ANNEX A: Technical Background

A.1 Background – Why did we start it?

ESA is obviously concerned by space weather effects which are taken into account in its various branches involved in design and operation but other industry sectors are also concerned. During the period 1998-2000 ESA has sponsored an analysis of the feasibility of a possible space weather applications programme that addressed the needs of ESA and others by two independent consortia respectively led by Alcatel and Rutherford Appleton Laboratory. They analysed the current sectors concerned with space weather, the European market, the measurement requirements and they outlined possible data provision infrastructure including ground and space elements. The work of the contractors was supervised by a Space Weather Working Team (SWWT) including experts from various space agencies and industry and from the directorates of Science and of Earth Observation.

Their conclusions emphasized the existence of well established small scale and independently run space weather services and of significant national interests in Europe. While a coordinated space weather activity could build on the large scientific expertise in Europe, and the existing ground based observatory network, it can only marginally use scientific space missions for integration into a service because of the requirements from service users for real-time data and continuity over a long-term.

Alcatel and RAL envisaged global space architecture based on a combination of dedicated spacecraft missions, hitch-hiker payloads and ground based networks. A particular space segment scenario (including a solar observatory, a solar wind monitor and a constellation of three radiation belt mappers) was refined by an analysis made with the ESA Concurrent Design Facility (CDF).

On reviewing the results, which suggested the establishment of a programme, the ESA management board considered that the proposed plan did not have strong enough economic justification and scientific maturity for such an undertaking in Europe and asked for a refined, quantitative, analysis of the potential benefits of such a programme.

A.2 Where do we stand now?

Following the outcome of the feasibility study and of the management board meeting where the results were presented, the SWWT recommended to federate the scientific activities and the service activities in two separate entities.

A.2.1 Federation of the scientific community
The European scientific space weather community organised itself with a 4 years COST action (COST724) under the meteorology programme and is now preparing a Eurocore activity on space weather effects on climate which has very good chances of being approved. A number of related national space projects are being supported by these networks, including: the British EARTHSHINE, the French DEMETER (in operation), PICARD, and TARANIS, and the German CHAMP (in operation). Furthermore, the recent ESA COSMIC vision call for ideas triggered proposals related to space weather.

International collaborations on space based space weather research are currently being discussed in various initiatives including the COSPAR panel on space weather, the SCOSTEP programme, CAWSES, the International Living with a Star programme which involves NASA, ESA, the Chinese space agency and the Canadian Space agency. World wide coordination of ground based observatories is progressing and should get a new impetus for space weather data acquisition and space weather service provision with the initiatives to celebrate the fifty years anniversary of the International Geophysical Year (IHY, IPY, eGY...).

Finally, it can be noted that the scientific community has now a space weather journal published by the American Geophysical Union. It features peer-reviewed articles presenting the latest engineering and scientific research in the field and up-to-date news as well as feature articles on government agency initiatives worldwide and space weather activities of the commercial sector.

A.2.2 Federation of the application community

ESA GSP made a 2M€ budget available for prototyping European space weather services which could then be used as a test for analysing actual benefits of such services and future measurements and service requirements. A condition was that service development activities should be at least 50% co-funded. As a result, a network of services has been constructed over the last 18 months which involves currently 27 service providers and at least as many users on a shared cost basis. A common IT infrastructure is being currently developed to support and monitor these services. An economic review was just initiated and should end April 2006 (cf schedule below). Most of the 27 services are already fully operational, the remainder should be operational within the next few months.

World-wide international collaborations for space weather service developments are discussed within the International Space Environment Service (ISES). The European Space Agency (ESA) recently joined ISES as a collaborative expert centre. Other members of ISES are Regional Warning Centers (cf Figure 1). It can be noted that the US warning centre, NOAA/SEC becomes this year a service center in the US National
A.3 What did we learn already and what can be anticipated?

In the rest of this report, an attempt is made to briefly review the achievements of the pilot project at its half way point and to identify what can be already anticipated as a possible outcome. It must be noted that there is still a strong uncertainty attached to the quantitative information provided in this report. This will part of the main objectives of the economic benefit review to improve the quantitative evaluation of costs and benefits and to identify the trends for future market development.

First of all, it is highly noteworthy that a significant amount of co-funding (approx. 3 M€) was “liberated” from 9 member state users and service developers for this project.

The community of users appear to be very broad and at least two of the services include military entities as users. About 90% of the pilot project activities addressed three main types of effects which are:

1. External (i.e. the short term variable component of) geomagnetic field
2. Ionospheric perturbations of radio (comms, nav) signals.
3. Direct space environment (radiation and other) effects on spacecraft.

The distribution of the Service Development Activities (SDA’s) according to these three types of effects are shown in Figure 1 below.

![Figure 2: Distribution of SDA’s by type of effects.](image)

Each of these three types is discussed in the technical Annex B in terms of
(i) Effects and concerned entities;
(ii) financial value;
(iii) current measurement and service chain;
(iv) trends for future evolution of the market;
(v) potential interest of space based measurements;
(vi) related activities.
Annex B – Review of the Pilot Project Results at Mid-term

B.1 External geomagnetic field

B.1.1 Effects and main concerned entities

The dc magnetic field measured in the Earth environment is the sum of the Earth's core magnetic field and of the external dc magnetic field. The external component of the geomagnetic field is generated by magnetospheric and ionospheric currents which are powered by the solar wind interaction with the Earth's magnetic field. Its response to variations in the solar activity depends on several factors. One of the most important variables is how the solar wind magnetic field will couple with Earth's magnetic field. Low frequency magnetic fluctuations of the dc field observed at ground are primarily due to ionospheric currents, which strongly vary during geomagnetic storms and substorms. They may affect activities requiring precise information on the amplitude and/or direction of the dc magnetic field (compass, geophysical surveying, etc.) and power lines (strong currents are induced on the lines) and pipelines (modification of the electric potential in anti-corrosion systems). Perturbations of the dc magnetic field in space are primarily due to magnetospheric currents. They also affect activities requiring precise information on the amplitude and/or direction of the dc magnetic field (observation of magnetic anomalies) and are important for the modelling of the energetic electrons and protons which may impact spacecraft and the modelling of the high energy particles (cosmic rays included) which impact the Earth atmosphere.

The sectors with a currently stated significant interest are geological surveying (for science and prospecting), electric power distribution, oil and gas transport via pipelines, military activities using compass. Planetary geomagnetic indices and solar wind magnetic field are widely used as inputs to application models (e.g. for thermosphere, radiation) but there seems to be no reliable quantitative information on the number of users and their distribution by sectors. The economic benefit analysis should help to clarify this aspect. It can also be noted that studies are in progress to identify short term and long term variations in the dc magnetic field on climate. This is still an area of scientific research.

B.1.2 Financial values

The direct effect of space weather may have high cost in exceptional individual events, e.g., when a geomagnetic induced current leads to power grid outage. Our pilot project indicates that even low-level disturbances have financial impacts. The current financial spending by governments and companies for space weather services in this area in Europe is estimated to be of a few M€/year mainly for data collection and processing and expert consultancy. This estimate will be refined by the economic benefit analysis.
B.1.3 Current measurement and service chain

The surveillance and protection against geomagnetic effects currently rely mainly on ground-based magnetometers and partly on solar wind measurements. Users generally rely on high accuracy spatial and temporal measurements dedicated measurements of fields, currents and voltage (often operated by scientific institutes).

Long-term monitoring of external geomagnetism is used to calculate geomagnetic indices and to model the response of the magnetosphere and ionosphere to variations in solar activity. Planetary and long-term monitoring of external geomagnetism requires less spatial and temporal accuracy but a good planetary scale homogeneity and a continuity of measurements over very long-time scales. These measurements currently rely on networks of magnetometers coordinated by scientific international unions and funded by national initiatives.

Recent efforts have been made to reduce the delay to make magnetometer data available to other scientists. The Intermagnet network gathers a large number of ground based magnetic observatory and is making use of meteorological spacecraft (GOES, Meteosat, ..) to distribute the data to the network members.

Solar wind magnetic field data have been available in near real-time on a nearly continuous basis since 1997 from the NASA ACE spacecraft with the help of NOAA which provided the required additional space hardware and set-up a network of receiving antennas involving a large amount of countries.

B.1.4 Trends for future evolution of the market

There is no reason identified at the moment to expect in a near future that the demand for supporting the oil industry with space weather data on external geomagnetism would significantly increase.

Although one may expect an increase of the number of pipe-lines especially at high latitude, the related increase in the demand of service will probably remain in the same order of magnitude. A significant increase of the demand for external geomagnetic field fluctuation measurements could be expected from increased concerns with GIC induced effects in power grids.

However, there are strong uncertainties on the magnitude of the future demand and whether it could trigger major space investment. Currently the risks related to GIC are small but are likely to increase because of the enhanced complexity of the systems, the larger amount of interconnections between national grids (cf e.g., Figure 1), the trends towards longer lines and higher voltages (which imply smaller resistances), and the use of the grids near the maximum capacity. However, many other problems raised by these same developments are likely to have higher priority for the power grid industry until a GIC major event occurs.
B.1.5 Potential interest of space based measurements

Space based measurements could allow in principle modelling of the time-dependent ionospheric current system from which the time dependent magnetic field on ground could be deduced for the relevant applications, however, the very small spatial scale (typically 100 km) of the current structure and the small time scale of their dynamics (typically 1 min) make it virtually impossible yet.

Space based measurements of external geomagnetic field would be more homogeneous than current geomagnetic network and could progressively replace them as the main monitoring technique for the long-term evolution of the geomagnetism, but many decades of data collection would be required before they would supersede ground based data. Also the measurements requirements need to be investigated.

Solar wind magnetic field measurements are much better performed by in-situ techniques than by ground based measurements (e.g., radio scintillation method). Furthermore, space based measurements of the solar wind can already provide rudimentary techniques to forecast periods with very strong perturbations of the field (the so-called geomagnetic storms). Testing of such techniques are ongoing (e.g., GIC-Fore SDA) with the use of the NASA ACE spacecraft located at L1.

B.1.6 Related initiatives

- ESA SWARM mission
- ESA CLUSTER mission
- NASA ACE mission
- NOAA TRIANA spacecraft
- Intermagnet magnetometer network
- Dst-index magnetometer network
- AE and Ap indices magnetometer networks
- Iridium magnetometer data
- International geophysical year 50th anniversary
- GSP study on space weather effects on climate.
- SDAs:
  - DMI-J (Dk), SWIMIC (Fin), CGS-Bot (Can), Pipe-lineNow (Fin), GIC-Fore (S), CORRENG (Can), BINCASTS (UK), ISGI (F).

B.1.7 Summary on external geomagnetic field

It is a domain with a solid interest from the science, the energy, and presumably from the military sectors. Related space weather research and services are well established in Europe and mainly rely on ground based measurements especially thanks to scientific resources. Space based measurement of solar wind magnetic field has already shown its strong value for scientific purpose and is being tested as a potential forecast method of geomagnetic storms. The interest of long-term continuity of such critical data on a key driver of space weather argues in favour of a successor of the
NASA ACE spacecraft. Space based Earth external magnetic field measurements could bring significant improvements in all sectors but the level of maturity and the measurements requirements vary from a sector to another and the economic analysis should provide a clear view of the expected benefits.

**B.2 Ionospheric perturbation of radio signals**

**B.2.1 Effects and main concerned entities**

The ionosphere results from the ionisation of the atmosphere by solar radiation. Time variation is due to daily and seasonal illumination pattern changes, solar eruptive phenomena, and, in a smaller extent, to geomagnetic perturbations. The ionosphere affects the propagation of radio waves especially through refraction for the waves in kHz to MHz frequency range and through diffraction for waves in GHz frequency range. Therefore HF ground-to-ground communication links and satellite based communication and navigation systems are subjects to perturbations due to ionospheric changes.

The downstream sectors with a current stated significant interest are the ones making use of HF applications (especially airlines, military and civilian security applications) and the ones making use of various navigation applications. Single frequency GPS users are numerous and may possibly use ionospheric correction to improve accuracy. Currently users with strong requirements on geodetic performance (typically 1 m or less in real time) and on reliability of GPS (geological surveying for prospecting, military activities based on GPS, off-shore drilling in very deep sea, airlines for airport approach) are using dual-frequency receivers. When ionospheric scintillations occur, at high latitude during geomagnetic disturbances or at low latitude due to ionospheric instabilities, the receivers may be seriously affected by scintillations effects up to a complete service disruption. An example of effects on dual frequency receiver is given in Figure 3 below.
B.2.2 Financial values

As shown by the pilot project, space weather effects on ionospheric propagation have a significant direct cost impact on the oil industry for drilling and surveying (the pilot project indicates a few millions €/Year for European companies) which requires high accuracy positioning data near the equator (Brazil, Nigeria, ...). The space weather cost impact for the HF communication users (airlines, vessels and some security activities) and for mono-frequency GPS users has not been evaluated yet. This will be done in the frame of the benefit analysis study. The current financial spending by governments and private sector for ionospheric space weather service in Europe is estimated to be close to 10 M€/Year including equipment and consultancy. This estimate will be refined by the economic benefit study.

B.2.3 Current measurements and service chain

The surveillance and protection against ionospheric effects on radio propagation in Europe currently rely mainly on ground based equipments: ionosondes (for sounding of the lower part of the ionosphere), scintillators and dual frequency GPS receivers (for modelling of effects on transionospheric signals). Most of the ionosondes are operated by scientific institutes. Scintillation detectors and dual frequency GPS receivers are operated either by scientific or private organisations. The EGNOS system is an example of service that helps to enhance the mono-frequency GPS and GLONAS users by providing ionospheric correction. It is a joint project of the
B.2.4 Trends for future evolution of the market

There is no reason identified at the moment to expect that the demand for supporting the use of HF telecommunication will significantly increase in the future and this is likely to remain an active but small market.

The applications of positioning data are anticipated to increase considerably in the next year. In addition, developments in this sector will presumably be encouraged in Europe in relation with the Galileo undertaking. What could be the trend of the market share for reliable high accuracy positioning data is not clear yet and should be clarified by the economic benefit study.

New potential applications of space based telecommunication systems may add more requirements on the reliability of the communication (e.g., for tele-surgery or security applications) and therefore require ionospheric perturbation forecast.

B.2.5 Potential interest of space based measurements

Ground based dual frequency GPS receivers are already commonly used systems to assess the state of the ionosphere. Space based navigation signal receivers can be used for generating ionospheric maps via tomography. This has been tested e.g. with the German CHAMP spacecraft. Similar space based techniques could be used for generating maps of scintillation index. It can be noted also that EGNOS signal is intended to be transmitted to users by 3 Inmarsat spacecraft.

Space based measurements in the solar wind that provide a rudimentary technique to forecast strong geomagnetic storms would be useful to assist the planning of user operations with a very high requirements on data reliability. Such techniques are being investigated by e.g., the SDA GIC-Fore (IRF).

B.2.6 Related initiatives

USAF GPS  
ESA EGNOS  
ESA GALILEO  
COST-271 Action  
CHAMP (DLR spacecraft)  
DIAS (European network of digital ionosondes, EU funded).  
SDAs: DIFS (UK), CLS-Scint (F), GIFINT (I), IONOSFERA (I), SOARS (UK), SWIPPA (D), SIDC (B), STIF (UK)

Other applications of ionospheric electromagnetic measurements are covered by:  
DEMETER (CNES spacecraft in operation),  
SICH-1M (Ukrainian spacecraft, on planning)  
GSP study on Earthquake precursors.
US HAARP programme for the study of man made perturbations of the ionosphere
SDA: SPECTRE.

B.2.7 Summary on ionospheric effects of radio signal

It is a domain with strong interest from a significant number of users in the security,
oil industry, transport, and telecommunication sectors. There are already well
established space weather services and others are being investigated. Current space
weather activities rely mainly on ground based measurements and ground based
receivers of space navigation signals. Space based measurements could provide better
géographical coverage of ionospheric effects, maps and new forecast methods.

A significant growth of the demand for space weather services is expected to go along
with the growth of navigation data applications.

B.3 Direct space environments effects on space systems

B.3.1 Effects and main concerned entities

The space environment has an adverse effect on space systems. Most of the problems
addressed are related to the ionising radiations (energy range: 10 keV to GeV)
travelling in the interplanetary medium (cosmic rays, particles associated to gradual
solar particle events) or confined in the radiation belts. The effects range from
cumulative damage on components and material to electronic upset and permanent
failure of sub-systems. Other space environment components, plasma, dust,
geomagnetic field may also lead to significant problems although less systematically
than the ionising radiations. Radiation induced DNA damages are also a concern for
manned space flights especially for possible future interplanetary manned missions.

Entities concerned are spacecraft designers who needs as good as possible information
on the actual environment, spacecraft operators for the diagnosis of problems,
downstream users of space systems who suffer from a reduction of the availability of
the system (both in capacity and duration) or unexpected interruption of services, and
agencies involved in manned missions.

B.3.2 Financial values

The effect can have high cost since it may lead to a partial or a complete loss of a
space mission (therefore of the order of 10-100 M€). Efforts put by European space
industry and governments for collecting and using ionising radiation (and other space
environment data) may be up to 10 M€/Year essentially for expert advising,
monitoring (hardware development and operation) and modelling.
B.3.3 Current measurements and service chain

The collection of measurements for improving radiation belt and solar proton models is an on-going process. This activity requires space in situ measurements. Most of the data are from US spacecraft operated by NASA, NOAA or USAF. Spacecraft and service operators tend to use the NOAA POES/SEM and GOES/SEM data which are accessible on-line with a few minutes delay. ESA astronomy missions are using more and more onboard radiation monitors for controlling the quality of measurements and for assisting observation planning (cf e.g. ESA Newton and Integral missions). ISS astronauts currently rely on NASA JSFC for radiation storm warning which works in collaboration with NOAA/SEC. A launch report procedure related to SEU risk on Ariane exists and is based on the US GOES datB.

B.3.4 Trends on future evolution of the market

Possible trends in this domain which are likely to increase the European demand for surveillance and modelling of space environment effect on space systems:

1. increased demand for using light-weight technology (which are more sensitive to external factors and lower energy particles);
2. increased demand on reliability of space systems e.g., for critical services (e.g., tele-surgery, high accuracy navigation, security applications,...);
3. development of manned space missions independent of the US (incl. commercial ones);
4. increased demand from operators and insurance companies for spacecraft health-check data.

Concerning the first point, one expects a need for completing models with lower energy data. Also lower energy particles (a few 100 keV) are encountered in a region broader than the so-called radiation belts and fluxes are more variable (cf e.g., Chandra concerns with 150 keV ions induced damages on CCD:s). Reduction of mass via reduction of the margin on the radiation shield requires improved models of the expected dose for given missions. The second point is related to the risk of service interruptions due to space weather induced spacecraft anomalies. Even a few minutes interruption (e.g. for rebooting a system) may not be acceptable for certain applications (e.g. tele-surgery). Space weather measurements could provide an estimate of the risk that certain anomalies would happen and hereby contribute to better planning of critical activities. They would also increase the lessons learned for improving the design of following spacecraft generations. At the moment, ISS astronauts entirely rely on the US Space Radiation Analysis Group (SRAG) in Houston (~6 people). It is expected that the possible cancellation of NASA involvement in the exploitation of the ISS would lead to the development of a European service to support space crews with radiation issues. On the longer term the ESA exploration initiative would also benefit from such a service. It can also be expected that a new era of space tourism has opened up with the recent success of SpaceShipOne which recently won the Ansari X-prize and raised interest of entrepreneurs like R. Branson. Even at such low altitudes, radiation level can be a significant concern. Although, much higher priority technical need to be solved before the market can develop, governments may be willing to encourage the development of such a sector by taking care of the hazardous radiation environment monitoring.
B.3.5 Potential interest of space based measurements

Very little useful information on space ionising radiation can be provided by ground based measurements. Neutron monitors are useful for the monitoring of cosmic rays and some exceptional solar particle events. There are currently strong data gaps in models for instance on MEO orbits and in interplanetary medium at other than 1 AU heliocentric distance. Even the solar particle events proton data records are still too small for allowing accurate modelling of this environment for mission design. There is also a gap of data on radiation in the lower energy range (~100 keV) which becomes a threat for more sensitive modern technology. Radiation monitors onboard spacecraft provide significant value for health check of spacecraft and seem to raise interest among spacecraft operators. Radiation detector data from spacecraft crossing many magnetospheric regions like on PEO could fill critical data gaps. There are various solar measurements and associated models for providing early warning of solar radiation burst but they are not very reliable yet and research activities to improve them are ongoing.

B.3.6 Related initiatives

NOAA Space Environment Centre (now moving to the US National Weather Service).
US Airforce space weather operations.
NASA SRAG.
NOAA GOES/SEM measurements.
NOAA POES/SEM measurements.
Inter-agency scientific programme ILWS.
ESA METOP/SEM measurements.
ESA XMM/ERM measurements.
ESA INTEGRAL/SREM measurements.
ESA GSTB-2/SURF and CREDO measurements.
ESA Proba-2.
SAC-C/ICARE measurements (Onera instrument on an Argentinian spacecraft).
SDAs: SHAFT (UK), GEISHA (F), SAAPS (S), SEIS (Port).
ARTES-5 study on space environment support for GSTB-2.
TRP study on multi-radiation monitor environment analysis.
GSTP SPENVIS radiation analysis tools.
COSPAR panel on radiation belts.

B.3.7 Summary direct space environment effects on space systems

This is an important component of space industry with a rather high cost impact. For some applications and manned space flight radiation effects are a limiting factor. The demand for radiation data is expected to grow especially due to the increased risk for new technology, the development of applications with more requirements on
reliability of spacecraft and the development of manned space flights independently of the US.
Annex C: Acronyms

CAWSES - Climate and Weather of the Sun-Earth System
CDF – Concurrent Design Facility
COST – European Cooperation in the field of Scientific and Technical Research
CNES – Centre National d’Etudes Spatiales
DLR – German Space Agency
ESA – European Space Agency
EU – European Union
eGY – electronic Geophysical Year
ESA – European Space Agency
GEO – Geostationary Orbit
GOES – Geostationary Orbiting Environmental Satellite
GPS – Global Positioning System
GSP – General Study Programme
GTO – Geo-transfer orbit
HF – High Frequency
HH – Hitchhiker instrument
IGY – International Geophysical Year
IHY – International Heliophysical Year
IPY – International Polar Year
ISES - International Space Environment Service
ILWS – International Living With a Star
L1 – First Lagrangian Point (~1.5 million km altitude along Sun-Earth axis).
LEO – Low Earth Orbit NASA – National Aeronautics and Space Administration
MEO – Medium Earth Orbit
MSG – Meteosat Second Generation
MSM – Manned Space Mission
NASA – National Aeronautics and Space Administration
NCEP – National Centre
NOAA – National Oceanic and Atmospheric Administration
PEO – Polar Earth Orbit
POES – Polar Orbiting Environmental Satellite
S/C – spacecraft
SCAR - Scientific Committee on Antarctic Research
SCOSTEP - Scientific Committee on Solar-Terrestrial Physics
SDA – Service Development Activity
SEU – Single Event Upset
SOHO – Solar and Heliospheric Observatory
SWENET – Space Weather European Network.
SWWT – Space Weather Working Team.