SPACE & GROUND SEGMENTS FOR A EUROPEAN SPACE WEATHER PROGRAMME

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ABSTRACT/RESUME

This paper presents the key space and ground segment concepts developed in the ESA Space Weather study led by RAL. An overview of the whole study is presented in a separate paper in this volume [1].

1. BACKGROUND

The development of the space and ground segment concepts followed the overall systems approach of the study as discussed in [1]. In the present context, this involved (a) the establishment of a set of well-defined requirements [2] before commencing work on the space segment, and (b) the establishment of the broad outlines of the space segment before commencing work on the ground segments. Thus the ideas presented below address a broad-based set of realistic requirements for the provision of space weather services.

An important objective of the study has been to maintain traceability between those requirements and the ideas developed for the space and ground segments. Thus if the underlying requirements change in the future, it will be straightforward to return to this study and adapt it in response to those changes.

2. GROUND VERSUS SPACE OBSERVATIONS

As noted above the measurements needed to support a space weather service were specified in [2]. They 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 coronal mass ejections 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).

This leads to a split between space and ground that is summarised in Tables 1 and 2 below.

Table 1 Space-based measurements

Measurement type
Solar images
Auroral images
Solar X-ray and UV fluxes
Solar wind plasma properties
Interplanetary magnetic field
Solar surface magnetic field
Magnetospheric magnetic field
Bulk plasma properties
Electron and ion fluxes
Debris and meteoroid properties
Dose measurements
Interplanetary radio emissions

Table 2 Ground-based measurements

Measurement type	Network	Index
Auroral image/intensity		
Solar 10.7 cm radio emission (Penticton index)		Y
Secondary neutron fluxes	Y	
Geomagnetic indices	Y	Y
Sunspot number	Y	Y
Solar surface magnetic field		
Geomagnetic variations	Y	
Interplanetary scintillation		
Ionospheric critical frequencies	Y	Y
Ionospheric total electron content	Y	
Cross-tail electric field / ionospheric convection	Y	
Spacecraft tracking		
Debris and meteoroid properties		

The second column of the ground-based 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. A co-ordinated international network of observations - with exchange of data between participants – is needed to deliver global picture of the measured quantity. There are already many well-established international arrangements to do this. 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.

The ground-based table includes two cases that address requirements covered in the space-based table:

- 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.
- 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.

Most of the techniques listed in Tables 1 and 2 are based on a well-developed instrumental techniques and scientific interpretation. But there are a few exceptions where we put forward techniques that exploit new ideas and thus will require development if they are to deliver their full potential. These are

- Solar surface magnetic field (space). This could support prediction of the heliospheric magnetic field at the Earth and thus complement in-situ measurements.
- Interplanetary radio emissions (space). These are thought to come from coronal mass ejections and may allow us to track CMEs as they move away from the Sun. A French-led demonstration of the technique is planned as part of NASA's STEREO mission [3].
- Ionospheric convection (ground). Measurements of high-latitude convection can be used to estimate the cross-tail electric field. This technique has been demonstrated very effectively as a scientific tool [4] but will require development before use as an operational tool.
- Interplanetary scintillation (ground). Heliospheric disturbances cause scintillation in observations of distant radio sources. Thus scintillation measurements can be used to track heliospheric disturbances. This has been demonstrated in scientific measurements but needs significant development to become an operational tool.

3. OPTIONS FOR SPACE OBSERVATIONS

A key issue in the ESA studies was to explore whether space observations should use: (a) existing and planned missions, (b) hitch-hikers – space weather instruments on other spacecraft, or (c) dedicated space weather missions. We discuss all three options below - but first we review the role of telemetry, which is critical for all three options.

3.1 Telemetry

Telemetry is a critical factor for space weather measurements. Near real-time telemetry is usually needed; our survey 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.

3.2 Existing/planned missions

There are only a few existing/ planned European missions that make measurements relevant to space weather. The most notable is, of course, SOHO; there is 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.

In addition, note that some missions will not provide adequate data all the time. The main problem is 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.

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.

3.3 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 modest 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.

3.4 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 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.

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.

4. 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 development.
These existing ground-based programmes can address most of the items in Table 2. We recommend that the space weather programme should 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 for 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).

5. DATA-HANDLING

5.1 Overview

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

- 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.
- 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.

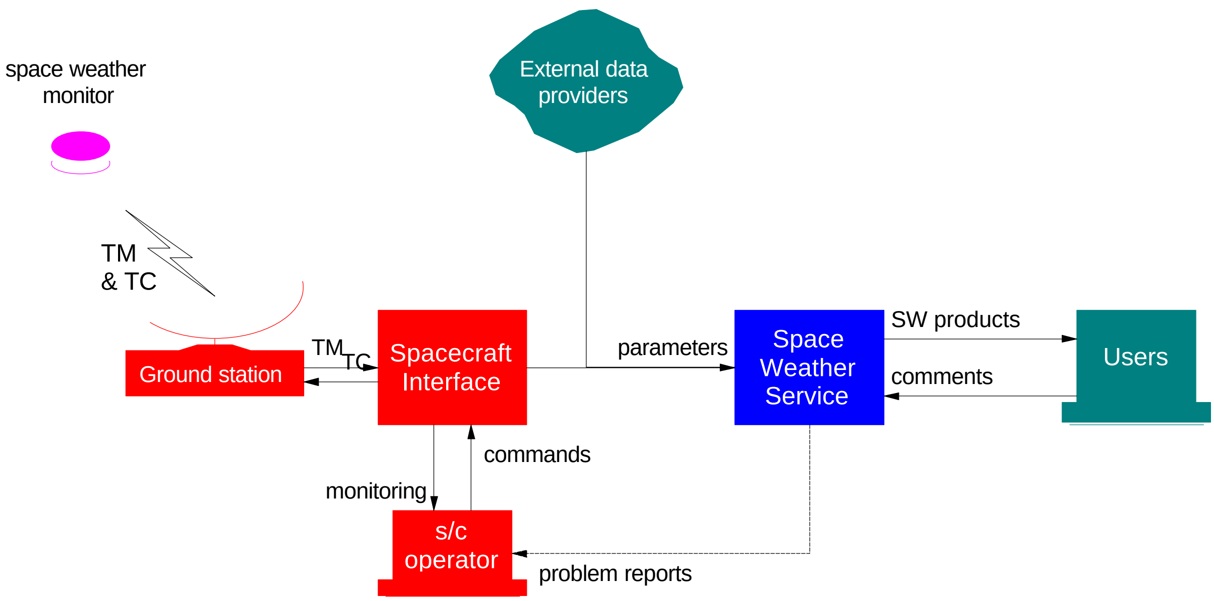

Fig. 1. Overview of data handling systems

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.

5.2 Spacecraft interface

This includes a wide range of functionality as follows:

- Generation of commands
- Ground station for uplink of commands
- Ground station for reception of telemetry data
- Telemetry processing
- Monitoring of the performance of the spacecraft and its sub-systems, including the payload
- Spacecraft operations team
- Deriving s/c orbit and attitude
- Generating orbit and event data
- Attitude planning
- Converting raw data into calibrated physical data
- Supplying data 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. 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).

5.3 Space weather service

We have reviewed user needs in order to establish a set of user requirements that describe what a space weather service must deliver. These are shown in Table 3 below. This also shows the basic functionality that should be associated with each user requirement ("service functional elements").

Table 3. Space weather service User Requirements and Service Functional Elements

User Requirement	*Service Functional Element*	*Comments*
Timely and reliable data from multiple sources	Networked and reliable data access	Delivery by magnetic media is too slow.
	Retrieval scheduler	Must be able to carry out retrievals automatically
Good documentation of system and data	On-line help	
	Comprehensive metadata	A prerequisite for sophisticated data provision
	Human support	For when all else fails.
Consistent interface to multiple datasets	Generic, comprehensive and accessible data output format	
Easy to identify relevant datasets	Data dictionary	Metadata must be query-able.
	Yellow pages system	For locating datasets at remote data providers
Access to enhanced products	Data aggregation.	
	Models and forecasts.	
Access to past data	A local archive of relevant data	e.g. for post-incident analysis
Personalised regular data retrieval	User accounts with personal profiles	
Access to informed advice and scientific technical support	Technically and scientifically competent personnel	A consultancy role
Background information on science and impact of space weather	On-line introduction to space weather.	Much pre-existing material exists.
	Outreach materials	Posters, curriculum materials, CD-ROMs, etc.
Graphical presentation of data products	Graphics engine	
Continuous service development.	Regular service monitoring	.
	User feedback facilities	On-line and face-to-face
	Medium and long-term strategy	

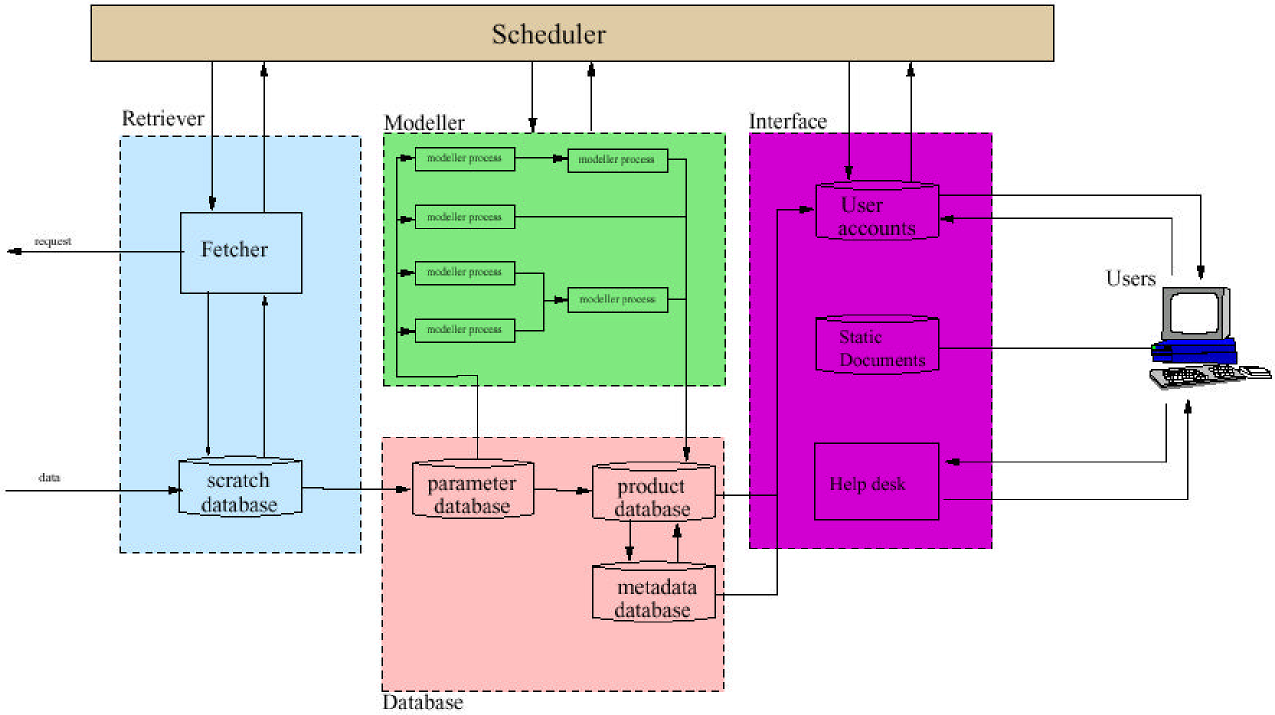

Fig. 2. Conceptual design for the Space Weather Service

Fig. 2 above shows a high-level design of the computer and database systems needed to meet the needs outlined in the user requirements. There are five major 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.

6. FUTHER INFORMATION

This paper has surveyed key space and ground concepts developed during the study. Much more information is available, e.g. the justification of these concepts and deeper aspects of their implementation. If you would like to know more, please see the detailed study reports. These are publicly available from our web site at http://www.wdc.rl.ac.uk/SWstudy; select the "Public Documents link" and you will be able to download the reports as PDF files.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. Hapgood, M., *Study of a European Space Weather Programme*, this volume.
2. Murphy, L. M. and Rodgers, D.J., *European Space Weather Programme, System Requirements Definition*, ESWP-DER-SR-0001, 2001.
3. STEREO SWAVES instrument, http://www-lep.gsfc.nasa.gov/swaves/swaves.html
4. Super Dual Auroral Radar Network (SuperDARN), http://superdarn.jhuapl.edu/