STUDY OF A EUROPEAN SPACE WEATHER PROGRAMME

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ABSTRACT/RESUME

This paper summarises result from an ESA-funded study of a European space weather programme. We first outline the study methodology with an emphasis on the systems approach adopted and the importance of the underpinning scientific knowledge. We then present some of the key results that have emerged from this study. The emphasis is to give the reader a flavour of those results rather than a detailed justification.

1. BACKGROUND

Over the past two years ESA has funded two parallel studies on a European Space Weather programme. These studies were 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 paper is a short report on one of the two studies – namely that led by RAL. This study has been carried out by a consortium of six groups:

- Rutherford Appleton Laboratory, UK (RAL)
- Qinetiq, UK (formerly Defence Evaluation and Research Agency)
- Astrium, UK
- Finnish Meteorological Institute (FMI)
- Office National d'Etudes et de Recherches Aérospatiales, Département Environnement Spatial, France (ONERA-DESP)
- Belgian Institute for Space Aeronomy (BIRA)

2. SYSTEMS APPROACH

An important aspect of the study is the use of a systems approach. This is illustrated by the study logic shown in Fig. 1 below. We started by establishing requirements for a space weather system (left hand side of Fig. 1) and then using these to build up a specification of the content of that system (right hand side of Fig. 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.

The requirements analysis started by identifying the potential benefits of a space weather programme - and by interviewing potential users in order to understand

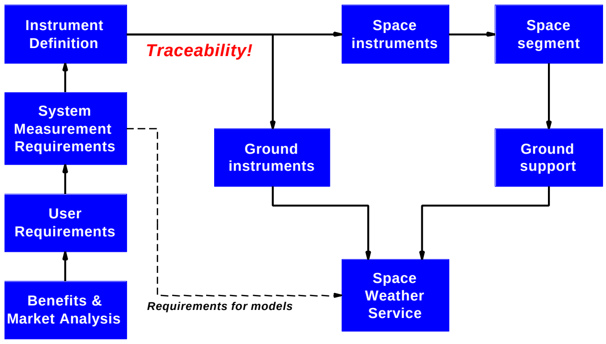

Fig 1. Simplified study logic. This logic is underpinned by our scientific knowledge of space weather.

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.

Given the consolidated system measurement requirements, 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 into 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 for 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 identify 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.

3. 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 assess the 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.

4. NICHE OPPORTUNITIES

Our study shows that there is significant user demand in Europe for specific and well-targeted space weather services, e.g. power systems, airlines, geological surveys/drilling. 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.

This user demand provides a series of niche opportunities that 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 see section 5.2).

What also follows here is that there is no user demand for an overarching service. The integration of space weather activities across different user needs must be justified by the underpinning science, 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.

5. DATA INFRASTRUCTURE

5.1 The role of data infastructure

Fig. 2 below shows a conceptual design of a space weather system to support real world applications. The blue items indicate that real world: on the right we have practical systems affected by space weather (e.g. spacecraft, aircraft, power grids, GPS services), whose functioning is supervised by an operator. The space weather effects result from changes in the local space environment (e.g. magnetic fields, particle fluxes, , plasma density). Those changes are the consequence of changes in an upstream environment such as the solar wind or the Sun itself and are mediated to the local environment via some physics. Our knowledge of that physics is usually imperfect and this is indicated by the cloud shape for that element.

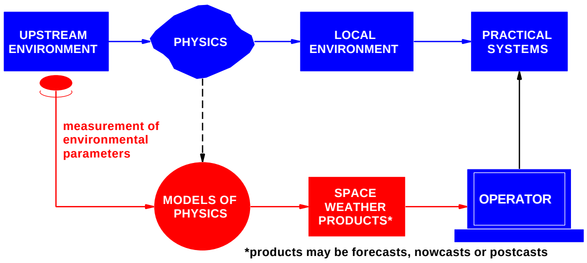

Fig 2. Data infrastructure for space weather services

The red items indicate a space weather service that can address real user needs. It comprises two main items: (a) models of relevant physics that can be used to generate useful space weather products and (b) measurements of the upstream environment that are needed as input to those models. These two items form the data infrastructure of a space weather service.

A detailed discussion of the content of the data infrastructure is presented in a companion paper [1]. It comprises data collection using a mixture of space- and ground-based sensors, the operation of those sensors and the processing of their data through to the level of calibrated physical parameters, and then the conversion of those parameters into space weather products that are of value to end users.

The space-based measurements include dedicated spacecraft and hitch-hiker payloads on other missions. Both require a ground segment to operate space systems, to collect telemetry and to convert it into calibrated physical parameters. In the case of a dedicated spacecraft this ground segment provides all services for spacecraft and payload. In the case of a hitch-hiker only a limited range of services are needed; this will vary from case to case depending on the services provided by the ground segment of the host spacecraft.

An important conclusion of our study was that hitch-hiker sensors are good for some specific applications, e.g. monitoring the environment in geosynchronous orbit. But we also concluded, contrary to our initial expectations, that dedicated space weather spacecraft have financial advantages compared with hitch-hikers. If a dedicated mission is required to address a specific issue, it is worthwhile to fly other space weather instruments on that mission - so long as the planned orbit is suitable for the measurements. Thus dedicated missions give economies of scale - by spreading fixed costs such as launch, spacecraft bus and ground segment over several instruments.

To provide useful space weather products the physical parameters from measurements must be passed to a space weather service. This service is distinct from data collection and processing. Its task is to take calibrated parameters and run them through appropriate models to generate useful weather products, e.g. measurements at the L1 point provide calibrated values of solar wind density and speed and of the heliospheric magnetic field (as done by NASA's ACE spacecraft). These parameters can then be run through models to predict geomagnetic activity 30 to 60 minutes ahead.

The space weather service must be able to ingest physical parameters from a variety of sources – not only from the dedicated spacecraft and hitch-hikers but also from other space missions and from ground-based observatories. This requires the specification of a simple but robust set of protocols for data exchange between the space weather service and its data sources.

5.2 The need for public sector funding

As discussed above, the provision of services to end users depends on access to basic data on the behaviour of the space environment (e.g. sunspot number, geomagnetic indices, ionospheric data, heliospheric 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.

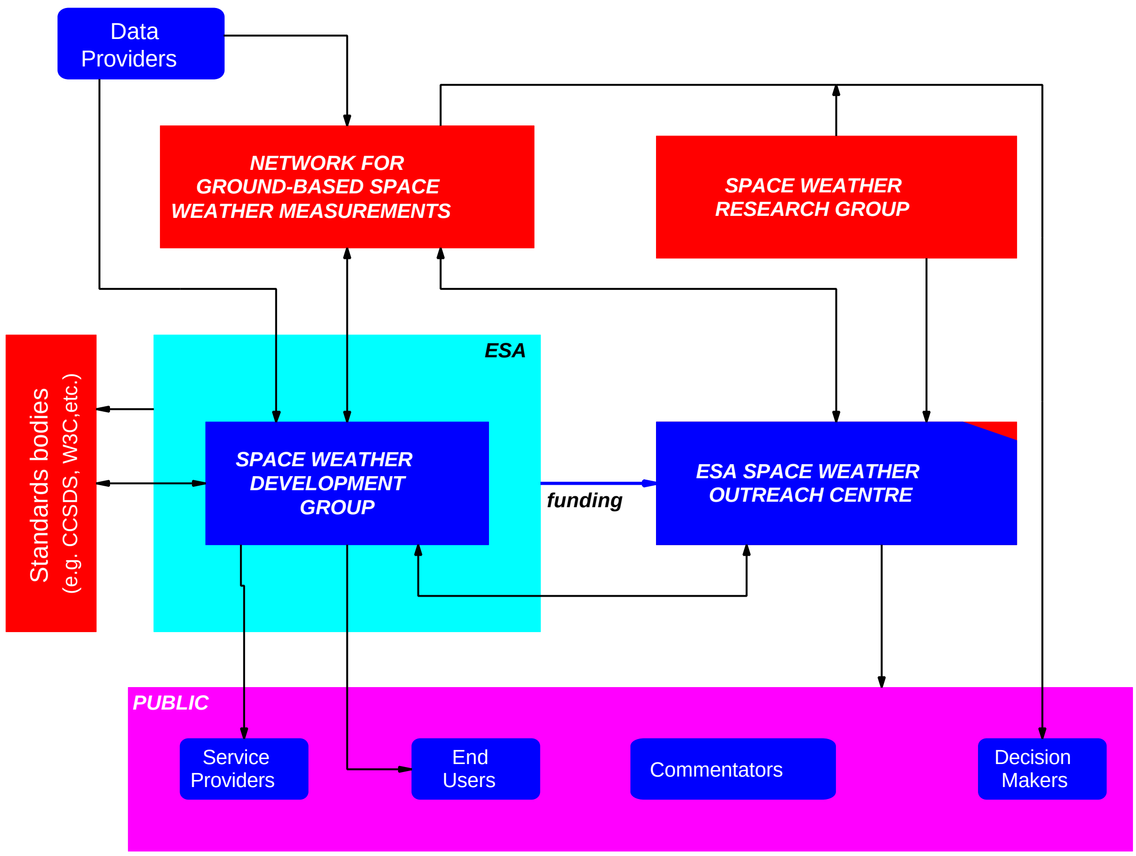

Fig 3. Entities for a European Space Weather Programme

6. IMPLEMENTATION PLAN

The ideas developed in the previous sections could be implemented by establishing four entities as shown in Fig 2 above. They are 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 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.
- 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.

In the rest of the section we describe these four entities in detail.

6.1 <u>Outreach and user education</u>

Our study shows a clear need to improve European awareness of space weather and its effects on technology and human society. 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.

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.

6.2 Network for ground-based measurement

A wealth of ground-based data is produced by organisations in the ESA Member States – see [1]. This is a considerable resource that can 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 and provide a basis on which individual groups can make a strong case for support and development of ground-based work.

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

- Developing and maintaining an inventory of European ground-based capabilities,
- Exchange of knowledge and ideas,
- Developing a conceptual framework to show how individual ground-based measurements fit with overall European needs for space weather data.
- Studying the roles of public, academic and commercial bodies in ground-based work.

We propose that ESA be a sponsor of this network but it 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.

6.3 Space weather research group

Another important result of the study is the need for further basic scientific research in topics that are relevant to space weather. Current scientific knowledge is adequate to support some space weather services – in particular, those based on L1 monitoring of the solar wind and the heliospheric magnetic field. But the potential for effective space weather services will be greatly enhanced by research on some key topics as shown in table 1 below.

Table 1. Space weather topics for basic research

Conditions leading to ejection of material from the Sun
Propagation of those ejecta, and their embedded magnetic fields, from the Sun to the Earth
Acceleration of energetic particles in the heliosphere and in radiation belts of the Earth and other planets
A much deeper understanding of how reconnection works, e.g. to resolve controversies over the location and, in particular, the extent of reconnection regions.
Magnetospheric dynamics, especially in 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. 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 missions are addressing other topics such as magnetospheric dynamics and particle acceleration.

Thus what is needed here is an action to maintain 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 independent of ESA and whose members are recognised to be of international standing. Its terms of reference should include:

- Periodic review of areas where scientific research is needed to improve our knowledge of space weather –monitoring progress in existing areas, identifying where changes would be appropriate.
- Linking these reviews to the general progress of STP research, e.g. emphasising links between space weather and emerging scientific objectives
- Providing a public report on its conclusions. This report should be made available to ESA, to funding bodies throughout Europe 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.

6.4 Space weather development group

To encourage the development of space weather activities in Europe, we propose the creation of a small team to act as enablers of that development. This should be an internal ESA activity during the initial development phase, but with a long-term aim of migrating out of the Agency when it becomes an operational activity. The terms of reference of this group should include:

- Provision of advice to potential service providers. This may include advice on technical and marketing issues, e.g. to encourage people in the research community who need help to convert good ideas into operational services.
- Development of standards for handling space weather data and encouraging their use, e.g. based on the work of the Consultative Committee for Space Data Standards [2].
- Identifying opportunities for data provision from ESA missions, liasing with mission project teams to facilitate that.
- Building a prototype space weather programme. This should include a prototype space weather service based on existing data sources. It may be extended to include a prototype space segment to provide additional key measurements.

A set of services that could be included in a prototype space weather service are shown in Table 2 below. These have been selected as services which can be developed now using existing European data sources and expertise. They are also services where important European interests are vulnerable to space weather. So a successful prototype can build support for a space weather programme.

Table 2. Elements of a prototype space weather service

Products	Application areas
Post-event data on radiation levels for air travel	Calculation of radiation exposure & investigation of equipment anomalies
Post-event data on geomagnetically induced currents.	Electric power grids (also railways and telephone companies)
Nowcasts of ionospheric reflection properties	Channel selection for high frequency radio
Nowcasts of ionospheric total electron content	Corrections to GNSS systems & radar systems
Nowcasts of atmospheric drag	Satellite operators

These services could be enhanced by building a prototype space segment. This can be scaled according to the available funding. For a full discussion of this complex subject, please see our detailed study reports.

6.5 Outline schedule

These options can be implemented in a phased way according to available funding:

- First, establish the Network for Ground-based measurements and Space Weather Research group. These have only minor costs as they only involve encouraging community initiatives.
- Second, add the Outreach Centre. This would require modest expenditure (~1 Meuro/year) but would address some critical needs - in particular, building support for the programme.
- Third, establish the Space Weather Development Group and build a prototype space weather system using data from existing and planned missions. This would require only modest expenditure (~1 Meuro/year) but serve as a demonstrator for the larger programme.
- Finally, establish a prototype space segment for space weather data. This would address key user requirements and involve flying a few hitch-hiker payloads and one or two dedicated missions. This would require major short-term expenditure (~50 Meuro/year)

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7. STUDY REPORTS

This paper gives a summary of the study results. If you are interested to read further, please see the key reports from our study. These are publicly available as PDF files which can be downloaded from our web site at http://www.wdc.rl.ac.uk/SWstudy. Please follow the link to "Public documents".

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Hapgood, M., *Space & Ground Segments for a European Space Weather Programme*, this volume.
2. Consultative Committee for Space Data Systems, http://www.ccsds.org/.