understand their perception of space weather, its impact on their activities and the likely demand for services to help them manage those impacts.

The market analysis was a key step since it established a set of raw requirements for space weather services. These were then interpreted to produce a set of user requirements, giving a clear specification of the products required from a space weather service. The next step was to identify the measurements required to generate those products. The resulting "system measurement requirements" identified:

- The physical parameters to be measured
- The locations at which those measurements should be made
- The required time resolution of the measurements
- The models which may be used to derive the products from the measurements

The final step of the requirements analysis was to consolidate the system measurement requirements so that only unique requirements are listed. In effect we identified synergies where one measurement can service multiple user requirements. This is a key aspect of the systems approach. It exploits our knowledge of the underpinning science to produce an efficient service and eliminate duplication.

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Given the consolidated system measurement requirements (CSMRs), we then proceeded through a series of steps to build a specification of the space weather service as follows:

Instrument Definition. The CSMRs were analysed to identify the instruments needed to make these measurements. The result was two lists: (a) space-based instruments (including options to use various different orbits), and (b) ground-based instruments.

Space Segment. The list of space-based measurements was then analysed to explore how those measurements might be satisfied: (a) by existing and planned missions, (b) by hitch-hiker solutions – space weather instruments flown on other missions, and (c) by dedicated space weather missions. The hitch-hiker and dedicated options were then analysed to establish the necessary space architecture (e.g. orbits, numbers of spacecraft and ground stations). At this point the merits and demerits of different orbits were explored in order to select from options established by the instrument definition. Finally, having established a space architecture, we specified how this might be implemented in terms of existing European space platforms (dedicated missions) or classes of potential hosts (hitch-hikers).

Ground support. Having established a specification of the space segment, we then analysed the ground segment required to support the various space segment options, e.g. services such as instrument and spacecraft commanding, ground stations for uplink and downlink, telemetry processing and data reduction to physical parameters, spacecraft tracking, orbit determination and prediction, attitude maintenance, etc.

Ground instruments. In this case, we first investigated how much these can be supported by maintenance and augmentation of existing ground-based systems. We also identified options for future development of ground-based systems.

Space Weather Service. In this final step we specified how to build the service that takes parameters from space and ground measurements, converts them to useful products and delivers them to prospective users.

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5 Key results

5.1 The state of scientific knowledge

Over the past fifty years, we have gained a broad understanding of the science needed to support a space weather programme. Examples of this understanding include:

- the existence of the solar wind and the magnetosphere,
- the division of the solar wind into high and low speed components and their interaction to produce co-rotating interaction regions
- the discovery of coronal mass ejections (CMEs) and their later identification as the major source of perturbations of the solar wind
- the role of solar flares as sources of X-rays and energetic particles
- the role of magnetospheric convection in terms of momentum transfer from the solar wind,
- the role of reconnection in driving magnetospheric dynamics both on the dayside magnetopause and in the tail.

Only a few of these ideas gained quick acceptance in the scientific community; most have grown to acceptance through many years of careful research. One important example is the general acceptance that CMEs, rather than solar flares, are the primary sources of solar wind perturbations. This only came to general acceptance during the 1990s – some twenty years after the discovery of CMEs. Another key example is the gradual acceptance that dayside reconnection is the dominant mechanism for coupling solar wind energy, mass and momentum into the Earth's magnetosphere.

This understanding of the physical mechanisms is the critical issue for space weather. It provides the knowledge that allows us to build successful space weather applications. Using the two examples above:

- It is our understanding of CMEs that allows us to use CME launches (and in particular halo events) as a crude, but often effective, advance warning of geomagnetic events (but see the caveats below).
- It is our understanding of dayside reconnection that allows us to be confident in using upstream measurements of the solar wind plasma and magnetic field to provide short-term warnings of geomagnetic activity. (In principle, one could base these warnings purely on the statistical relationships between geomagnetic activity and upstream data. But our physical understanding gives us confidence in scope and validity of those warnings.)

Note that physical understanding allows us to do far more than would be possible if we just had a correlation between two phenomena, but no physical understanding. First of all, the physical understanding allows us to assign limits to our use of knowledge. For the examples this understanding tells us that:

- halo CMEs may travel towards us or away from us (so we need some way to determine that from observations),
- CME-driven solar wind perturbations will cause geomagnetic activity only if Bz, the z-component of the heliospheric magnetic field, is pointing southward rather than northward (so if that field component is not known, we must assume a 50/50 chance of geomagnetic activity when a solar wind perturbation encounters the Earth).

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Physical understanding also helps us to seek financial and political support for space weather applications. It allows us to demonstrate that we really understand the problem and thus that the proposed application is truly worth supporting. Put bluntly, it makes it easier to “sell” space weather applications to sources of funding[1].

Our broad understanding of the science underpinning space weather is now sufficient to support simple applications, e.g. prediction of geomagnetic activity based on observations of solar ejecta and on upstream monitoring of the solar wind as discussed above. It also seems likely that we have discovered most of the phenomena that can cause space weather effects, though one must never rule out new discoveries (e.g. the recent discovery of complex millisecond time scale optical activity in the middle atmosphere above thunderstorms is perhaps a good example here).

However, it is equally clear that there remains considerable scope to improve space weather applications by improving our knowledge of the underpinning science. In some cases we need to improve detailed scientific understanding in order to advance existing space weather applications. A prime example would be the provision of advance warnings of geomagnetic activity based on observations of CMEs. Here it is essential to develop the ability to model the propagation of the CME from the Sun to the Earth and thus predict the sign of Bz on arrival at Earth. In other cases we lack physical understanding and thus can develop space weather applications only on a statistical basis. A prime example would be solar proton events. There is, as yet, no scientific consensus on the source region where these particles are accelerated to high energies. Thus it is hard to build a reliable application to predict individual solar proton events. What is possible, of course, is to build statistical models of the cumulative exposure to solar protons over a period of time (e.g. JPL 91). These models can then be used to guide the design of systems that must cope with solar proton events. This is essentially a conservative engineering approach and is clearly an excellent way to work round space weather problems where the underpinning scientific knowledge is poor. Table 1 on the next page lists examples of areas where further scientific research could be of great value in supporting new space weather applications:

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In addition to these specific areas, there are two more general concerns where work is required to improve scientific understanding:

- *Engineering impacts.* New space weather problems seem more likely to arise when technological developments lead to new devices that are vulnerable to already known space weather effects. Thus research is needed to monitor the impact of space weather on new technologies. In some cases, e.g. use of new devices on spacecraft, this requirement is self-evident and should be picked up as part of quality assurance for space projects. The more problematic issue is the development of new technologies where sensitivity to space weather may be less obvious (e.g. the power supply industry prior to Quebec failure in March 1989). Thus there is a need to maintain general awareness of space weather issues to try to detect these problems before they make themselves obvious through a disastrous event. Sadly history shows that the discovery of problems in new technologies often does occur through disasters.

[1] One can draw an interesting comparison with Sun-weather studies. This subject has been around for decades but was long regarded as highly speculative and thus only weakly supported. Over the last few years we have seen the formulation of plausible physical mechanisms and consequently much greater interest and support.

- *Extreme events.* Another concern for the future would be if we were to experience known space weather effects at extreme values well-beyond previous experience. The historical record makes it clear that the solar and geomagnetic activity do vary on a time scale of centuries. Thus it is important to support studies of long-term change in space weather, e.g. using historical records of solar and auroral activity or using proxy data such as isotopic composition in dateable samples.

Finally, we note that it is important, indeed essential, to have an outreach programme to ensure that this scientific knowledge is disseminated widely. This applies as much to current knowledge as to any future advances.

Table 1. Some open areas for scientific research to underpin space weather applications

Scientific problem	*SW effects*
Solar atmosphere, where and when events take place: This is a major problem to be solved to obtain reliable warnings and forecasts in the time scale of days.	All
Acceleration of solar energetic particles: This is a fundamental scientific problem related to the above. Different CME events produce different high-energy ion fluxes toward the Earth, and we do not know why.	Solar proton effects
Prediction of the structure and interplanetary propagation of CMEs: Even after observation of a CME around the solar disc, we cannot tell if the event will be geoeffective. Critical features are whether the CME can produce a shock and what is the magnetic field within the CME structure.	Ionosphere, GIC, rad belt
Magnetospheric acceleration (killer electrons, storms/substorms): These are major unknowns in magnetospheric physics. To reconstruct a major acceleration event is still very difficult even afterwards, as the events take place during most active phases of magnetospheric storms and require setting up very strong localised and transient electric field structures.	Rad belt
Storm dynamics: This is a wide complex of insufficiently solved problems, in particular in the near-Earth region (inside the geostationary orbit). Storm dynamics are usually described in terms of global geomagnetic indices, but it is still uncertain how different magnetospheric current systems contribute to these indices, and what factors in storm dynamics are the most critical to space weather effects. Problems are related to storm drivers, acceleration events, magnetosphere-ionosphere coupling, etc. In addition to warning and forecasting, this is also a major issue in after-the-fact reconstruction of the space environment.	Ionosphere, GIC
Exceptionally big GIC events: Serious damages on ground are associated with particularly large GICs. However, as these events are very localised, they are extremely hard to predict, making development of useful warning systems difficult.	GIC
Dynamics of the upper atmosphere: The dynamical response of the upper atmosphere to magnetic activity is very complex and is important both for drag and for ionospheric effects. Good progress is being made but further work, particularly in terms of model development is required.	Ionospheric effects, drag

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Scientific problem	*SW effects*
Coupling to the lower atmosphere: Finally, space weather is coupled to the atmosphere through complicated processes, ranging from penetration of GCRs to long-term relationship between solar activity and climate. These processes are still poorly understood, which slows down useful space weather product development.	Climate change
Studies of planetary magnetospheres, ionospheres and thermospheres: The study of these domains around other solar system bodies is of great value for space weather - especially in terms of model development. The basic physical principles are the same as for the domains around the Earth, but the greater range of physical parameters allows better testing of those models and their underlying concepts. This may be see, e.g., in the development of models of the thermospheres of Mars and Titan.	All

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5.2 The case for a space weather programme

In the previous section we showed that existing scientific knowledge is adequate to start a space weather programme (though further research is very likely to have great benefits for such a programme). In the present section we discuss the general case for having that programme. We describe the potential benefits that may be obtained by initiating such a programme and then discuss the market perception of the value of those benefits. We also use the market survey to draw some conclusions about the funding of various aspects of space weather services and to argue that better outreach is needed to improve user awareness of space weather issues.

5.2.1 Benefits of a space weather programme

A wide range of users may potentially benefit from a European Space Weather Programme. These include pan-European bodies, governments, armed forces, multi-national companies, small and medium-sized enterprises and individuals.

Potential benefits fall in four main categories. These are:
- strategic – affecting Europe's industrial, military, technological and scientific independence;
- economic – affecting the price consumers must pay for services and the competitiveness of the businesses in which they work;
- technological and scientific – affecting the development of new products and industries; and also affecting pure and applied research in a wide range of areas;
- educational – affecting people's understanding of science, space and how space weather impacts their lives.

These four categories are described in more detail in the table opposite.

In general, the extent of the benefits that will accrue from a European Space Weather Programme scale with the programme size. This size may be defined as:
- *small* if only existing space resources are utilised,
- *medium* if a small number of hitchhiker payloads and dedicated missions are procured in addition to use of existing resources, and
- *large* if an extensive programme of hitchhikers and dedicated space weather monitoring spacecraft are flown in addition to existing resources.

Assuming the programme is approved, some strategic, technological, scientific and educational benefits should be seen within a relatively short time (< 3 years). Economic benefits are less likely in the short-term due to the nature of the measures required to achieve them, but in the medium term (3-10 years) these should be significant.

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Table 2 Benefits of a space weather programme

Strategic benefits include:

- Reduced dependence on non-European resources for forecasting, warning, reporting and analysis of space weather effects and hazards. Such information is currently predominantly non-European in origin.
- The strengthening of ESA's role in co-ordinating European space co-operation.
- Improved competitive advantages for pan-European organisations and businesses.
- Improved effectiveness and independence of European defence forces.
- Improved competitiveness of European industry through the bringing together of expertise from a wide range of disciplines.
- Opportunities for growth of European industries in high-technology fields such as information systems, space platforms, sensors, launch services and ground segment equipment.
- The strengthening of relations with non-European nations through co-operation agreements, industrial partnerships and scientific exchange.
- The raised profile of European capabilities in space.

Technological and scientific benefits include:

- The opportunity to increase the robustness of technology, to optimise its performance and to understand its limitations.
- The development of new sensors, new platform technology such as micro- and nano-satellites, and new data handling technology.
- Monitoring of the effects of technology on the space environment.
- The development of novel technologies that exploit changes in space weather and, potentially, technologies that modify space weather phenomena.
- The stimulus of basic science through improved data availability.
- The improvement of physical modelling and use of data-driven models.
- Improved resilience of scientific missions

Economic benefits include:

- Decreased risk of disruption of terrestrial power grids.
- Decreased risk to aircraft safety and decreased radiation exposure of crew.
- Improved accuracy and reliability of global navigation satellite systems.
- Improved air and marine safety and military effectiveness through better use of radar systems.
- More efficient use of HF and satellite radio communication systems.
- Reduced satellite operations costs, increased satellite reliability and extended lifetime.
- Greater launcher reliability.
- Improved competitiveness of spacecraft insurers.
- Reduced radiation exposure of astronauts, giving reduced cancer risk, longer working life, reduced medical costs and lower risk of legal action.

Educational benefits include:

- A stronger presence for European space activities on the world wide web and thus visibility to the world at large.
- A greater emphasis on space weather in university courses.
- Improved continuing professional development for scientists and engineers.
- Improved awareness of basic science and space issues among school students.
- A raised profile of ESA and space among the tax-paying public.

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5.2.2 Market interest in space weather

A market survey undertaken as part of our study showed that there is significant user demand in Europe for specific and well-targeted space weather services. Survey respondents included representatives from many of the economic sectors discussed in the benefits section, e.g. airlines, power systems, HF radio propagation (which includes over-the-horizon radars), the insurance industry and satellite operations. Other economic sectors which provided interest in space weather services were geological surveys/drilling and auroral tourism.

The survey also made some inferences about military interest in space weather services. This sector is particularly difficult to access because its critical requirements are necessarily secret (i.e. information on those requirements might allow an adversary to identify and exploit weaknesses). Nonetheless, it is clear that space weather is relevant to important military systems such as navigation and communications. The best example of this is the enormous interest of the US military in space weather. However, it is important to recognise that the US military expresses an interest in all space weather issues, so it is not clear what are their critical requirements.

The survey shows that many users are willing to pay for services that interpret space weather measurements to generate products that they can use - without themselves having to gain specialist knowledge of space weather or its impact on their systems. The table below provides a comparison of the different market sectors with respect to their attractiveness as space weather customers, based on the results of the interviews with the market survey respondents.

Table 3 Relative attractiveness of market segments

Market sector / *Market issues*	*Air*	*Power*	*Geo.*	*HF Radio*	*Ins.*	*Mil.*	*Sat.*	*Tour.*
Well-defined space weather issues	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Awareness of benefits of space weather to sector	High	High	Low	High	Med	Low	High	Med
Willingness to pay for services	Yes	Yes	No	No	No	Yes	Yes	Yes
Needs addressed by service providers	Yes	Yes	No	Yes	Yes	No	Yes	No
Easy to access	Yes	Yes	Yes	Med	Yes	No	Yes	Yes

It is important to note that the user demand identified by the survey forms a series of niche opportunities defined by the specific services for which users are willing to pay. Those niches may be exploited by industry, government laboratories and academia. Such services can be efficiently developed by a bottom-up approach that encourages competition between providers, i.e. a market approach is appropriate to provision of specialist services to end users (but also see sub-section 5.2.3 below).

But what also follows from the survey is that there is no user demand for an overarching service. Indeed users were very suspicious that their specialist demands might be transmuted into a large generic service that provides a less good service for them. Thus the integration of space weather activities across different user needs must be undertaken only when it can be shown to improve the delivery of services to all the different users. Thus integration is an implementation issue that may

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be justified if it provides technical or financial advantages. The obvious example is where the underpinning science shows that it is advantageous to end users, i.e. that different users are affected by factors that are inter-related. A simple example is that high-frequency radio propagation and over-the-horizon radar respond to ionospheric critical frequency whereas global position system measurements respond to total electron content. But science tells us that these are both functions of the same parameter – namely the height profile of plasma number density in the ionosphere. The critical frequency is determined by the peak of that profile while total electron content is the integral of that profile. Thus ionospheric effects are one good example of how we can use scientific understanding to combine services.

5.2.3 The need for public sector funding

The provision of specialist services to end users, as discussed in the previous section, depends on access to basic data on the behaviour of the space environment (e.g. sunspot number, geomagnetic indices, ionospheric data, interplanetary magnetic field, etc.). Our study shows that, while users are prepared to pay for interpretation of those data, they are not prepared to pay for its collection. They consider that the collection of "basic scientific data" is a public sector responsibility. This is an important message. There is some pressure from government bodies in Europe that end users should pay for collection of basic data. This probably reflects a lack of understanding of space weather issues and demonstrates the need for better outreach with respect to decision-makers.

5.2.4 Outreach

Perhaps the most important result to emerge from the study is the need for outreach, i.e. to improve understanding of space weather among various target groups. The study, and in particular the market analysis, has shown a critical need to improve knowledge of space weather among potential users across Europe. Key target groups for outreach are:

End users, i.e. the organisations whose activities are directly impacted by space weather. It is particularly important to inform technical managers in these organisations so that they can understand the potential impact of space weather on the systems for which they are responsible.

Decision-makers. This is a wide set of people whose decisions affect the operation of systems impacted by space weather. They include senior management (especially non-technical management) of organisations impacted by space weather, regulatory authorities where these oversee the operation of those organisations and, of course, governments.

Commentators. This is the body of experts outside industry and government which provides specialist commentary on issues affecting specific technological activities. Typical examples would be technical journalists (most technological sectors have a lively set of specialist journals) and consultants. They are often in the vanguard for exploring new issues and acting as a source of information for specialists in industry and government.

Students. These are the young people who will become members of the three previous groups. Thus we should encourage them to gain some appreciation of space weather issues during their studies.

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5.3 Requirements

5.3.1 Introduction

As we noted in section 3.1 a key step in the study logic was to establish the system requirements against which we would then design the space and ground elements of a space weather programme. In developing these “System Measurement Requirements” (SMRs), a key consideration was to ensure traceability to an underlying set of user requirements. The main foundation for the user requirements was the market analysis exercise which included a series of interviews with potential users of space weather information and services. Because of the differing viewpoints of the interviewees, careful consideration of the market interview findings was necessary in some cases to ensure the correct interpretation.

The SMRs provide a guide to the type of information needed to meet each user requirement as well as the model processes needed to generate that information. They also provide a guide to the availability and/or maturity of the necessary model process. In general, each identified model process generates a number of SMRs, depending on the input data it requires. Each SMR comprises a concise statement of the physical parameter to be measured and the necessary spatial and temporal sampling. A simple example of the breakdown of a user requirement to derive this information is shown in Figure 2 on the next page. In this case, we identify five model processes that can generate the required information and then specify the space weather parameters that must be measured to provide the inputs needed by these processes. Each set of parameters in this figure is then treated as a separate SMR.

The SMRs have been captured separately for each user requirement in order to ensure traceability. However because the same space weather data can often meet the needs of several users, there is inevitably a considerable amount of repetition in the individual SMRs. The Consolidated System Measurement Requirements (CSMRs) are a collation of the SMRs in which duplicate requirements have been removed. For example, looking again at Figure 2 you can see that the second and fifth SMRs are identical and thus can be folded into the same CSMR (in fact, number 19 in Table 5).

The CSMRs have provided the foundation for our space and ground segment definition work. However the extent to which the CSMRs are met will depend to a large extent on the size (in terms of level of funding) and scope of the proposed programme. Should it be decided to pursue only a small scale programme using only existing and planned space assets, it will clearly be impossible to meet any *new* measurement requirements. This objective could however be achieved with a larger programme involving the use of hitchhiker payloads and/or the development of new instruments and spacecraft. In theory, a programme could be designed to address the full set of CSMRs, thereby meeting all identified user needs, although in reality this is unlikely to be possible due to cost and/or technical constraints. The principal purpose of the CSMRs is to provide a basis for trade-off analysis of the various options in which the potential benefits of new measurement capabilities are weighed against the associated programme costs and risks.

The following two sections summarise: (a) the user requirements established in this study, and (b) the consolidated system measurement requirements derived from those user requirements.

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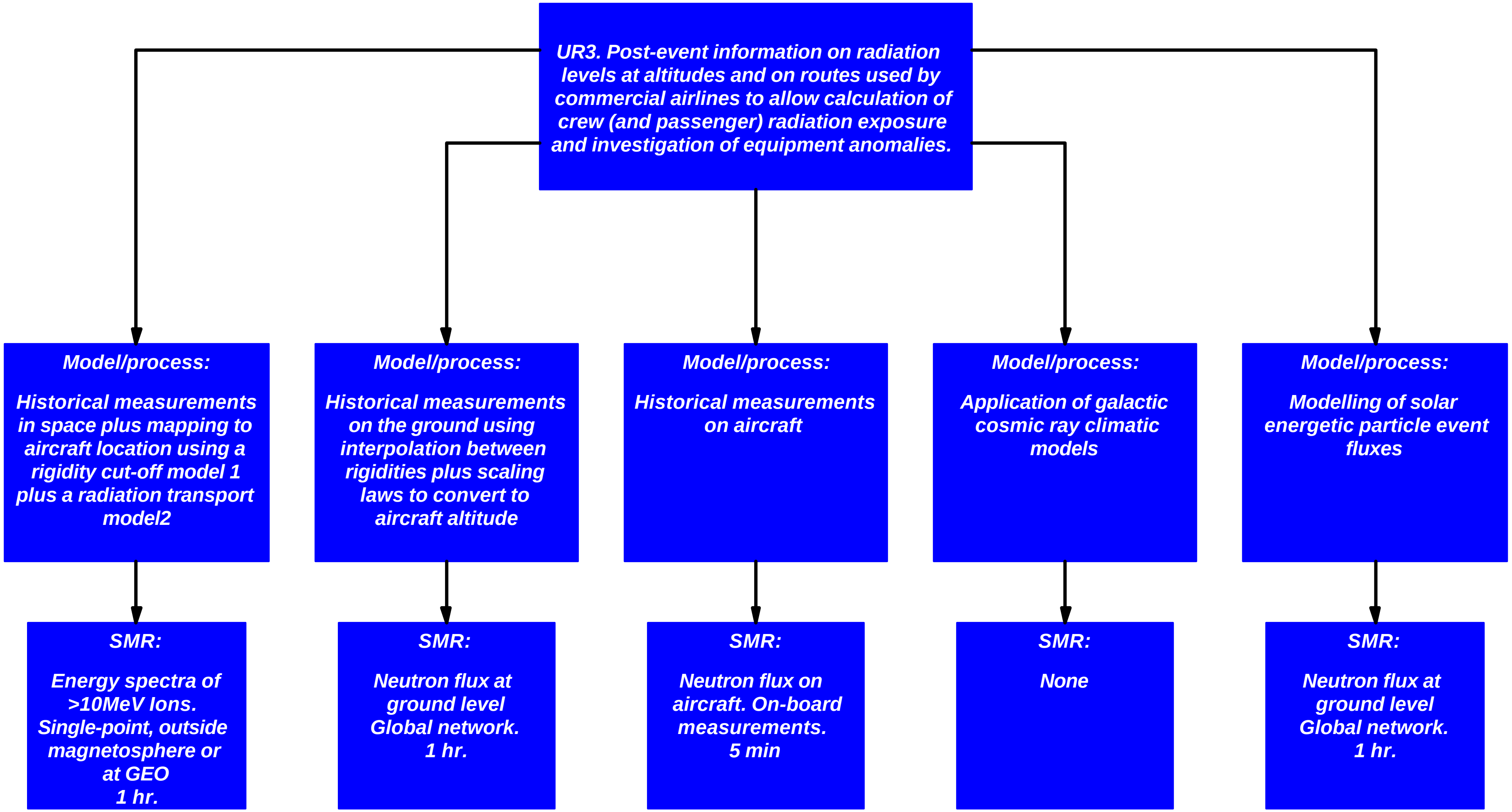

Figure 2. Example showing breakdown of a user requirement into system measurement requirements

5.3.2 Table of user requirements for a space weather service

The table below specifies products that an operational space weather service should deliver. Where appropriate, the potential users and the required timeliness of the products are also shown.

Table 4 User requirements for space weather products

UR no	User requirement	Timeliness	Potential Users
1	Forecasts of hazardous radiation levels at altitudes and on routes used by commercial airlines, that may be dangerous to aircrew or may affect avionics systems.	~18 hours preferred	Airlines and air safety organisations
2	Now-casts of hazardous radiation levels at altitudes and on routes used by commercial airlines, that may be dangerous to aircrew or affect avionics systems.	Near real-time (<30 minutes)	Airlines and air safety organisations
3	Post-event information on radiation levels at altitudes and on routes used by commercial airlines to allow calculation of crew (and passenger) radiation exposure and investigation of equipment anomalies.	<1 week (2-3 months if no severe events occur)	Airlines and air safety organisations
4	Spatially resolved forecasts of large geomagnetically induced currents, to allow mitigation measures to be taken to protect distributed conductor networks e.g. power grids	>1 hour (1-2 days preferred)	Electric power transmission organisations (also pipeline operators and railways and telephone companies)
5	Spatially resolved now-cast information on large geomagnetically induced currents.	< 5 minutes	Electric power transmission organisations (also pipeline operators and railways and telephone companies)
6	Spatially resolved post-event information on geomagnetically induced currents of all sizes.	< 1 month	Electric power transmission organisations (also railways and telephone companies)
7	Forecasts of perturbations in the geomagnetic field	>1 day (2-4 weeks preferred)	Geological prospectors and military
8	Now-cast of perturbations in the geomagnetic field	<5 minutes	Geological prospectors and military
9	Post-event knowledge of perturbations in the geomagnetic field	<1 day	Geological prospectors and drilling industry
10	Forecasts of ionospheric disturbances leading to loss of range, degradation and outage of radio communications e.g. fadeout, polar cap absorption and scintillation	> 1 day	RF systems (civil and military)

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UR no	User requirement	Timeliness	Potential Users
11	Now-casts of ionospheric reflection properties for HF frequency selection	< 5 minutes	RF systems (civil and military)
12	Now-casts of ionospheric total electron content	< 5 minutes	GNSS location systems and radar systems (civil and military)
13	Post-event information on environments affecting operational satellite systems, e.g. radiation and charging environment	< 1 day	Satellite operators (civil and military) and insurance and financial services
14	Forecasts of hazardous environments affecting operational satellite systems.	>1-2 days	Satellite operators (civil and military)
15	Now-casts of hazardous Environments affecting operational satellite systems	< 5 minutes	Satellite operators (civil and military)
16	Now-casts of atmospheric drag affecting LEO spacecraft	< 5 minutes	Satellite operators (civil and military)
17	Forecasts of auroral Intensity, duration and location	>12 hours	Tourism
18	Forecasts of all hazardous environments affecting humans in space	> 1 day	Space Agencies
19	Now-casting of all hazardous environments affecting humans in space	< 30 minutes	Space Agencies
20	Post-event knowledge of radiation environments affecting humans in space	<2-3 months	Space Agencies
21	Forecasts of severe SPE/SEPE affecting spacecraft launch operations	>1 day	Launch Providers
22	Post-knowledge of SPE/SEPE affecting spacecraft launch operations	<1 day	Launch Providers
23	Continuous data availability during and after extreme events		General
24	Continued data availability in the event of premature failure or end-of-life of key space weather systems		General
25	Efficient distribution of data to users and continuous availability		General

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5.3.3 Consolidated system measurement requirements for a space weather service

The table below shows the measurements needed by a space weather service in order that it be able to deliver the full set of products listed in Table 4. Subsets of these CSMRs may be associated with each individual user requirement.

Table 5 Consolidated system measurement requirements

CSMR no	Physical parameter to be measured	Spatial sampling requirement.	Temporal sampling requirement
1	Solar EUV/ X-ray images	Single point measurement in space	1 hour
2	Solar coronograph images	Single point measurement in space	1 hour
3	Stereo visible or UV images of Sun-Earth space	2 points well separated from Earth, e.g. L4 and L5	1 hour
4	Auroral imaging	From polar elliptical orbit	1 hour
5	Auroral imaging	From the ground	1 hour
6	Auroral oval, size, location and intensity	Single point measurement	1 hour
7	Auroral equatorward boundary	Ground, local midnight	3 hours
8	X-ray flux	Single point measurement in space	1 min
9	X-ray flux	Single point measurement in space	5 mins
10	X-ray flux	Single point measurement in space	1 hour
11	X-ray flux and spectrum	Single point measurement in space	1 hour
12	UV flux	Single point measurement in space	1 day
13	EUV flux	Single point measurement	1 day
14	F10.7	Single point measurement on the ground	5 mins
15	F10.7	Single point measurement on the ground	1 hour
16	F10.7	Single point measurement on the ground	1 day
17	F10.7	Single point measurement on the ground	1 month
18	*Obsoleted during study*		
19	Secondary neutron flux	Ground measurements. Global coverage over a range of rigidities from the equator to the polar cap and a range of longitudes.	1 hour
20	Secondary neutrons (GCR)	Ground, range of rigidities	1 day
21	Secondary neutrons (GCR)	Ground, range of rigidities	1 month
22	Secondary neutron flux	Aircraft based measurements	5 minutes
23	Vsw	Single point measurement in IMF, e.g.at L1 point	1 minute
24	Vsw	Single point measurement at L1	15 minutes

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CSMR no	Physical parameter to be measured	Spatial sampling requirement.	Temporal sampling requirement
25	Vsw	Single point measurement in interplanetary space (L1 preferable for some requirements)	1 hour
26	Nsw	Interplanetary space	15 minutes
27	Nsw	Interplanetary space, preferably L1	1 hour
28	Kp	Global index	3 hours
29	Kp*	Global index	5 minutes
30	Ap	Global index	1 day
31	Dst	Global index	1 hour
32	Dst*	Global index	5 minutes
33	AE index (alternatively AKR)	Global index	1 minute
34	SSN	Global index	1 day
35	SSN	Global index	1 month
36	IMF (B-field)	Single point measurement in interplanetary space, e.g. at L1 point	1 minute
37	IMF (B-field)	Interplanetary space, preferably L1 or closer	15 minutes
38	IMF (B-field)	Interplanetary space, preferably L1	1 hour
39	Magnetospheric B-field	Multi-point measurements in mgnetosphere	1 minute
40	Magnetospheric B-field	Multi-point measurements in mgnetosphere	5 minutes
41	Magnetospheric B-field	Multi-point measurements in mgnetosphere	< 30 minutes
42	Magnetospheric B-field	Multi-point measurements in mgnetosphere	30 minutes
43	Magnetospheric B-field	Multi-point measurements in mgnetosphere	1 hour
44	Terrestrial B-field (hence dB/dt)	Measured on the ground at a range of latitudes and longitudes. Particularly dense measurements in auroral zone.	10-second resolution (1 hour average for drilling)
45	Interplanetary radio scintillation	Multiple measurements from multiple points on the ground	1 hour
46	f0F2 from ionosonde (also E1 and F1)	Local or multipoint measurements	5 minutes
47	f0F2 from ionosonde	Local or multipoint measurements from the ground	1 hour
48	TEC, derived from GNSS propagation delay	Many measurements across the globe	5 minutes
49	TEC, derived from GNSS propagation delay	Local, or global with 100km separation	5 minutes
50	Cross-tail electric field	Tail or PEO	3 hours

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CSMR no	Physical parameter to be measured	Spatial sampling requirement.	Temporal sampling requirement
51	Ionospheric ion drift velocity	PEO	Seconds
52	Cold ions. Total density only.	L=7 and below	1 minute
53	1-10keV electrons. Good spectral information	L=3 to 9, GEO	1 minute
54	10-100keV electrons. Good spectral information	L=3 to 9, GEO	1 minute
55	10-100keV electrons. Good spectral information	L=3 to 9, GEO	1 minute
56	>10MeV ions (SPE/SEPE)	Single point measurement in interplanetary space	<30 minutes
57	>10MeV ions (SPE/SEPE)	Single point measurement in interplanetary space (GEO would suffice)	1 hour
58	>10MeV ions (SPE/SEPE)	Single point measurement in interplanetary space / outer magnetosphere	1 day
59	>10MeV protons (trapped)	Throughout inner radiation belt	<30 minutes
60	>10MeV protons (trapped)	Throughout inner radiation belt	1 hour
61	>10MeV protons (trapped)	Throughout inner radiation belt	1 day
62	>100MeV ions. Energy spectra required	Single-point measurement in interplanetary space preferably external to magnetosphere (GEO orbit would suffice however)	1 hour
63	>100MeV ions (GCR)	Single point measurement in space	1 hour
64	>100MeV ions (GCR)	Single point measurement in space	1 day
65	>100MeV ions (GCR)	Single point measurement in interplanetary space (GEO would suffice)	1 month
66	Relativistic electrons (>0.3MeV). Including spectra	GEO, GTO	<30 minutes
67	Relativistic electrons (>0.3MeV). Including spectra	GEO, GTO	1 hour
68	Atmospheric scale height	Global average	1 day
69	Debris size and velocity distribution	LEO	6 months
70	Meteoroid size and velocity distribution	Above atmosphere	6 months
71	Meteoroid size and velocity distribution	Above atmosphere	1 days

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CSMR no	Physical parameter to be measured	Spatial sampling requirement.	Temporal sampling requirement
72	Dose rate and LET Spectrum	Onboard spacecraft	5 minutes
73	Total dose	Sensor worn by astronaut	Mission integrated
74	Satellite position	LEO and below	30 minutes
75	Interplanetary radio bursts	Single point measurement in space.	1 hour

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5.4 Data infrastructure

5.4.1 Introduction

This section looks at what is needed to satisfy the measurement requirements discussed in the previous section. We first consider the instruments required to make those measurements and then at what is required in the way of supporting infrastructure, e.g. a spacecraft and its ground support for space-based instruments.

The required measurements fall into two naturally distinct parts – namely space-based and ground-based measurements. This division is an important issue for any programme of space weather measurements. Many space weather parameters can be measured from the ground. Furthermore, the scope of such measurements is likely to increase with advances in scientific understanding and technological capability. Such measurements have practical advantages over space-based measurements. They avoid the extra costs associated with: (a) qualifying instruments for space flight, and (b) launch and operations. It is also vastly easier to maintain and upgrade ground-based instruments. Thus we consider that space-based measurements can only be justified on grounds that they provide significantly better performance than is possible with ground-based measurements, e.g.

- Practicability, e.g. ground-based solar UV and X-ray images are impossible because of atmospheric absorption. Such observations must be space-based.
- High quality, e.g. coronagraph images of CMEs are much clearer when taken in space because of the absence of stray light from atmospheric scattering (indeed CMEs were not recognised prior to their observation with the Skylab coronagraph).

The proposed assignment of measurements into space-based and ground-based techniques is summarised in Table 6 and Table 7 below and then discussed in the subsequent two sub-sections.

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Table 6 Measurements that require space-based instrumentation

CSMR number(s)	*Measurement type*
1 to 3	Solar images
4, 6	Auroral images
8 to 13	Solar X-ray and UV fluxes
23 to 27	Solar wind plasma properties
36 to 38	Interplanetary magnetic field
36 to 38	Solar surface magnetic field
39 to 43	Magnetospheric magnetic field
52	Bulk plasma properties
53 to 67	Electron and ion fluxes
69 to 71	Debris and meteoroid properties
72 and 73	Dose measurements
75	Interplanetary radio emissions

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Table 7 Measurements that can be done on the ground

CSMR number(s)	*Measurement type*	*Network*	*Index*
5 and 7	Auroral image/intensity		
14 to 17	Solar 10.7 cm radio emission (Penticton index)		Y
19 to 22	Secondary neutron fluxes	Y	
28 to 33	Geomagnetic indices	Y	Y
34 and 35	Sunspot number	Y	Y
36 to 38	Solar surface magnetic field		
44	Geomagnetic variations	Y	
45	Interplanetary scintillation		
46 and 47	Ionospheric critical frequencies	Y	Y
48 and 49	Ionospheric total electron content	Y	
50 and 51	Cross-tail electric field / ionospheric drift	Y	
68 and 74	Spacecraft tracking		
69 to 71	Debris and meteoroid properties		

Notes on tables

1. The third column of the ground-based measurement table indicates measurements that require a global network of measurements and not just one or two spot measurements. This is an important aspect of many ground-based measurements. Their value lies in a co-ordinated international network of observations - with exchange of data between participants – so that a global picture of the measured quantity can be derived. For many of the measurement types listed above there are already well-established international arrangements to do this.
2. The last column of the ground-based measurement table indicates measurements from which internationally-recognised indices are derived. These include the sunspot number (available as a monthly value from 1759), various geomagnetic indices (Kp/Ap from 1932, AE and Dst from 1957) and solar 10.7 cm radio emission (from 1947). Thus there has been a long history of maintaining support for the measurements behind these indices and for their processing through to the level of indices.

5.4.2 Space-based techniques

The proposed assignment of measurements into space-based techniques is summarised in Table 6 above. Most of these are based on a well-developed understanding of instrumental techniques and the science to interpret the results. But two of the measurements are more speculative in that they seek to exploit new ideas:

1. The proposed use of a magnetograph to measure the surface magnetic field of the Sun and thus support prediction of the heliospheric magnetic field at the Earth and thus complement in-situ measurements. This is a technique with great potential but its success will require development of reliable models of solar wind evolution between the Sun and the Earth.

The proposed monitoring of interplanetary radio emissions. These are thought to be characteristic of coronal mass ejections and offer the possibility to remotely-sense CMEs as they move away from the Sun. Ground-based measurements of CME emissions close to the Sun are used in some state-of-the-art models - to help predict CME arrival at the Earth (and thus the possible onset of geomagnetic activity) [MODELS]. However, these emissions are detectable from the ground only when the CME is close to the Sun (as the CME moves away from the Sun its emission frequency drops below the ionospheric cut-off frequency). Thus this technique is greatly improved if measurements are made above the ionosphere. A French-led demonstration of the technique is planned as part of NASA's STEREO mission [SWAVES].

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5.4.3 Ground-based techniques

The proposed assignment of measurements to ground-based techniques is summarised in Table 7. This includes a couple of cases that address requirements covered in the previous table of space-based measurements. These are:

1. the use of ground-based magnetographs to measure the surface magnetic field of the Sun. As with space-based versions of the same instrument, this technique can be used to predict the heliospheric magnetic field at the Earth. The choice between ground- or space-based solutions will depend on whether ground-based systems can provide data of adequate quality.
2. the use of optical and radar systems to monitor debris and meteoroid properties. These measurements allow us to monitor micro-particles with larger masses (> 10^{-8} kg), which are not easily measured by space-based detectors.

There are two ground-based techniques that have considerable potential but require further development:

- The use of a HF backscatter radar network to measure the cross-tail electric field (via the cross-polar cap potential) is a well-established example of a modern ground-based technique that can be applied to replace a space-based measurement. It relies on both advances in scientific understanding and technological capability. The radar network simply measures the pattern of high-latitude ionospheric motions via the Doppler effect. It is modern scientific understanding that allows us to interpret this in terms of the electrodynamics of the coupled ionosphere-magnetosphere system. Technological advances have made it possible to deploy a suitable radar network and to collect and interpret such data. This is demonstrated by the existing SuperDARN system. But development would be required to convert this into a fully operational space weather tool - in particular, to improve real-time data access and to improve coverage of the high-latitude ionosphere.

- The use of the interplanetary scintillation (IPS) technique as a ground-based technique for monitoring the propagation of interplanetary disturbances. This technique was explored as a space weather measurement in the early 1990s (e.g. see [IPS1]), but proved disappointing in that role (though a number of good scientific papers did result). However, advances in the understanding of IPS over more than a decade since that attempt indicate that we could now build a much better hardware for IPS observations (A. Breen, private communication) as well as better software for reducing those observations [IPS2].

5.4.4 Options for space instruments

The implementation of a space and ground segment to support space instruments is a key issue for the ESA studies. In particular, the studies are charged to explore three options - whether to use: (a) existing and planned missions, (b) hitch-hikers – space weather instruments on other spacecraft, or (c) dedicated space weather missions. We have looked at all three options. The results may be summarised as follows:

5.4.4.1 Existing/planned

There are only a few existing/ planned European missions that make measurements relevant to space weather. The most notable is, of course, SOHO; there are also a range of smaller missions such as the German CHAMP mission. The scope of this option increases if co-operation with non-European (and especially US missions) is considered. However, even then these missions only go part way to meeting some of the CSMRs and the extent to which they do so is limited in time. Many CSMRs are not met or are only poorly met by existing and planned missions.

It must also be said that some missions may not support the CSMR all the time. The main problem would be ground station coverage. As many of these missions will be served by only one ground station, the durations of gaps in ground station view may exceed the maximum gap that can be tolerated when data are used for space weather purposes. This would be prohibitive unless either multiple ground stations or multiple spacecraft were to be used. An example of this would be SOLAR B, which could support CSMR 1 (images of the solar disc) and 8-11 (solar X-ray fluxes), but only when close enough to its ground station. The gap requirement is 20 minutes for CSMR 1, which would be difficult to meet (Solar-B will have a 97 minute period). For CSMR 8-11 the situation is impossible as the gap requirement is only 20 seconds.

An important result is that one of the most critical space weather measurements, the monitoring of the interplanetary magnetic field upstream of the Earth (CSMR 36 to 38), is not covered by existing and planned missions between:

- end of 2002 (current planned end of ACE operations), and
- beginning of 2007 (launch of Solar Dynamics Observatory)

This gap may be ameliorated by one of several possibilities: (a) an extension of ACE operations (if the magnetometer and spacecraft remain healthy) , (b) implementation of a recent NASA proposal to move the Wind spacecraft to the L1 point to serve as a hot-backup, or (c) by identification of a launch slot for NASA's Triana spacecraft (which is currently in storage).

In summary, there are possibilities to use existing and planned space missions as sources of data for space weather monitoring. However, these opportunities are limited. A long-term space weather programme will need to develop data sources that are better suited to the requirements for space weather monitoring – and especially the requirement to provide continuous near real-time data.

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5.4.4.2 Hitch-hikers

There are good possibilities for space weather monitoring at geosynchronous orbit using hitch-hiker instruments on the many spacecraft placed in that orbit. Meteorological satellites may be particularly good candidates as they are usually run by governmental organisations concerned with environmental monitoring. Thus one may hope for a sympathetic response to requests to fly hitch-hikers to monitor the space environment. In contrast, commercial operators of geosynchronous satellites may be less willing to fly hitch-hikers if these were to use space, mass and power that could be used for a revenue-earning payload such as a satellite television transponder. There are also possibilities to fly hitch-hikers on spacecraft in another commonly visited orbit - namely low earth orbit. This case is especially valuable if the instrument has relaxed requirements concerning speed of telemetry delivery to the ground (≥1 hour).

These orbits provide excellent options for some specific problems. The types of measurements that can be made include measurements of energetic particles (e.g. cosmic rays, solar protons, radiation belt ions and electrons) and of micro-particles (debris and meteoroids). It may also be possible to fly hitch-hikers to make observations of the Sun and the aurora (photometry and imaging at various wavelengths). However, in these cases, it will be important that the instrument pointing requirements are not burdensome on the host spacecraft. For the imaging instruments it will also be necessary to ensure that optical path length does not result in instrument dimensions that are too large.

In summary, hitch-hikers are an excellent way to address some space weather issues. However, there are also some issues that require dedicated missions as discussed in the next section.

5.4.4.3 Dedicated missions

This option has the obvious advantage that one can select the orbit and thus optimise it to sample locations that are important for space weather monitoring. For example interplanetary and highly elliptical orbits are rarely visited by spacecraft launched for commercial or applications purposes. Thus this option is excellent for measurements that require orbits not usually visited by other spacecraft. Examples include e.g. L1 orbits for monitoring the solar wind, orbits away from the Sun-Earth line to allow optical monitoring of Earth-directed CMEs and elliptical orbits to sample the radiation belts over a range of L values. In practice, dedicated spacecraft are not just good for such orbits, they are almost mandatory. It would be a matter of great luck to find another mission travelling to these locations.

Surprisingly, dedicated missions have some financial advantages. If a dedicated mission is required to address a specific issue, it could be very worthwhile to consider flying other space weather instruments on the same mission - so long as their measurements can be made from the planned orbit. Thus one can use dedicated missions to obtain economies of scale - by spreading fixed costs such as launch, spacecraft bus and ground segment over several instruments.

One could also consider options in which the mission comprises several spacecraft. This could still present financial advantages: (a) by sharing launch costs and (b) by allowing the use of small spacecraft optimised to their payload rather than one large spacecraft whose design represents a compromise between different payload requirements.

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The types of measurements that require dedicated missions include monitoring of the heliospheric medium upstream of the Earth (e.g. at L1), solar and auroral monitoring using large imaging instruments, radiation belt monitoring over a range of L values, simultaneous monitoring of the magnetosphere at many locations.

In summary dedicated missions are required for some types of space weather monitoring - including some key measurements such as L1 monitoring of the solar wind.

5.4.5 Implementation of hitch-hiker and dedicated mission options

5.4.5.1 Telemetry - a critical factor for space weather missions

The critical factor in deciding how to implement the hitch-hiker and dedicated missions options is telemetry. Near real-time telemetry is usually needed for space weather measurements; our study of space instruments showed that the maximum gap that can be allowed in the telemetry stream is usually less than 20 minutes and often down to a few seconds. This demand drives the space architecture (orbits, numbers of spacecraft and ground stations). We find that geosynchronous and L1 are good locations for space weather measurements since they allow continuous observation periods with just a few spacecraft and ground stations. In contrast, we find low Earth orbit has limited utility for space weather work because it drives you to use larger numbers of spacecraft and ground stations.

The central role of telemetry will drive space weather missions to use architectures that are fundamentally different from the typical architecture of an ESA science mission. The latter use state-of-the-art space techniques in order to do cutting-edge science, but they can usually wait several days to get the data back, e.g. with the present Cluster mission, data may not arrive at ESOC until 1 to 3 days after being recorded on the one of the spacecraft. In contrast space weather monitoring needs near real-time telemetry as we have already discussed and would be adequately served by using well-established space measurement techniques.

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5.4.5.2 Hitch-hiker solutions

The table on the next page shows the options for which we have identified hitch-hiker solutions. Each entry describes a possible hitch-hiker instrument; it gives the CSMR that the instrument satisfies, a short description of the measurement and the instrument and the required orbit. The table below summarises the orbit options.

Table 8 Orbits for hitch-hiker solutions

Orbit code	*Orbit description*	*Number*	*Notes*
GEO	Geosynchronous	11	Many flight opportunities on applications and perhaps commercial satellites
SS	Sun-synchronous low earth orbit	2	Flight opportunities on remote sensing missions
On-board	Instrument on s/c where measurement required	1	Fly as required
	Total	14	

You can see that geosynchronous orbit dominates. This is not surprising; it just reflects the relatively high availability of potential hosts in that orbit.

Table 9 Hitch-hiker options

CSMR	Measure what?	What instrument?	Orbit selected for hitch-hiking	Number of instances
1	Solar EUV / X-ray images	Whole disk imager	GEO	2
2	Solar coronagraph images	Coronagraph	GEO	2
4,6	Auroral Imaging, Auroral oval, size, location & intensity	Auroral imager	SS	2
8 to 11	X-ray flux & spectrum(CSMR 11)	X-ray photometer / spectrometer	GEO	2
12	UV flux	UV photometer	GEO	2
13	EUV flux	EUV photometer	GEO	2
36 to 38	IMF (B-field)	Magnetograph	GEO	2
53 to 55	1-10keV electrons and 10-100keV electrons	Medium energy electron spectrometer	GEO	4
56 to 58, 62	>10MeV ions (SPE / SEPE) and >100MeV ions. Energy spectra required (CSMR 62)	High energy ion detector	GEO	1
59 to 61	>10MeV protons (trapped)	High energy ion detector	GEO	3
63 to 65	>100MeV ions (CGR)	High energy ion detector	GEO	1
66 to 67	Relativistic electrons (>0.3MeV) incl spectra	High energy electron spectrometer	GEO	3
69 to 71	Debris size & velocity distribution and Meteoroid size & velocity distribution	Debris monitor	SS	1
72	Dose rate & LET spectrum	Dose monitor	Onboard s/c	1

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The table also shows the number of instances of each instrument (and thus hosts) required in each orbit. This number is driven by one of two factors: (a) the need to provide sufficiently continuous data, or (b) the need to sample the space environment at multiple locations. For example, solar observations from geosynchronous orbit (CSMRs 1, 2, 8-11, 12, 13, 36-38) are driven by the need for continuous data. In this case we require two instances to cover the eclipse seasons around the equinoxes. During these periods either host may be eclipsed by the Earth and thus unable to observe the Sun; but if the two hosts are well-separated they will never be in eclipse at the same time. Thus with two instruments on different hosts, we can obtain the continuous observations that are required. In contrast, radiation belt observations (CSMRs 53-55, 59-61, 66-67) are driven by the need for multiple sampling - to provide simultaneous measurements over a range of L values and a range of local time.

5.4.5.3 Dedicated solutions

The hitch-hiker solutions in Table 9 cannot satisfy the following CSMRs.

Table 10 CSMRs not satisfied by hitch-hiker solutions

CSMR	Measurement
3	Off Earth-Sun observations of CMEs
23-27	In-situ measurements of upstream solar wind density and velocity (also CSMR 36-38 for in-situ magnetic field)
39-43	Magnetospheric magnetic field
52	Cold ion density in plasmasphere
75	Interplanetary radio emissions

Thus dedicated missions are required to address these requirements, which include the crucial measurements of the upstream solar wind and magnetic field.

The table on the next page shows the options for which we have identified dedicated mission solutions. These address the CSMRs listed above - but also include other instruments that can conveniently be included on the dedicated missions, i.e. we use the dedicated mission as a "host" for other instruments. Each entry describes a possible dedicated mission; it gives the CSMRs that the mission satisfies, a short description of the measurements and of the instruments. It also shows the required orbits. These are much more diverse than for the pure hitch-hiker options because we have the freedom to select the optimal orbit for each solution.

The table also shows:

- the names of European spacecraft platforms whose design could be re-used for these missions
- the number of instances required for each mission. In this case, the driver is always the need for multiple sampling, e.g. plasmasphere and radiation belt observations (CSMRs 52, 53 to 55, 59 to 61, 66 to 67) should be simultaneous measurements over a range of L values and a range of local time.

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Table 11 Dedicated mission options

CSMR	What instrument ?	orbit selected	Platform selected	No. of s/c each round
3	Coronagraph	leading heliocentric (L4)	PICARD	1
2 3 75	Coronagraph Coronagraph Radio Wave Detector	trailing heliocentric (L5)	LEOSTAR 200	1
39 to 43	Magnetometer	M/sphere	SWARM	30
52 53 to 55 59 to 61 66 to 67	Thermal energy ion spectrometer; Ionosonde, UV Imager Medium energy electron spectrometer Thermal energy ion spectrometer High energy electron spectrometer	GTO	STRV c/d	4
1 8 to 11 12 13	Whole disk imager X-ray photometer / spectrometer UV photometer EUV photometer	L1	LEOSTAR 200	1
23 to 27 36 to 38 56 to 58, 62 63 to 65	Thermal energy ion spectrometer Magnetometer Thermal energy ion spectrometer High energy ion detector	L1	ASTRID	1
4,6 69 to 71	Auroral imager Debris monitor	SS	PICARD	1
4,6	Auroral imager	SS	PICARD	1

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5.4.5.4 Prioritisation of space segment options

In order to develop the implementation plan in the next section, we need here to establish a prioritisation of the various options to be flown as hitch-hikers or as dedicated missions. We have done this separately for these two sets of options and show the results in two tables below. Note that this separate ranking of hitch-hikers or as dedicated missions will allow us to compare the relative benefits of investing in a various mixes of hitch-hikers and dedicated missions.

Table 12. Prioritisation of hiker-hiker options (1 = highest rank)

Rank	*Description*	*Rationale for ranking*
1	Dose monitor	Monitors radiation exposure of humans and equipment on host spacecraft.
2	High energy ion detector	Monitors cosmic ray particles (including very energetic solar protons) that cause radiation exposure for aircraft crew and passengers. Also cause single event upsets in electronic devices.
3	High energy electron spectrometer	
4	Debris monitor	Monitors a major hazard to host spacecraft
5	Medium energy electron spectrometer	Monitors electrons that can cause spacecraft charging
6	High energy ion detector/GEO	Monitors solar system fluxes of MeV energy particles (e.g. solar protons) that can radiation exposure for humans and equipment in space. Given lower priority than the most energetic particles as they present no hazard to aircraft and are a lesser hazard for spacecraft.
7	High energy ion detector/GTO	Monitors radiation belt particles that can radiation exposure for humans and equipment in space. Broadly the same as the previous item but monitoring a different source of particles.
8	EUV photometer	Monitors solar activity important for prediction of ionospheric behaviour. Can be replaced by proxy data such as solar 10.7cm radio flux so of lower priority than points above.
9	UV photometer	
10	X-ray photometer / spectrometer	Important for nowcasting ionospheric behaviour Also useful for nowcasting solar proton activity but direct measurements above may be better.
11	Auroral imager	This instrument would monitor the size of the auroral oval, which can be valuable as an indicator of the state of the magnetosphere (e.g. in magnetospheric models). However, its implementation as a hitch-hiker may be difficult in terms of telemetry requirements. Thus it is given a low priority just ahead of the solar instruments (which face a wider range of implementation constraints).
12	Coronagraph	These three instruments monitor key aspects of solar activity but are given the lowest set of priorities as it may be difficult to find hosts for these instruments both in terms of instrument size and of telemetry requirements. The ranking within the groups reflects the relative priority of observations of CME launches, of structures in the photosphere and lower corona and of solar magnetic field measurements.
13	Whole disk imager	
14	Magnetograph	

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Table 13. Prioritisation of dedicated options (1 = highest rank)

Rank	*Description*	*Rationale for ranking*
1	Thermal energy ion spectrometer, Magnetometer, Thermal energy ion spectrometer, High energy ion detector	This is a package of measurements to monitor the solar wind and the heliospheric magnetic field in-situ at a location upstream of the Earth. Thus it provides measurements that are immensely useful in predicting geomagnetic activity and the space weather impacts that follow from that, e.g. ionospheric propagation, drag, ground-induced currents, etc. It is also very convenient to add a monitor for solar protons.
2	Whole disk imager, X-ray photometer / spectrometer, UV photometer, EUV photometer	This is a package of measurements to monitor the Sun in order to predict solar phenomena (e.g. CME launches, coronal holes, flares) that have space weather effects. This is given a slightly lower priority than the in-situ monitor because it is less certain that events seen by this mission are geoeffective.
3	Thermal energy ion spectrometer;/Ionosonde,/ UV Imager, Medium energy electron spectrometer, Thermal energy ion spectrometer, High energy electron spectrometer	This is a package of instruments to monitor the radiation belts. There are an important space weather issue – especially as the behavior of the outer belt is not yet well understood – and thus has a high priority. But it covers a smaller scope of space weather applications than the in-situ and solar monitors and hence is ranked behind them.
4	Coronagraph	This is a speculative mission to monitor Earth directed solar ejecta by observing from a location off the Earth-Sun line. This would be immensely valuable and is included in the table for that reason. But it is given a lower priority because of its speculative nature.
5	Coronagraph, Radio Wave Detector	This is similar to the previous mission but includes additional monitoring capability in terms of radio wave remote sensing of CMEs. It is more complex than the previous option and for that reason is ranked lower.
6	Auroral imager, Debris monitor	This is a mission to monitor auroral activity. This is valuable as it could provide a means of imaging and monitoring the current state magnetospheric dynamics. It is ranked below the previous options as they are concerned measurements further upstream in the flow of energy from the Sun to the Earth chain. The orbit for this option is also suitable for debris measurements and so that simple instrument is included.
7	Auroral imager	This is the same as the previous option but given lower priority because of the exclusion of the debris monitor.
8	Magnetometer	This is an ambitious mission to monitor magnetospheric dynamics by flying a large number of small spacecraft. Its successful realisation would be immensely valuable. But the technical challenge involved makes this a long-term objective and for that reason it is given the lowest priority.

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5.4.6 Options for ground observations

Europe already has a wealth of ground-based measurements related to space weather. As part of our study we carried out a survey of European space weather resources. This identified some 222 resources of which 99 were ground measurements. These mainly focus on observations of the Sun (23%), the ionosphere (34%) and ground-effects (37%). These measurements are spread over many European countries. There are strong activities in France, Germany, Italy, Scandinavia and the UK as well as strong Pan-European activities (e.g. EISCAT, THEMIS) and strong participation in global networks (e.g. INTERMAGNET, SuperDARN). There is clearly a good base for further European collaboration and co-ordination.

These existing ground-based programmes can address most of the CSMRs that we identified in Table 7. We recommend that the space weather programme should include an element to encourage the maintenance and augmentation of these existing programmes. It is vital to ensure visibility of ground-based activities as a core part of space weather activities in Europe – to encourage use of their products and to sustain political support in order to underpin their funding.

It is important to recognise that many ground-based measurements come from networks spread across Europe. The value of the measurements comes from the combination of data from many nodes rather than from the data taken at any individual node. Thus funding agencies get a very good return for their investment - support of one or a few nodes gives them access to the whole dataset.

These ideas also apply on a global scale. European measurements often contribute to global networks and thus provide contributors with a global view. This is important for space weather as it is global not regional in nature (space weather is very different in this respect from tropospheric weather).

The support of ground-based measurements should also include development of new techniques. We have already discussed the two prime candidates (HF backscatter radar and interplanetary scintillation) in section 5.4.3. The key issue for a space weather programme will be to migrate these techniques into an operational environment, i.e. providing continuous coverage and consistent high quality data.

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5.5 Data handling

5.5.1 Overview

The figure below summarises the handling of data in the ground segment of a space weather service. There are two main entities:

1. The spacecraft interface, which is concerned with the ground segment activities required to operate space-based instruments and convert their output into calibrated physical parameters (e.g. the conversion of particle counts to fluxes). Where required, it will include ground stations providing telemetry links to spacecraft carrying out space weather monitoring and staff responsible for flight operations of instruments and spacecraft.
2. The space weather service, which is concerned with the use of calibrated physical parameters to provide a service for end users. This includes (a) the conversion of physical parameters into useful space weather products, (b) the dissemination of those products and of physical parameters (e.g. to external organisations who use the data to provide specialist services for end users) and (c) user support to provide advice to users (via both computer and human interfaces) and to receive their feedback on the service provided.

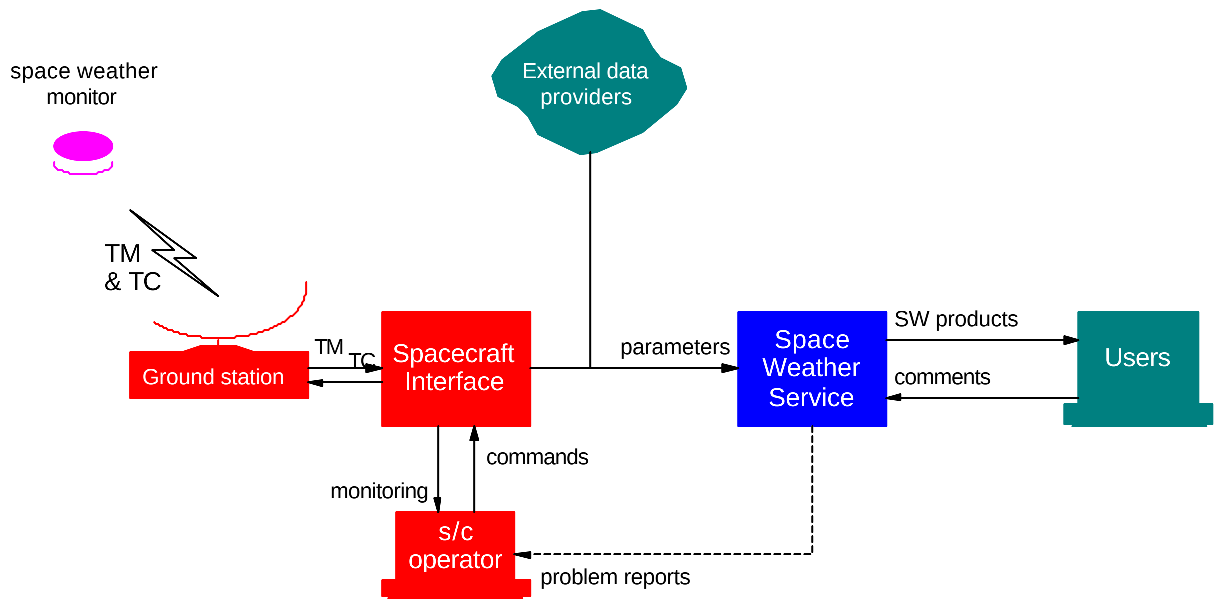

Figure 3 Overview of data handling systems

The interface between these two entities should be based on simple internet concepts, e.g. using protocols that allow the space weather service to access remote files via a uniform resource locator (URL). This interface will also allow the space weather service to retrieve data from external data providers (e.g. existing and planned missions, ground-based facilities). The remote access may be initiated in a variety of ways, e.g. at fixed times, by responding to an email trigger or by scanning a new products file to determine what is currently available. The space weather service should support a variety of access methods in order to allow it to access data from a wide variety of sources.

5.5.2 Spacecraft Interface

The figure on the next page shows an expanded view of the spacecraft interface. This includes a wide range of functionality as follows:

- Generation of commands and delivery to ground station
- Ground station for uplink of commands
- Ground station for reception of telemetry data
- Telemetry processing (extract packets, timestamping)
- Monitoring of the performance of the spacecraft and its sub-systems, including the payload
- Spacecraft operations team
- Deriving s/c orbit and attitude from tracking data etc.
- Generating orbit and event data
- Attitude planning
- Conversion of instrument data into calibrated physical data,
- Making all relevant mission data available to the Space Weather Service

All these services are required in the case of a dedicated mission, in which case the space weather programme would have full responsibility for spacecraft operations.

The hitch-hiker case is more variable. Many of the services listed above will be provided by the host spacecraft and its ground segment. For example the spacecraft interface will then have to communicate with the host ground segment to deliver commands for uplink and to retrieve orbit and attitude data. The retrieval of data may be done via the host ground segment or it may be downlinked to a dedicated space weather ground station operated as part of the spacecraft interface above. There is also the possibility that both approaches are used but at different times (as is done now for data from the real-time solar-wind experiment on ACE).

Note that the spacecraft interface is not required for use of data from existing and planned missions. The data are routed direct to the space weather service.

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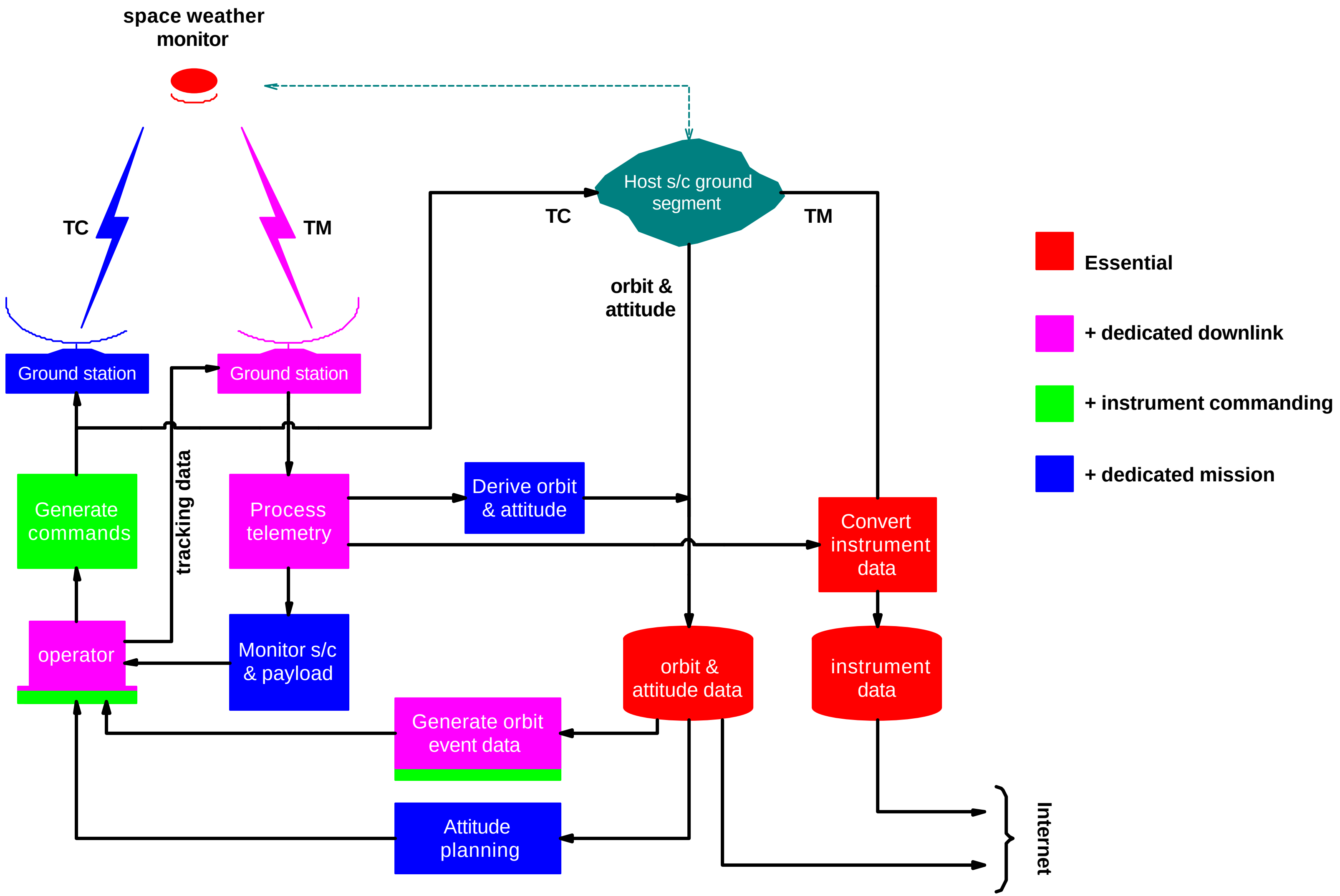

Figure 4. Ground segment support for hitch-hiker and/or dedicated options

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5.5.3 Space Weather Service

5.5.3.1 User requirements and conceptual design

We have reviewed user needs in order to establish a set of "service user requirements" that describe the products of the space weather service. These are shown in Table 14 on the next page. This also shows the basic functionality that should be associated with each user requirement ("service functional elements").

The figure below shows a high-level design of the computer and database systems needed to meet the needs outlined in the user requirements. There are five large components:

- **Retriever** Those elements that fetch relevant data from data providers.
- **Database** Storage for parameters, enhanced products and associated metadata.
- **Modeller** The collection of modelling and forecasting processes that work on data to generate more sophisticated data products.
- **Interface** The modules concerned with handling interactions with users.
- **Scheduler** A generic module that schedules the many system processes that need to happen at specific times.

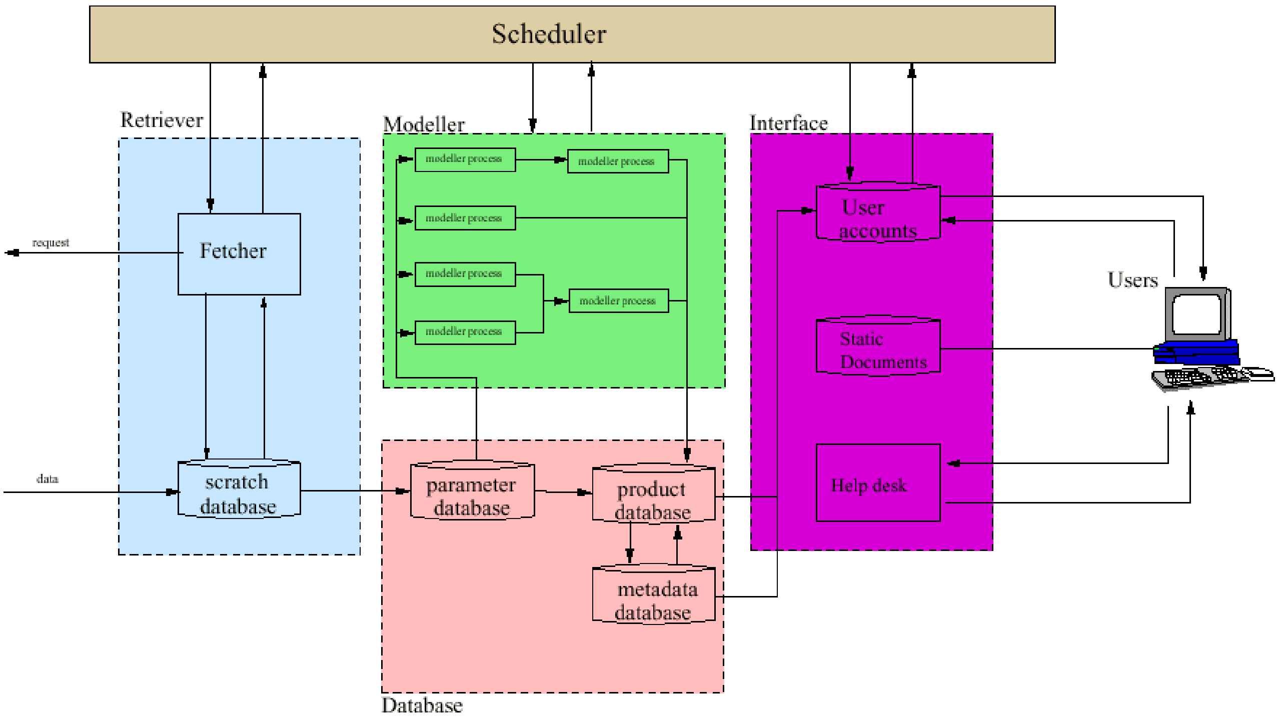

Figure 5. High-level design for the Space Weather Service

Table 14 Space weather service User Requirements and Service Functional Elements

SUR	*User Requirement*	*SFE*	*Service Functional Element*	*Comments*
1	Timely and reliable data from multiple sources	1	Networked and reliable data access	Delivery by magnetic media is too slow.
		2	Retrieval scheduler	Must be able to carry out retrievals automatically
2	Good documentation of system and data	3	On-line help	
		4	Comprehensive metadata	A prerequisite for sophisticated data provision to users.
		5	Human support	For when all else fails.
3	Consistent interface to multiple datasets	6	Generic, comprehensive and accessible data output format	
4	Easy to identify relevant datasets	7	Data dictionary	Having metadata is not enough - it must be query-able.
		8	Yellow pages system	For locating datasets at remote data providers
5	Access to enhanced products	9	Data aggregation.	
		10	Models and forecasts.	
6	Access to past data	11	A local archive of relevant data	Important for post-incident analysis and monitoring of quality of warnings.
7	Personalised regular data retrieval	12	User accounts with personal profiles	
8	Access to informed advice and scientific technical support	13	Technically and scientifically competent personnel	A consultancy role
9	Background information on science and impact of space weather	14	On-line introduction to space weather.	Much pre-existing material exists..
		15	Outreach materials	Posters, stickers, curriculum materials, CD-ROMs, displays, museum exhibits
10	Graphical presentation of selected data products	16	Graphics engine	
11	Continuous service development.	17	Regular service monitoring	.
		18	User feedback facilities	On-line and face-to-face
		19	Medium and long-term strategic planning	

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5.5.3.2 Models run by Space Weather Service

The conceptual design also shows that the SWS will run a variety of models to convert environmental parameters into space weather products required by users. The table below shows an initial set of models that should be run - as taken from the system measurements requirements [SRD]. The columns headed 'T', 'M' and 'UR' show:

- Time of operation: F = forecast, N = nowcast, H = hindcast (i.e. post-event analysis)
- Mode of operation: S(tandard), C(ustom). Standard outputs would be generated routinely and stored; custom outputs would require user input to generate the desired outputs on demand.
- The User Requirement numbers from [SRD] that would be satisfied by a service using this model

The "Update period" column shows the frequency with which standard outputs should be updated.

Table 15 Initial set of models for the SWS to provide

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Model	T	M	Update period	UR
Plasma and Radiation Environment				
Climatic models of solar protons from Solar Proton Events e.g. JPL-91	F	S	6 monthly	1
Climatic models of GCR e.g. CREME [CREME], CARI [CARI] or EPCARD [EPCARD]	H	S	6 monthly	3
Magnetic field rigidity models to map observed fluxes of GCR, SCR, solar protons, energetic ions and neutrons to arbitrary orbits or spacecraft positions	NH	C	30 minutes	13 15 19 20
Rigidity cut-off models (e.g. Størmer [STØRMER] or Shea and Smart [SHEA]) to map observed fluxes of >100 MeV ions to altitudes, routes and locations of aircrew, avionics equipment and spacecraft launches.	NH	C	hourly	2 3 22
Radiation transport model (e.g. GEANT [GEANT]) to map >100 MeV ions to aircraft altitudes and routes.	NH	C	hourly	13 15
Magnetic field model(s) (e.g. those of Tsyganenko [TSYG]) to map observed fluxes of electrons, ions and protons of all energies along field lines to arbitrary orbits and spacecraft locations	NH	C	1 minute to hourly	13 15
Prediction of Solar Proton Events from CME and flare detection	F	S	1 minute	1 18
Plasma environment modelling (e.g. Salammbo [SALAMMBO] or MSFM) to fill gaps where good plasma measurements are not available.	NH	C	3 hourly	13 15
Solid Body Environment				
Climatological models of debris (e.g. MASTER-97 [MASTER] or IDES [IDES]) and random meteoroids.	FNH	S	6 months	13 15 18 19
Gravitational modelling of debris and random meteoroids to Low Earth Orbit	FNH	S	6 months	13 15 18 19
Orbit propagation modelling of large debris	F	S	6 months	14
Models of meteoroid streams [METEOR]	FNH	S	daily	13 14 15 18 19

Model	T	M	Update period	UR
Magnetic Environment				
Predictions of Kp from solar rotation out to 27 days.	F	S	daily	7
Predictions of Kp from CMEs or flares out to 2 or 3 days	F	S	hourly	4 7
Predictions of Kp from solar wind 1 or 2 hours (Lund [LIND2, LUND3] or Costello [COSTELLO] models).	F	S	15 minutes	7
Predictions of Dst from solar rotation out to 27 days	F	S	daily	7
Predictions of Dst from CMEs or flares out to 2 or 3 days.	F	S	hourly	7
Predictions of local dB/dt from CME detection	F	S	15 minutes	4
Estimates of dB/dt by interpolation from local field measurements. This is probably better done directly by end users with their service providers because of the high temporal resolution required.	NH	C	10 seconds	5
Atmospheric Environment				
Predicted Ne profiles from climatic models driven by SSN, F10.7, EUV flux and Kp (e.g.IRI [IRI]).	F	C	daily	10
Derived Ne profiles from ionosonde observations and interpolations of global or regional models e.g. ITU-R [ITU-R].	N	C	15 minutes	11
Derived Ne profiles by scaling static models with dynamic TEC data. e.g. PRISM [PRISM], PIM [PIM] updated by JPL GIM [GIM].	N	C	5 minutes	11
Ionospheric scintillation from the NWRA model WBMOD [WBMOD1, WBMOD2] driven by Kp and SSN forecasts.	F	S	15 minutes	10
Polar Cap absorption driven by CME/flare detection	F	S	5 minutes	10
SW fadeouts from flare detection.	F	S	5 minutes	10
Predictions of decreased S/N ratio from solar radio emissions	F	S	5 minutes	10
Ionospheric storm forecasts from Kp predictions based on solar rotation	F	S	3-hourly	10
Ionospheric storm forecasts from Kp predictions based on CME and solar flare detection	F	S	hourly	10
Ionospheric storm forecasts from Kp predictions based on solar wind (Lund [LUND2, LUND3] or Costello [COSTELLO] models).	F	S	15 minutes	10
TEC from GNSS.	N	C	5 minutes	12
Atmospheric model (e.g. UCL CTIP) modulated by solar activity to get atmospheric drag in LEO.	N	S	daily	16
Statistical model of auroral location (e.g. NOAA POES [POES]) from geomagnetic activity using Kp forecasts.	F	S	3 hourly	17

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5.5.4 Case studies and prototyping

To support the definition of the space weather service we have also carried out a prototyping activity. This involved the development a software prototype and the preparation of a set of case studies that could be used to test that prototype (with ESA to select one case for testing).

We first outline the case studies. This work identified four major space weather events for which adequate background data are available. These are shown in Table 16 below. Note that the requirement that adequate data be available implies that the case periods must be in recent years (given the greater availability of appropriate data since the mid-1990s) but not too recent (since there must have been adequate time to data to become available).

Table 16. Case studies for prototyping

Case	*Period*	*Notes*
1	April 2000	This was the case selected by ESA for testing the prototype
2	May 1998	
3	May 1997	
4	January 1997	

We now turn to the software prototype. This was developed using a three-level approach proposed by ESA. The levels were as follows:

1. Level 1 involved the building of the Space Environment Yellow Pages. These are a compilation of services, accessible through Internet, that provide useful resources to reconstruct the space environment at a particular location and time. They include cross-referenced catalogues of references to servers with space environment data and/or models, descriptions of satellite or ground missions related to the measurements of environment components, and parameters and physical quantities acting on the environment. They also include information needed to retrieve and access the referenced data. The interface to the Yellow Pages is a set of dynamic web pages that generate database queries and present the query results. Different access routes are available, e.g. starting from a list of physical parameters or of satellite missions.
2. Level 2 involved building a system to automatically retrieve, store and disseminate data from some of the resources in the Yellow Pages. The retrieved data are presented to the user in flat ASCII files containing a descriptive header and a simple column layout.
3. Level 3 extended the prototype to allow a user to supply a physical quantity, a region in space, and a time frame, and to then identify the resources that can satisfy his or her request. The list of resources (if any are found) is presented to the user, who can then make a selection and activate the data retrieval procedure. As an example, if GTO electron fluxes above 1 MeV are required, the prototype identifies data from the GOES and SAMPEX missions as the required resource, and selects the electron channels nearest to the required energy. Tools are implemented to facilitate the input of co-ordinate ranges (e.g. pre-defined locations such as GEO and L1). Level 3 also demonstrated the provision of access to models of the space environment. In order to demonstrate the prototype interface to such models, a trapped radiation model was implemented locally and made available to the prototype as an external resource.

The prototype is Web accessible and may be inspected via a main entry point on http://eve.oma.be/ESWS/. To view the detailed pages it is necessary to register and obtain a username and password.

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6 What is needed in the Implementation Plan?

6.1 Outreach and user education

This is one of the key proposals from our study. There is a clear need to improve European awareness of space weather and its effects on technology and human society. This applies across a wide range of audiences including end-users, decision-makers, informed commentators, educators and students.

We therefore propose that ESA should establish, as soon as possible, an ESA Space Weather Outreach Centre. This might be established within an existing ESA centre or be contracted out to one of the many suitable organisations in the ESA member states. The terms of reference of the centre should include:

- To build an on-line database of information about space weather and provide internet access to this for any interested party in the member states,
- To identify potential European audiences in which awareness of space weather might be improved, to develop links with those audiences and undertake activities to improve that awareness. This is an important proactive task for the Centre.
- To support, so far as its resources allow, other public and private initiatives within the member states that aim to improve awareness of space weather. Examples of such initiatives may include (a) programmes to improve public understanding of space science, (b) science and technology programmes that address issues related to space weather, and (c) special interest groups that address specific space weather problems.
- To exchange ideas and materials with similar centres outside Europe, e.g. in the US, Japan and China.

It would also be appropriate to set up the Centre so that it is permitted, and indeed encouraged, to seek supplementary funding from a variety of sources. We envisage that direct ESA funding would support the core infrastructure of the Centre but specific initiatives would be funded separately, e.g. by interested industrial or governmental groups. Thus the Centre would operate under the auspices of ESA but be able to tap into additional sources of funding.

6.1.1 Management

To achieve this, the Centre would require a management structure that represented the interests of ESA, the interests of the host institution (if not ESA) and the broader interests of the community. Thus the policy of the Centre should be directed by a management board containing representatives of ESA, representatives of the senior management of the host institution and a number of independent members selected by ESA for their high standing in fields related to space weather.

The day-to-day management of the Centre would be carried out by the senior members of the dedicated staff according to a structure to be determined by the management board. This structure must take account of the management approach of the host institution.

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6.2 Securing existing data provision

6.2.1 Ground-based data

A wealth of ground-based data is already produced by organisations in the ESA Member States - as discussed in section 5.4.3. This is a considerable resource that could be exploited as part of a European space weather programme. However, it is funded in a very piecemeal manner and is therefore under constant threat from funding cuts. We propose action to raise awareness of the strategic value of European ground-based data for space weather and provide a basis on which individual groups can make a strong case for continued support and development of relevant ground-based measurements.

The key question is what should be the ESA role in this action. Strictly speaking support for ground-based observations lies at the margins of ESA's remit but can be justified as ground-based support of space-based activities. We propose that ESA encourage the development of a human network that brings together the people responsible for ground-based observations across Europe. The goals of this network should include:

- Developing and maintaining an inventory of European ground-based capabilities,
- Exchange of knowledge and ideas across political and topical boundaries,
- Developing a conceptual framework which shows how individual ground-based space weather measurements fit with overall European needs for space weather data.
- Studying the roles of public, academic and commercial bodies in the operation of ground-based space weather measurements.

We propose that ESA should be a sponsor of this network but should also seek participation from other appropriate bodies, e.g. European Science Foundation, etc. This network must develop links with a number of existing initiatives such as INTERMAGNET, JOSO, etc.

This network would be an example of the type of initiative that should be supported by the proposed ESA Space Weather Outreach Centre. Indeed, the Centre would be the natural point of contact between ESA and the network – though that must not preclude direct participation in the network by other ESA groups that can contribute to, and derive benefit from, the network.

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6.2.2 European space-based

The main European contribution to current space weather monitoring is ESA’s SOHO mission – in particular through the images from the LASCO and EIT instruments, but also the solar wind plasma measurements from the CELIAS instrument. The other active ESA space science missions (Ulysses and Cluster) address our understanding of the science of space weather but do not contribute to space weather monitoring. This is simply a consequence of mission design - in particular the orbit. For SOHO that design fortuitously yields data products suitable for space weather monitoring. This is not the case for Ulysses and Cluster.

We therefore propose an action to raise awareness of the European leadership of SOHO in the space weather arena. This is sometimes not well understood because of NASA’s major role in SOHO spacecraft and payload operations. This is a task that could be undertaken by the proposed ESA Space Weather Outreach Centre. It is perhaps worth noting here that one can use this as a good example of the value of ESA-US collaboration in space weather. The value of SOHO has been publicly recognised by both the civilian and military space weather programmes in the US.

We also note that the continuation of SOHO operations would be of great benefit for space weather monitoring. We recognise that the main driver for funding of further SOHO operations is the scientific return but recommend that the space weather monitoring be recognised as a substantive secondary return from the mission. During the course of this study, some influential end users of space weather products commented that the scientific community should exploit such secondary returns where they were possible.

In addition to SOHO there are a number of smaller European activities that provide space-weather related data:

- Auxiliary measurements on other spacecraft, e.g. the radiation monitor on Newton-XMM.
- National agency missions such as DLR's CHAMP mission, which includes GPS phase measurements from which ionospheric densities can be derived - [CHAMP1. CHAMP2].

There are two actions required here: (a) to develop and maintain information on relevant space weather measurements from these smaller activities (perhaps as part of a more general inventory of space weather resources) and (b) to ensure that the space weather community has good visibility of these resources. Again these are potential tasks for the proposed ESA Space Weather Outreach Centre.

6.2.3 Non-European space-based

There is also substantial European involvement in non-European space weather monitoring missions. A prime example of this is the collection of real-time solar wind data from NASA's ACE mission by ground stations operated by European groups such as RAL and CNES. We recommend that the proposed outreach centre should monitor these activities and promote their visibility as a European contribution to the global effort on space weather.

6.3 Supporting value-added services

The second major proposal from our study is that ESA should encourage the provision of value-added services that deliver space weather products. There is a significant demand for products that are truly useful to end-users, e.g. expressed in forms that they can easily apply to their activities without specialist knowledge of space weather and its interaction with their activities. Users are prepared to pay for services where the provider has that specialist knowledge and uses it to convert space weather measurements to operational products. Users are not prepared to pay for the measurements themselves – they firmly see that as a public sector responsibility in the same way as has been traditional for meteorological and other environmental measurements. Users clearly consider that is a good tradition that should not change.

We recommend an open approach to the development of value-added services, i.e. that appropriate groups across Europe should be encouraged to identify opportunities and to develop services to fill them. The role of ESA should be to build the environment in which those developments can take place. That environment should include:

- Development of standards for provision of space weather data to service providers and encouraging their use by both data and service providers. These standards should be based on the existing work undertaken by the Consultative Committee for Space Data Standards

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[CCSDS] which already has major participation from ESA and several member state national agencies (including BNSC, CNES and DLR).
- Identifying opportunities for data provision from ESA missions and liasing with the mission project team to ensure that the data meets the above standards.
- Acting as a broker between data and service providers.
- Provision of advice to potential service providers. This may include advice on broader space weather issues and on technical and marketing issues. A key target group to encourage here is people in the research community who have good ideas but who need help to convert the idea into an operational service (perhaps as a spin-off service).

To provide this environment, we recommend that ESA establish a Space Weather Development Group that is charged to develop the environment described above. This group should be distinct from the Outreach Centre as it has a different mandate. Indeed, this Group should be within the Agency in order to have sufficient standing to achieve that mandate. The Group needs particularly to include staff with strong management skills including project management and negotiation with third parties. It also requires staff with a good knowledge of modern data handling techniques in order to liase with developments in CCSDS and with peer staff in data and service provider teams. Liaison with the Outreach Centre will be required to exchange information on space weather issues and with the ESA Technology Transfer Programme [TTP] to seek help on the transition of service ideas into operational services.

6.4 Seeking new data infrastructure

Our third major proposal is that ESA should encourage the further development of space weather monitoring in Europe. There is a clear need for new developments to complement the substantial level of activity discussed above. In particular, new activities are required (a) to provide good-quality measurements where present coverage is poor (e.g. the radiation belts) and (b) to replace existing measurements when the current instrumentation comes to the end of its useful life. An important aspect of the latter is to develop replacements that are optimised for space weather monitoring in terms of robustness, reliability and cost.

The development of space weather monitoring has many aspects. For space-based measurements these include:
- Establishing dedicated space weather missions for high priority objectives that require dedicated missions, e.g. L1 and sub-L1 monitoring of the solar wind, imaging of solar activity and ejecta.
- Seeking opportunities for hitchhiker missions where appropriate and supporting their implementation and operation
- Encouraging the development of new instrumentation for space weather monitoring – in particular to sponsor technology developments such as miniaturisation and data compression that will increase flight opportunities. Improved robustness against severe space weather is also a concern here.
- Encouraging space and ground segment developments that improve telemetry coverage, e.g. use of standards, use of small dishes, etc.
- And. above all, encouraging the view that space weather monitoring is a rolling programme in which instruments should be replaced in a timely fashion (e.g. balancing cost against the need to avoid gaps in coverage).

How to organise a programme to achieve this? It is an activity that ESA could initiate since it will inevitably have an initial development phase that sits well with ESA's role as a research and

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development organisation. But as that development moves into implementation, the activity will acquire a strong element of routine operations – in particular, to sustain the rolling programme. This will sit much less well with ESA's role. Thus when this stage is reached it may be appropriate to migrate this activity into a spin-off organisation – perhaps on a similar model to the development of EUMETSAT.

Many space weather parameters can be measured from the ground. So a programme to develop space weather monitoring should include development of ground-based measurements in its remit. This will allow the programme to take an overall view of possible solutions to the requirements for space weather monitoring. In particular, this allows the programme to compare relative quality and cost when measurements can be made from both space and ground.

6.4.1 Prototype programme

With these points in mind we propose that ESA establish a Prototype Space Weather Monitoring Programme with the remit discussed above (including development of ground-based monitoring). The programme should initially be operated within ESA but there should be a long-term objective of migrating this activity when, and only when, the time is right. To this end the programme should be subject to periodic reviews. We propose that the following criteria be applied to judge when the time is right:

- More than 70% of programme resources should be devoted to routine operations (where routine operations include the costs of implementing replacements for existing instruments).
- Adequate arrangements have been put in place for funding of the activity. Given the strong views expressed by end users and service providers, we anticipate that this should be public funding.

It is perhaps worth stressing that in this model we very much perceive ESA's role as the initiator of a new activity and that, once it is firmly established, this activity should evolve into a separate organisation. This is an organic approach that provides the positive environment needed for development of a new programme that will be of long-term importance for the European space business.

The programme will need to develop appropriate links with other ESA programmes and, in many cases, might retain those after the proposed migration to a separate organisation. One key example of this is the relationship with the ESA Science Programme. As previously discussed, our study shows that there is a fundamental conflict between the typical architecture of an ESA science mission and that anticipated for an effective space weather monitoring programme[2]. Thus there is limited potential for synergy at the level of flight opportunities. Where there is synergy is at the level of development of new instrument technologies since this is a common objective of both programmes. Indeed, the space weather programme could benefit from flight experience gained by the science programme in the operation of new instruments. Similar relationships may exist with other ESA programmes in respect of flight experience.

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[2] Space weather architecture is driven by the need for near real-time telemetry from well-established space measurement techniques whereas science missions use state-of-the-art space techniques but can usually wait days to get the data back.

6.4.2 Detailed scope of the prototype programme

6.4.2.1 Prototype space weather service.

This is the most important element of the programme as it is needed irrespective of the data sources (i.e. existing & planned missions, hitch-hikers, dedicated spacecraft). It should therefore be the first element of the prototype to be established. We propose that its first objective should be the early provision of a simple but useful service in order to demonstrate what is possible and thus build support for a space weather programme. This service should be based initially on European data sources in order to demonstrate our current capabilities - but that must not exclude exchange of data with sources outside Europe. That is often essential to obtain a global view of space weather conditions - and is another a good point to demonstrate using the prototype system. The table below lists some services that might be provided by the prototype. They have been selected on the basis that they are useful services for which data is likely to be available from European sources and that we consider there is a good possibly of quickly developing a reliable service. The latter point is very important if the prototype is to be a vehicle to demonstrate the value of a space weather programme.

The services shown in the table were selected from the user requirements given in Table 4. For each entry we give the user requirement number, the products required by users and the application area that these serve. We also show the numbers of consolidated system measurement requirements (CSMRs), as given in Table 5, that satisfy these user requirements.

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Table 17 Table of services to be considered in the prototype

UR	Products	Application areas	CSMRs
3	Post-event information on radiation levels at altitudes and on routes used by commercial airlines	Calculation of crew (and passenger) radiation exposure and investigation of equipment anomalies	19, 22, 43, 62
6	Spatially resolved post-event information on geomagnetically induced currents of all sizes.	Electric power transmission organisations (also railways and telephone companies)	6, 28, 31, 33, 44
11	Now-casts of ionospheric reflection properties	HF frequency selection for RF systems (civil and military)	46, 48
12	Now-casts of ionospheric total electron content	Corrections to GNSS location systems and radar systems (civil and military)	49
16	Now-casts of atmospheric drag affecting LEO spacecraft	Satellite operators (civil and military)	12, 16, 74

We now look in more detail at the CSMRs needed for the prototype service. These are listed in Table 18 below. We describe each measurement and discuss possible data sources - with emphasis on European sources but also indicating where collaboration with non-European sources would be useful. We also indicate the models that may be used to convert measurements into useful space weather products.

Table 18 Measurements and models needed by the prototype service

CSMR	*Measurement*	*Data source*	*Models used*
6	Auroral oval location and size	Ground-based instruments, e.g. ALIS system run by IRF, instruments on Svalbard may also be useful	Physics-based modelling of local dB/dt as response to global effects. Then derive GIC from dB/t by physical or empirical modelling.
12	UV flux	No European source - may be available from NASA TIMED after its launch in December 2001	Atmospheric models (e.g. MSIS) adjusted for solar activity
16	F10.7	Dominion Observatory, Ottawa	Atmospheric models (e.g. MSIS) adjusted for solar activity
19	Ground-based neutron monitors	Various monitors run by groups in Belgium, Finland, France, Russia and Slovakia - plus possible collaboration with groups outside Europe to obtain global picture	Historical measurements plus interpolation in rigidity, use scaling laws to adjust to aircraft altitude
22	Aircraft neutron monitors	There are few if any monitors flown in an operational role. But there is considerable recent European expertise[3] in flying research instruments.	Historical measurements
28	Kp	INTERMAGNET - using both European and other stations in order to obtain a global picture	Physics-based modelling of local dB/dt as response to global effects. Then derive GIC from dB/t by physical or empirical modelling
31	Dst	INTERMAGNET as above	Physics-based modelling of local dB/dt as response to global effects. Then derive GIC from dB/t by physical or empirical modelling
33	AE index	INTERMAGNET as above	Physics-based modelling of local dB/dt as response to global effects. Then derive GIC from dB/t by physical or empirical modelling

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[3] Examples include: (a) the EC funded "Study of Radiation Fields and Dosimetry at Aviation Altitudes", (b) a UK-funded study involving MSSL, National Physical Laboratory and Virgin Atlantic airways, and (c) QinetiQ flights of the Cosmic Radiation effects and Activation Monitor on various aircraft including Concorde.

CSMR	*Measurement*	*Data source*	*Models used*
43	Multi-point magnetic field in magnetosphere	Not available	
44	Terrestrial magnetic field	INTERMAGNET as above	Derive GIC from dB/t by physical or empirical modelling
46	foF2 from ionosonde network	Various ionosondes run by groups in Belgium, Finland, Germany, Greece, Italy Norway, Spain, Sweden and the UK. French activities may also be included but their status is not clear.	Global or regional models from ITU, interpolation between measurements
48	Global TEC measurements	GPS monitoring in space (e.g. CHAMP)	Models of ionospheric electron density profile scaled for TEC
49	Local TEC measurements	GPS monitors on ground and in space	Models of ionospheric electron density profile scaled for TEC
62	> 100 MeV ion flux outside magnetosphere	ERNE instrument on SOHO measures protons & alphas to 120 MeV per nucleon and other ions to 540 MeV per nucleon	Rigidity cut-off plus radiation transport model
74	LEO satellite position	Spacecraft tracking by CNES, DLR and ESA.	Adjust atmospheric models in response to observed drag

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The table shows that data are available to satisfy all of the CSMRs except for CSMR 43, which requires magnetic field measurements on a large set of multiple spacecraft within the magnetosphere (e.g. on the lines of the UK SWARM concept [SWARM]). The model column for CSMR 43 is left blank as no data are available. Thus the table demonstrates that it is feasible to establish a prototype service to address some or all of the services listed in the Table 17 above.

It will be very important to design the prototype to ensure it has a good capability for expansion as part of any later evolution towards a full service. We suggest that a distributed architecture is important for long-term growth even if only a single node is deployed in the initial system (but it would be appropriate to start with several nodes if at all possible - in order to demonstrate distributed operation).

The prototype should not be allowed to become a static service. It is important that it grows by starting new services and moving to use of new data sources and new models for existing services. Expansion into a truly distributed system with multiple nodes is a high priority and will probably be important as a means to integrate new measurements and new models. The use of modern distributed technologies such as the Grid may be important here.

The prototype should also be a basis to encourage development of new models including research on new numerical techniques (e.g. neural networks, etc.).

6.4.2.2 Prototype space-based measurements

The tables in the previous section show that there are only a few European space-based measurements that could be used for space weather monitoring (but many suitable ground-based measurements). Thus the prototype space weather service can start by building on Europe's strength in relevant ground-based measurements. But since ground-based measurements are not sufficient to cover all space weather needs, it is important for Europe to develop a better set of space-based measurements for space weather monitoring. This should form the second pillar of the prototyping activity.

This prototype set of space-based measurements should probably be a mix of hitch-hikers and dedicated missions. It was originally envisaged, e.g. in the proposal for this study, that hitch-hikers would be markedly cheaper than dedicated missions so that:

- one could develop a medium-scale space weather programme using hitch-hiker missions,
- while a large-scale programme would involve dedicated missions
- similarly a small-scale programme would just use existing and planned mission.

Our study has shown that the distinction between hitch-hikers and dedicated missions is not so clear cut - though it is true that a small-scale programme could be developed using existing and planned missions (this is essentially what is proposed above under the prototype space weather service). To show this the costs of the dedicated mission and hitch-hiker options are shown in Table 19 and Table 20 below but are there ranked using our assessment of priority order as discussed in section 5.4.5.4.

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Table 19 Summary of dedicated options

Option	*CSMR*	*Description*	*Rank*	*Rationale*	*Cost (Meuro)*
6	23 to 27, 36 to 38, 56 to 58, 62, 63 to 65	Thermal energy ion spectrometer, Magnetometer, Thermal energy ion spectrometer, High energy ion detector	1	Upstream solar wind monitoring	56
5	1, 8 to 11, 12, 13	Whole disk imager, X-ray photometer / spectrometer, UV photometer, EUV photometer	2	Solar monitoring	173
4	52, 53 to 55, 59 to 61, 66 to 67	Thermal energy ion spectrometer;/Ionosonde,/UV Imager, Medium energy electron spectrometer, Thermal energy ion spectrometer, High energy electron spectrometer	3	Radiation belt monitoring	250
1	3	Coronagraph	4	Viewing Earth-directed CMEs	72
2	2, 3, 75	Coronagraph, Radio Wave Detector	5	Viewing Earth-directed CMEs	158
7	4,6, 69 to 71	Auroral imager, Debris monitor	6	Auroral monitoring	99
8	4,6	Auroral imager	7	Auroral monitoring	90
3	39 to 43	Magnetometer	8	Magnetospheric dynamics	153

Table 20 Summary of hitch-hiker options

Option	*CSMR*	*Description*	*Rank*	*Rationale*	*Cost (Meuro)*
14	72	Dose monitor	1	Human safety	32
11	63 to 65	High energy ion detector	2	GCRs, SEPEs	24
12	66 to 67	High energy electron spectrometer	3	Killer electrons	91
13	69 to 71	Debris monitor	4		21
8	53 to 55	Medium energy electron spectrometer	5		70
9	56 to 58, 62	High energy ion detector	6		21
10	59 to 61	High energy ion detector	7		60
6	13	EUV photometer	8		20
5	12	UV photometer	9		17
4	8 to 11	X-ray photometer / spectrometer	10		67
3	4,6	Auroral imager	11		106
2	2	Coronagraph	12		60
1	1	Whole disk imager	13		49
7	36 to 38	Magnetograph	14		135

But it is hard to assimilate these data just from the two tables above. To overcome this we have developed a way of visualising the relative cost of investment in dedicated missions or hitch-hiker

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payloads. The method is to calculate the cost of implementing all hitch-hitch options up to rank M and all dedicated options up to rank N. We then produce a colour plot showing the cost of implementing both options up to any combination of M and N.

Figure 6 shows the result of doing this with the ranking that we developed in section 5.4.5.4. We will apply that ranking in the rest of this report and thus will use this figure to assist our analysis. However, it is important to note that the method is general and could be adapted to analyse any other ranking scheme.

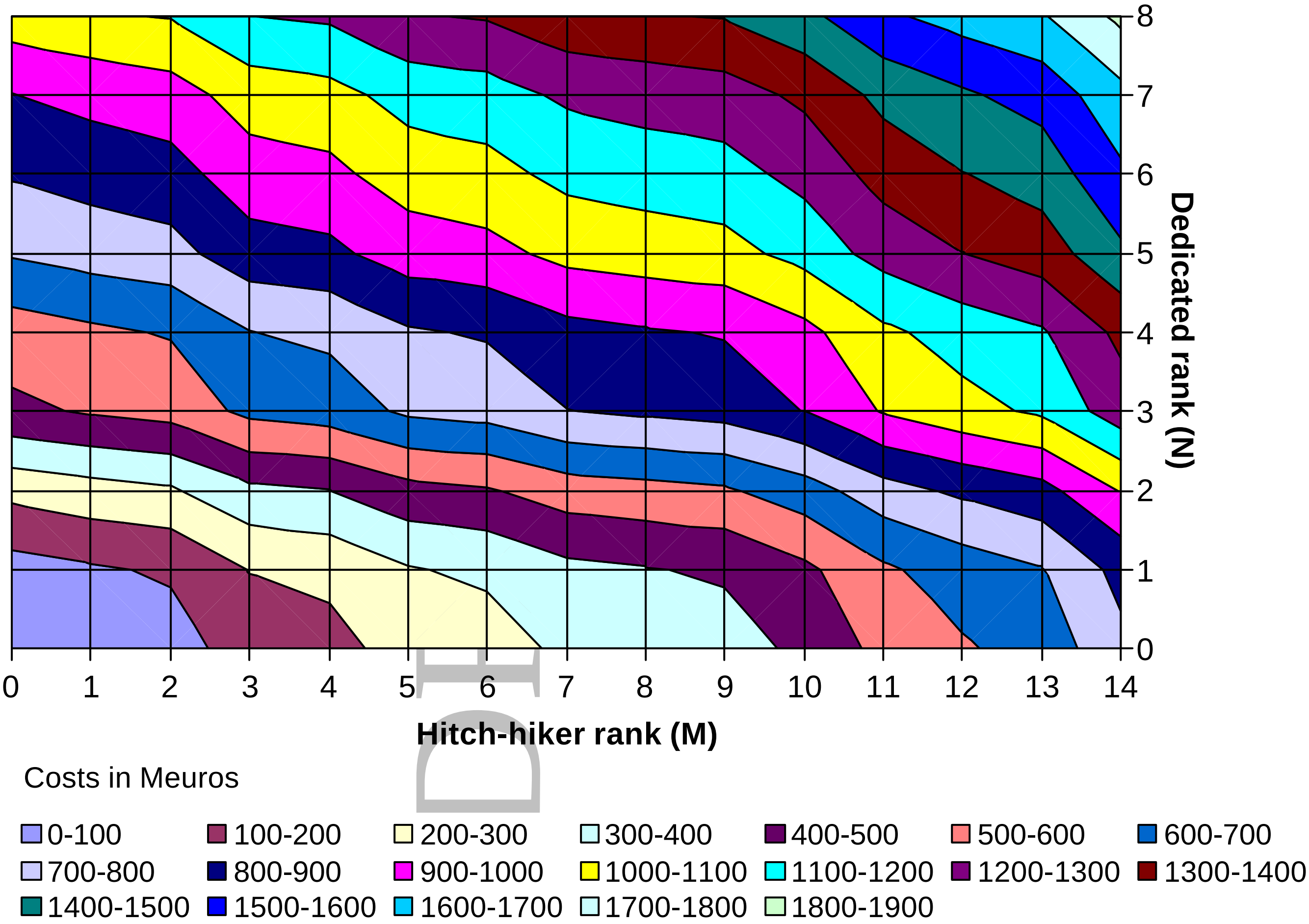

Figure 6. Example plot showing cumulative costs of hitch-hiker and dedicated options

The colour plot of cumulative costs in Figure 6 provides a way of visualising what can be done with any particular resource. Given resources up to value X, one can address the range of options below the contour at level X. For example, given a resource of 300 Meuro, one could support two unique options.

Table 21. Example of unique options for mix of hitch-hikers and dedicated missions

Hitch-hiker rank M	*Dedicated mission rank N*	*Hitch-hiker options supportable*	*Dedicated mission options supportable*
2	2	Dose monitoring, cosmic rays	L1 plasma, L1 solar
5	1	Dose monitoring, cosmic rays, killer electrons, debris	L1 plasma

Other options such as M=1, N=1 are also supportable but these are just subsets of the two unique options above. Thus this approach allows you to see what are the choices to be made within any given budget. In the example above, the choice is between (a) solar monitoring on a dedicated spacecraft and (b) hitch-hiker payloads to monitor radiation belt electrons and debris. Thus it depends on the perception of the relative values of these measurements. The dedicated spacecraft would be focussed on measurements that underpin many space weather products but whose conversion to those products requires significant modelling expertise. In contrast the hitch-hiker measurements would have more immediate relevance to the space environment near the Earth. The solar measurements are probably of greater value for the prototype system, because they will support and encourage the development of better modelling, which is itself an important objective.

Thus we recommend that the prototype space weather programme should include a second element to develop space-based measurements. These should include both hitch-hiker paylods and dedicated missions in order to explore and test the concepts developed here. The (2,2) option above would be a good target to aim for - but the methodology above can be adapted to specify a programme for any level of funding.

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6.5 Need for research

6.5.1 Basic science

Another key element in this plan is the need for further basic scientific research in some key topics that are relevant to space weather. Current scientific knowledge is adequate to provide some space weather services – in particular, those based on L1 monitoring of the solar wind and interplanetary magnetic field. But the potential for effective space weather services will be greatly enhanced by research on some key topics as discussed in section 5.1. These topics include:

- The conditions leading to ejection of material from the Sun
- The propagation of those ejecta, and their embedded magnetic fields, from the Sun to the Earth
- The acceleration of energetic particles both in the heliosphere (solar protons and electrons) and in the radiation belts of the Earth and other planets
- A much deeper understanding of how reconnections works, e.g. to resolve controversies over the location and, in particular, the extent of reconnection regions.
- Magnetospheric dynamics, especially during major storms
- The coupling of the space environment to the neutral atmosphere of the Earth and other solar system bodies

These topics lie at the heart of contemporary solar-terrestrial physics and are widely considered to be of great scientific interest[4] independently of the needs to improve space weather services. For example, ESA's recently-selected Solar Orbiter mission is intended to build on the success of SOHO in addressing the first two topics in the list above. Similarly, ESA's Cluster and Ulysses mission are addressing other topics such as magnetospheric dynamics (Cluster) and heliospheric particle acceleration (Ulysses).

Thus what is needed here is an action aimed at maintaining the European funding of STP research relevant to space weather. To succeed, it is essential that this action is scientifically credible, i.e. that the science is competitive at an international level. To do this we propose that this action should be carried out by a group of scientists that is independent of ESA and whose members are recognised to be of international standing. Its terms of reference should include:

- Periodic review of the areas in which scientific research is needed to improve our knowledge of space weather – in particular monitoring progress in existing areas, but also identifying where changes in emphasis would be appropriate.
- Linking these reviews to the general progress of STP research – in particular emphasising any relationships between space weather and emerging scientific objectives
- Providing a public report on its conclusions. This report should be made available to ESA (e.g. for review by SSWG), to funding bodies throughout Europe (perhaps via ESF) and to active members of the space weather and STP communities.

Essentially, this would be a group to act as an advocate for high-quality scientific research relevant to space weather. It would raise the profile of space weather-related research, make decision-makers aware of the importance of particular scientific issues and provide a better base on which individual science groups can develop proposals for funding new space weather science.

[4] Indeed, some of these topics address fundamental problems in the physics of collisionless plasmas and are therefore fundamental issues in our understanding of the physical universe.

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We propose that ESA should encourage the setting up of this group but should not run it. The group could run as a separate body or perhaps under the auspices of a European body independent of governments. This is important for two reasons: (a) the group would be independent of ESA, and (b) successful operation would be a strong demonstration of intent by the scientific community. These are both important messages to send to decision-makers.

The need to be independent of ESA does not exclude all contact. It would certainly be very appropriate for ESA scientists to act as a point of liaison between this group and the scientific activities of the Agency. There is also value in a link between this group and the proposed Outreach Centre given that explaining the science of space weather will be a major outreach objective.

6.5.2 Modelling techniques

A related, but distinct, research topic is the development of model techniques including research on numerical techniques (e.g. neural networks, etc.). This area is fundamental to the development of new and better space weather applications because modelling is central to generation of useful products. But the area is distinct from basic research in that it cannot be directly justified as a means of advancing our understanding of the physical universe (and thus funded via budgets established for that purpose). Instead, work on modelling techniques should be justified as a development of new techniques for managing and manipulating data and funded under budgets appropriate to that type of work (as, for example, in the current development of a Grid applications for space weather within ESA's SpaceGrid study).

To encourage work on new modelling techniques we recommend to include this type of research as additional item within the remit of the Space Weather Research Group but also charge that group to maintain and develop the distinctions discussed.

While encouraging the development of modelling techniques for space weather, we should stress the roles and limitations of both physical and numerical models. For numerical models we identify two important factors:

- That the development of space weather models must be constrained by physical concepts wherever possible, in particular by causality. One must not use numerical models to predict across impulsive events (e.g. CMEs) unless the inputs are upstream of the event whilst the predicted parameter is downstream. If inputs and outputs are both downstream of the impulsive event, the inputs contain no information on the impulsive event and so reliable prediction is impossible.
- That numerical models are very valuable for handling and predicting complex repetitive patterns. The ionosphere is a prime example since it follows at least three temporal patterns (diurnal, annual and solar cycle) and two spatial patterns (geographic and geomagnetic).

For physics-based modelling we identify the need to develop models so that they can migrated from physics research into operational systems. Speed of execution time and robustness are issues here. For operational use a space weather model must generate products in time to be useful and must do that in a reliable fashion day after day.

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7 Consolidation of the Plan

The proposals developed in the previous section can be summarised as the need to establish four entities as follows:

- An ESA Space Weather Outreach Centre funded by ESA but with its implementation and operation contracted out to one of the many suitable organisations across Europe.
- A Space Weather Development Group set up within ESA with the role of encouraging the development space weather services - both through the establishment of an prototype space weather system and through encouragement of service developments throughout the Member States.
- A Network for Ground-based space weather measurements. This would draw together the many European groups that make ground-based space weather measurements and act as an advocacy network to demonstrate the importance of these measurements and to encourage their use for space weather purposes..
- A Space Weather Research Group. This would be a team of scientists that is independent of ESA and whose members are recognised to be of international standing. Its task would be to undertake periodic reviews of the science underpinning space weather and provide advice to ESA and other bodies.

In the rest of the section we describe these four entities in detail. We then discuss options for funding some or all of these entities according to the level of resources available. Finally we present an outline schedule for establishing these entities and their associated activities.

7.1 Detailed description

These groups and the links between them are shown in Figure 7 below. This also shows links with external entities. Following that we provide a more detailed specification for each entity as a set of tables (Table 22 to Table 25).

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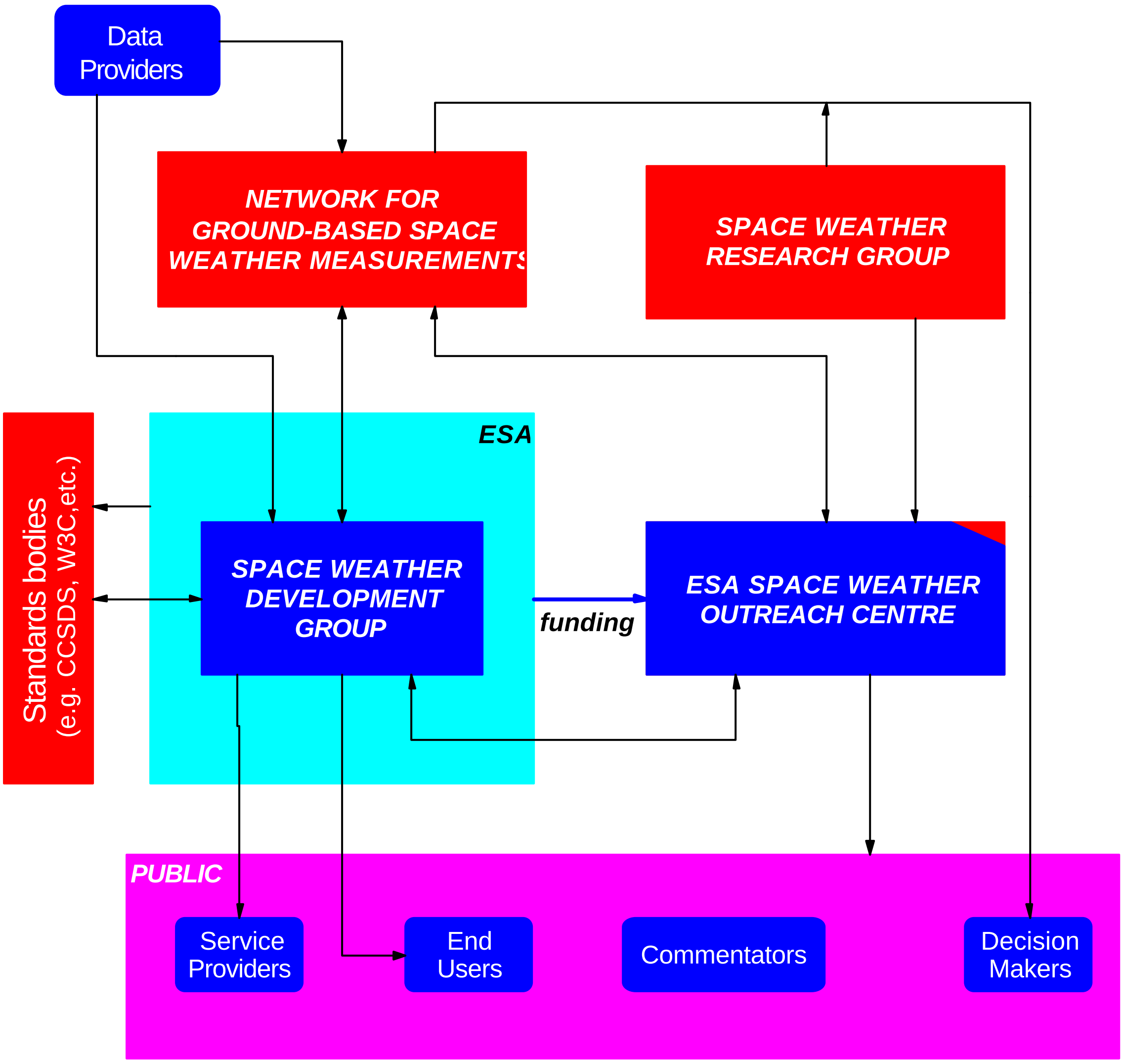

Figure 7 Entities for a European Space Weather Programme

Table 22 Specification for ESA Space Weather Outreach Centre

Composition: Small project team. Skills required include space weather, database and web servers, web design and project management.

Funding: ESA funding for activity but contracted out to suitable European entity selected and reviewed in open competition. The entity hosting the centre should be encouraged to seek additional funding from other sources and use this to expand the range of activities supported by the centre.

Terms of reference:

- To build an on-line database of information about space weather and provide internet access to this for any interested party in the member states,
- To explain the science underpinning space weather in ways that can be understood by a broader public audience (e.g. by a 16-year old considering a career in science).
- To identify potential European audiences in which awareness of space weather might be improved, to develop links with those audiences and undertake activities to improve that awareness. This is an important proactive task for the Centre.
- Raise awareness about existing European space weather activities in space and on the ground. This should include awareness of European contributions to the space weather programmes of the US and other countries outside Europe.
- To support, so far as its resources allow, other public and private initiatives within the member states that aim to improve awareness of space weather. Examples of such initiatives may include (a) programmes to improve public understanding of space science, (b) science and technology programmes that address issues related to space weather, and (c) special interest groups that address specific space weather problems.
- To exchange ideas and materials with similar centres outside Europe, e.g. in the US, Japan and China.

Interfaces:

- With the Network for Ground-based space weather measurements, e.g. by receiving and disseminating information collected by the Network, by providing them with materials to assist their advocacy programme.
- With the Space Weather Development Group, e.g. by providing them with the latest background information on space weather issues, by receiving and publicising information on Development Group activities
- With the Research Group, e.g. by receiving and disseminating information on developments in the science underpinning space weather
- With the European public - including specialist groups such users, decision-makers and commentators, as well as the general public, e.g. to disseminate information on space weather activities.

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Table 23 Specification for Space Weather Development Group

Composition: Small project team. Skills required include software integration, data management, spacecraft engineering and project management.

Funding: Internal ESA activity during the initial development phase. There should be a long-term objective of migrating this activity out of the Agency when it becomes an operational activity, e.g. when more than 70% of programme resources should be devoted to routine operations. At this stage there must be adequate arrangements in place for funding of the activity external to ESA.

Terms of reference:

- Provision of advice to potential service providers. This may include advice on technical and marketing issues. A key target group to encourage here is people in the research community who have good ideas but who need help to convert the idea into an operational service (perhaps as a spin-off service).
- Establishment of a Prototype Space Weather Programme. At a minimum this should include a Prototype Space Weather Service based on existing resources as discussed in section 6.4.2.1. It may also be extended to include a prototype space segment to provide additional key measurements as discussed in section 6.4.2.2.
- Development of standards for provision of space weather data to service providers and encouraging their use by both data and service providers. These standards should be based on the existing work undertaken by the Consultative Committee for Space Data Standards [CCSDS] which already has major participation from ESA and several member state national agencies (including BNSC, CNES and DLR).
- Identifying opportunities for data provision from ESA missions and liasing with the mission project team to ensure that the data meets the above standards.
- Acting as a broker between data and service providers.

Interfaces:

- With the Space Weather Outreach Centre, e.g. by receiving the latest background information on space weather issues, by providing them with information on Development Group activities
- With potential service providers, e.g. by acting as a source of advice and assistance
- With potential users of the prototype space weather service, e.g. supplying them with them with outputs from the prototype, receiving their feedback on the value of those outputs
- With standards bodies such as CSSDS and W3C, e.g. to obtain information on existing data and software standards relevant to space weather applications, to influence the development of new standards to ensure that the needs of the space weather community are taken into account
- With other ESA projects and with data providers outside the Agency, e.g. to establish and operate links that can provide data for a space weather programme. A good link with the Network for Ground-based space weather measurements will cover a major part of this interface.

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Table 24 Specification of Network for Ground-based space weather measurements

Composition: Network group open to membership by any European entity that is involved with ground-based operational measurements of space weather parameters. Involvement may include the making of measurements, the construction and support of instruments, the handling of data from the instruments and the funding of those measurements. The Group could decide to allow wider attendance, e.g. by users or by non-European groups, whenever it considers that is beneficial to the Group.
Funding: We recommend that ESA provide some money to set up the network but that, in long-term, it should be self-supporting. Self-support is important because that will provide a clear demonstration of the health of the network and the interest of groups in the network.
Terms of reference: • Developing and maintaining an inventory of European ground-based capabilities, • Exchange of knowledge and ideas across political and topical boundaries, • Developing a conceptual framework which shows how individual ground-based space weather measurements fit with overall European needs for space weather data. The group should provide a basis on which individual groups can make a strong case for continued support and development of relevant ground-based measurements. • Studying the roles of public, academic and commercial bodies in the operation of ground-based space weather measurements.
Interfaces: • With the Space Weather Outreach Centre, e.g. by providing them with information collected by the Network, by receiving materials to assist the Network's advocacy programme. • With the Space Weather Development Group, e.g. to establish and operate links that can provide data for the Prototype Space Weather Service. • With relevant decision-makers across Europe, e.g. to provide them with information demonstrating the value of a ground-based space weather measurements and to show how individual measurements (and the individual funding decisions behind them) contribute to a pool of data that is of great value to everyone.

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Table 25 Specification for Space Weather Research Group

Name: Space Weather Research Group

Composition: Small group of scientists that is independent of ESA and whose members are recognised to be of international standing with good expertise in space weather and the underpinning science

Funding: To ensure its independence the group could perhaps run under the auspices of a European body preferably in a way that is seen to be independent of governments. Independence would be valuable as a strong demonstration of intent by the scientific community. This is an important message to send to decision-makers.

Terms of reference:

- Periodic review of the areas in which scientific research is needed to improve our knowledge of space weather – in particular monitoring progress in existing areas, but also identifying where changes in emphasis would be appropriate.
- Reviewing progress of research on modelling techniques, e.g. identifying problems that are relevant to space weather applications.
- Linking these reviews to the general progress of STP research – in particular emphasising any relationships between space weather and emerging scientific objectives
- Providing a public report on its conclusions. This report should be made available to ESA (e.g. for review by SSWG), to funding bodies throughout Europe (perhaps via ESF) and to active members of the space weather and STP communities.

Interfaces:

- With the Space Weather Outreach Centre, e.g. by supplying information on developments in the science underpinning space weather
- With decision makers in ESA and funding bodies across Europe, e.g. to provide information on progress with fundamental scientific problems relevant to the provision of good space weather applications in the future, to suggest priority areas for research
- With scientists across Europe, e.g. to monitor progress in STP research underpinning space weather, to provide information that scientists can use when lobbying for support of scientific research that helps progress space weather activities

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7.2 Funding options

Within the four entities discussed above it is straightforward to identify some options for different levels of funding. These are presented in Table 26 below. This table presents the options in a stepwise manner, i.e. each option includes all previous options.

Table 26 Funding options for a space weather programme

Option	Description	Discussion
1	Set up the *Network for Ground-based space weather measurements* and the *Space Weather Research Group*	These have very minor cost implications for ESA. They amount to encouraging valuable initiatives among some key elements of the space weather community. We recommend this be done irrespective of other decisions.
2	Also set up the *ESA Space Weather Outreach Centre*	This would require a moderate long-term financial commitment by ESA (of order 1 Meuro per year). But it would be a very valuable step in developing a community of support for a European space weather programme. It would also benefit ESA by it being seen to provide a service with a strong public image.
3	Establish the *Space Weather Development Group* but with its remit limited to the provision of advice and the prototype space weather service	This would require further moderate long-term commitment by ESA (a further 1 Meuro per year). But it would be a valuable step in demonstrating the value of a European space weather programme. Note that this step builds on the Outreach Centre activities and for this reason is ranked after that Centre.
4	Extent the remit of the *Space Weather Development Group* to include a modest prototype space weather space segment	This would require substantial medium-term commitment by ESA (perhaps 60 Meuro per year for 5 years) to implement a space weather space segment on the lines discussed in section 6.4.2.2.
5	Extent the remit of the *Space Weather Development Group* to include a modest prototype space weather space segment	This would require very substantial long-term commitment by ESA (perhaps 150 Meuro per year for 15 years) to implement a full-scale space weather space segment to address all the measurements discussed in 5.4.5. We believe this is unrealistic at this time and include this simply to show what a maximum space weather programme would cost.

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We consider that a combination of options 1, 2 and 3 is affordable and would be a good way to start to build and explore European interest in a space weather programme. Successful implementation of these options would build support for option 4 within a few years and thus continue to build support for the space weather programme. Option 5 is an objective for future decades.

7.3 Outline schedule

Figure 8 shows an outline schedule for implementation of the four entities.

In the cases of the Network for Ground-based space weather measurements and Space Weather Research Group, we assume that a formal kick-off meeting of interested parties is required to initiate these activities, to agree the terms of reference and to determine responsibility for providing a secretariat. We assume that a period of three months is then required to establish the secretariat and to complete any other initial organisational tasks. Thereafter these two entities are considered to be operational.

For the Space Weather Outreach Centre we assume that a period of eight months is required to develop and obtain approval for an Invitation to Tender. This is followed by a period of three months for the preparation of bids by interested parties and then a period of four months for evaluation of the bids and any residual negotiations with the selected bidder. The Outreach Centre is considered operational after the start of the contract. We have not attempted to prescribe details of the start up of the Outreach Centre since that could depend greatly on existing resources that are folded into specific bids.

For the Space Weather Development Group we assume that a period of nine months is required to develop and obtain approval for the proposal to set up this group and also to agree its remit. This is followed by a three month period to establish the group. We assume that the advice and support service (e.g. to prospective service providers) can commence once the group is established. We also assume that, at this time, the group can start work on the prototype space weather service (as discussed in section 6.4.2.1); we propose that they take a short time (3 months) to review and approve the specification of that service before moving to implementation. The main implementation phase is assumed to require a year at which point the first operational services should become available. Thereafter we assume that these services will continue in operation by the Group and, in parallel, that the group will develop new services and migrate these in operations.

We suggest that work on the prototype space segment (as discussed in section 6.4.2.2) should not begin until the first operational services are available, i.e. initial development efforts should be focussed on the goal of the prototype service. Once effort becomes available to work on the prototype space segment, we propose a nine-month period to review and approve its specification before moving to implementation. We assume that the latter requires a period of four years before moving into operations.

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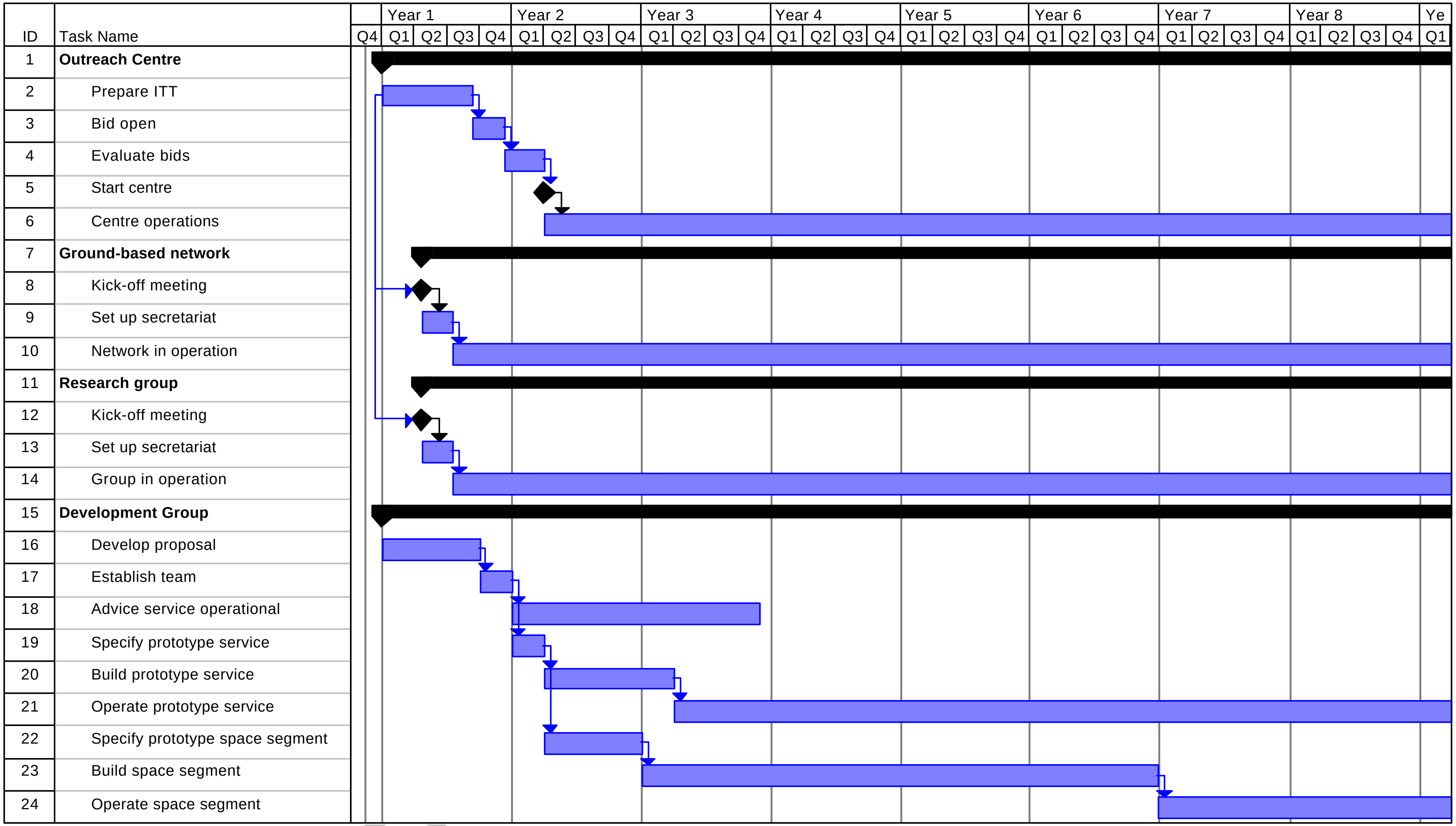

Figure 8. Outline schedule for development of an ESA space weather programme

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8 Conclusions and recommendations

The result of the study is a proposal to establish a space weather programme that collects data on relevant space weather parameters through a combination of space-based and ground-based sensors and processes these to deliver products that are of potential use to organisations affected by space weather. We have developed a plan for the organisation and implementation of this programme. The core element is a recommendation to establish the following organisational structures:

- A Network for Ground-based space weather measurements. This would be an advocacy group to co-ordinate and promote ground-based measurements of space weather parameters. There is already an extensive base of suitable measurements made by European countries but these are funded by a variety of local, national and European sources. They are rather fragmented and at risk from funding cuts. The aim of the network would be provide a more integrated view that demonstrates the value of these measurements and thus provides a basis to persuade funding agencies to slow down, and eventually reverse, funding cuts.
- An Space Weather Outreach Centre funded by ESA to promote understanding of space weather issues among a number of key target groups including end users, decision makers and technical commentators. This is a key proposal; the survey of user needs showed that there is a major need to improve that understanding across Europe. We recommend that this activity should be contracted out of ESA to one of the many appropriate groups within Europe. This would allow the Centre the freedom to seek additional funding sources and thus expand the scope of its outreach activities.
- A Space Weather Development Group within ESA to encourage the development of space weather activities both within the Agency and across Europe. The group's remit should include advice to European groups wishing to set up space weather services, the promotion of standards for use by service and data providers, the development of a prototype space weather service and a prototype space segment for space weather measurements.
- A Space Weather Research Group. This would act as an advocacy group to encourage and help the scientific community to address key science topics relevant to space weather- typically in understanding fundamental plasma processes. The group would periodically review progress in key areas and suggest future objectives for scientific research in support of space weather.

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We have identified a set of options to allow the phased implementation of these structures and their programme according to the available funding. We recommend the following approach:

- First we propose the establishment of the Network for Ground-based space weather measurements and the Space Weather Research group. This is the most basic option because these two groups have only minor costs for ESA; they amount to encouraging key initiatives with the European space weather community.
- Secondly we propose to add the Outreach Centre. This would require modest expenditure by ESA, would address some critical needs and, most importantly, would begin to build support for a larger programme.
- There are then three phased options that involve establishing the Space Weather Development Group at three different levels of activity ranging from modest to major short-term and then major long-term activity.
  - The modest approach would be to build a prototype space weather system using data from existing and planned missions.
  - The major short-term approach would be to add the construction and operation of a prototype space segment to collect space weather data. This would address a number of key

user requirements and involve flying a few hitch-hiker payloads and one or two dedicated missions.
- The major long-term approach would implement a full scale space weather programme that can address all the user requirements identified earlier in the study.

Our overall assessment is that a reasonable immediate aim is to establish the two advocacy groups, the Outreach Centre and a modest level of activity by the Space Weather Development Group (i.e. establishing a prototype space weather service). The successful implementation of this level of activity could then build support for major short-term activity with the building of a prototype space segment. Our last option, the implementation of a full scale space weather programme, is included for completeness but is regarded as a very long-term aim.

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