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Nano Satellite Beacons for Space Weather Monitoring
WP110 Analyse effects and requirements

Space weather effects and requirements analysis for space weather monitoring by nanosats

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1 INTRODUCTION

1.1 Document change record

Issue	Date	Notes/remarks
Issue 1.0	09 Dec 2004	First issue for review by ESA
Issue 2.0	24 Jan 2005	Major update following formal review at PM#1: • Section 1 – definitions extended to cover new items in v2.0, overview updated to cover changes from v1.0 • Section 3 - added service requirements for calibration, data quality and quality assurance • Section 4, Table 6 – clarified descriptions of sub-requirements, unspecified time resolutions indicated by NA • Section 4, add new sections: 4.4 to refine the time resolution requirements, 4.5 to compare with SDA data inputs and add new requirement 1.5, 4.6 to provide final summary of requirements. Add text to sec 4.2 to cross-reference Annex D • Section 5. Change manual assessment of req 10.1 to 1, add new req 1.5. Also add short discussion on role of cost as an alternative selection criterion. • Section 6. Add discussion of power issues, update table 10 to include new orbit locations • Section 7. Table updated to reflect all changes made above • Section 8. Conclusions edited and extended to take account of key changes from v1.0. • Annex C – new annex to show cross-references between SDA data inputs and measurement requirements • Annex D – new annex to describe orbits and multiplicity of space weather monitors • Annex E – new annex to analyse multiplicity of rad belt monitors • Minor editorial updates throughout
Issue 2.1	03 Feb 2005	• Section 6.3, add paragraph on Taiwan/US COSMIC project, plus reference to COSMIC web site • Annex D, expand description of SWARM orbit, also update reference to SWARM documents. • Add new annex F to discuss issues that need to be addressed in using space-based magnetometer data in space weather applications. Also add cross-reference in section 4.5. • Throughout: replace Solar-GEO by GEO to reduce confusion as many non-solar observations made from this orbit.

Issue 2.2	06 Apr 2005	• New SDA requirement for Lyman-alpha monitoring added with (a) reference to SOHO/ SWAN in CLS/SFC entry in Annex C; (b) new text in Section 4.6, (c) new entry in Tables 7, 9 and 14, (d) new item in section 7. • Replaced ionospheric-polar orbit by Molniya to exploit advantages discussed at ESTEC workshop: (a) updated orbit description in Annex D; updated Tables 10 and 12 and section 7 as appropriate. • Updated figures 1, 2 and 3 to take account of above changes. • Updated section 4.4 to note that cadence for science is only indicative of upper limit • Updated section 6.2 to include notes on variable ranges

1.2 Purpose of Document

This document specifies user and data requirements for developing the design of a nano-satellite programme for space weather monitoring.

1.3 Definitions, Acronyms and Abbreviations

ACE	Advanced Composition Explorer (NASA spacecraft)
AKR	Auroral Kilometric Radiation (radio emission produced by auroral electron precipitation)
Ap	Planetary index of geomagnetic activity at mid-latitudes
B-field	Magnetic field
CCD	Charged coupled device
CCLRC	Council of the Central Laboratory of the Research Councils
CDF	Conceptual Design Facility
CHAMP	CHAllenging Microsatellite Payload
CME	Coronal Mass Ejection
COSMIC	Constellation Observing System for Meteorology, Ionosphere and Climate
CSMR	Consolidated System Measurement Requirement
dB/dt	Rate of change of magnetic field
Dst	Index of equatorial geomagnetic activity due to ring current in magnetosphere
ECSS	European Co-operation on Space Standardisation
ESA	European Space Agency
ESTEC	European Space Technology Centre
EUV	Extreme ultra-violet
F10.7	Index of solar radio emission at 10.7cm wavelength. Also called the Penticton index.
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.
GCR	Galactic cosmic rays
GEO	Geosynchronous orbit
GIC	Ground induced current
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GTO	Geosynchronous Transfer Orbit
HF	High frequency (radio)
HMF	Heliospheric magnetic field
IMF	Interplanetary magnetic field

IRF	Swedish Institute of Space Physics
ISO9001	Quality assurance model adopted as a standard by the International Standards Organisation. Appropriate for organisations that design, develop, produce, install, and service products.
keV	kilo-electron-volt (unit of energy)
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.
KP	Key parameter
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
L1	Lagrangian point 1 (1500000 km sunward of Earth)
LEO	Low Earth orbit
LET	Linear energy transfer
MDI	Michelson Doppler Imager
MeV	mega-electron-volt (unit of energy)
MLT	Magnetic local time
MST	Microsystem technologies
NASA	National Aeronautics and Space Administration
Ne	Number density (of a plasma)
Nsw	Number density of the solar wind
PEO	Polar Earth orbit
QA	Quality Assurance
RAL	Rutherford Appleton Laboratory
RF	Radio frequency
S/c	Spacecraft
SDA	Service Development Activity
SEPE	Solar energetic particle event
SMR	System Measurement Requirement
SOHO	Solar and Heliospheric Observatory
SPE	Solar proton event
SR	Service Requirement
SSN	Sunspot number
STP	Solar Terrestrial Physics
SWAN	Solar Wind Anisotropies
SWENET	Space Weather European Network
SWWT	Space Weather Working Team
TBD	To be done
TEC	Total electron content
UR	User requirement
UV	Ultra-violet
Vsw	Velocity of the solar wind

1.4 References

We list here the various documents used as source material for this report. These include both hardcopy and web sources. Documents may be referenced in the text and this is indicated by a sequential code of the form Xn, where n is an integer and X = A or R (for applicable and reference documents respectively). The series of integers are separate for applicable and reference documents.

1.4.1 Applicable documents

A1 Statement of Work, Nano-Satellite Beacons for Space Weather Monitoring, Reference: TOS-EES/2004.153/AG
A2 ESTEC Contract No. 18474/04/NL/LvH Nano Satellite Beacons for Space Weather Monitoring
A3 Proposal for Nano Satellite Beacons for Space Weather Monitoring, RAL/RRS/228/03

1.4.2 Reference documents

R1 Space Weather Feasibility Studies (RAL): http://www.wdc.rl.ac.uk/SWstudy/
R2 Space Weather Feasibility Study (Alcatel): http://www.estec.esa.nl/wmwww/WMA/spweather/esa_initiatives/spweatherstudies/public_doc.html
R3 Space Weather CDF Study final Report: http://www.estec.esa.nl/wmwww/wma/spweather/esa_initiatives/spweatherstudies/CDF_study/cdf.htm
R4 European Space Weather Programme System Requirements Definition, ESWP-DER-SR-0001, available via http://www.wdc.rl.ac.uk/SWstudy/
R5 ESA Space Weather Programme - Alcatel contract, Space segment - Measurement and system requirements, WP 2200 and 2300 reports, available via http://www.estec.esa.nl/wmwww/WMA/spweather/esa_initiatives/spweatherstudies/public_doc.html
R6 Project Implementation Plan and Final Report, ESWS-RAL-RP-0002 http://www.wdc.rl.ac.uk/SWstudy/public/wp600_report_v11.pdf
R7 A definition of instruments needed for space weather measurements ESWS-RAL-TN-0001
R8 Magnetic maps of the whole Sun, http://soi.stanford.edu/data/farside/index.html
R9 MDI-SOI Observations and Observables , http://soi.stanford.edu/science/obs_prog.html
R10 SWARM Homepage, http://www.space-plasma.qmul.ac.uk/SWARM/
R11 Constellation Observing System for Meteorology, Ionosphere and Climate, COSMIC, http://www.cosmic.ucar.edu/
R12 J.K. Hargreaves, The solar-terrestrial environment. Cambridge University Press, 1992.
R13 SWAN Far Side imaging, http://sohowww.nascom.nasa.gov/data/summary/swan/
R14 The SOHO Mission: Scientific and technical aspects of the instruments. ESA SP-1104.

1.5 Overview of Document

Section 2 reviews the results of the previous ESA-sponsored space weather studies that are the key input to this study – namely the parallel assessment studies led by RAL [R1] and Alcatel [R2] plus the internal ESA design study using the ESTEC Conceptual Design Facility [R3]. This section describes how requirements data was abstracted from the reports of these prior studies and stored in the database used to support the present study.

Section 3 discusses the service requirements derived from the three prior studies, together with additional requirements discussed with ESA during the review of the first issue of this document, - and summarises them for use in the present study.

Section 4 describes how we synthesised the measurement requirements derived from the RAL and Alcatel studies and produced a consolidated set of detailed requirements for use in the present study. This includes a description of how the database was used to produce and store this synthesis and to provide traceability to the previous studies. This traceability through the database is important because it allows us to retrieve and manipulate requirements attributes from the previous studies. This section also includes analysis of the measurement requirements for the service development activities within ESA's Space Weather Applications Pilot Project; this shows how the SDA requirements can be satisfied by the requirements in this document.

Section 5 describes how we map each of the 33 detailed requirements to three solution levels required in the Statement of Work [A1]. This mapping is performed in three different ways in order to demonstrate that we have a robust and objective set of results.

Section 6 describes how we assess the suitability of the different requirements for nanosat monitoring. This is the most speculative step in the analysis reported here and has, therefore, been left as the last analysis stage in order to facilitate change. The most critical aspect of this section is the development of objective criteria for assessing the appropriateness of nanosat solutions. This is discussed in some detail and then applied to exclude one requirement from nanosat solutions and to divide the remaining 32 requirements into three different priority groups and one low priority group for nanosat solutions.

Section 7 presents a set of tables giving a detailed description of the 32 detailed requirements selected for nanosat solutions. This followed by a summary of conclusions in section 8.

Finally there are five annexes. Annex A presents tables of the key input data abstracted from the three prior studies. Annex B presents two landscape diagrams that illustrate prioritisation schemes discussed in section 6 on nanosat solutions; these are placed at the end of the document for ease of document formatting. Annex C shows how the data inputs used by the Pilot Project service development activities are satisfied by measurement requirements in this study. Annex D describe the orbits and multiplicity of the space weather monitors needed to address the measurement requirements. This includes a rationale for the choices made and an indication of how the requirements would be affected by descoping the multiplicity. Annex E presents a detailed analysis of the multiplicity needed for radiation belt monitors.

2 PREVIOUS ESA STUDIES

2.1 Introduction

This present study seeks to build on work done during the three space weather studies performed for ESA in 2000-2001 – namely the two study contracts led by RAL [R1] and Alcatel [R2] and the study carried out by the ESA Space Weather Working Team using ESTEC Conceptual Design Facility (CDF) [R3]. These studies provided (1) a wealth of information on requirements for space weather products and their timely dissemination to potential users and (2) a description of the measurements and models needed to generate those products and (3) an analysis of the space and ground infrastructure needed to support those measurements.

The aim of the present study is to synthesise the previous results so they can be used to derive a set of user and data requirements that could be addressed by a nanosat-based monitoring programme. Thus we focus on those parts of the previous results that describe requirements for space weather monitoring – but, where appropriate, take account of other parts of the results that expand on the scope and understanding of requirements.

Both the RAL and Alcatel studies carried out market surveys to explore user needs for space weather products and then interpreted these needs into sets of user requirements. It was quickly realised that it would be advantageous to harmonise these two sets of user requirements so that the subsequent parts of the RAL and Alcatel studies were built on a common set of user requirements. This common set is presented in Annex A of this document. It comprises some 22 *product requirements* that specify the types and timeliness of data products to support required space weather activities and 3 *service requirements* that specify generic requirements for the availability, continuity and distribution of all space weather data products. Further information of service requirements has been taken from the CDF study.

The product requirements were then the subject of independent analysis by the two study teams in order to establish measurements requirements as discussed below. The CDF study took these measurement requirements as its inputs and, for this reason, it is not used here as a separate source of such requirements. To confirm this we will later demonstrate that the synthesised measurement requirements encompass the requirements analysed in the CDF study (see Table 20).

2.2 Measurement requirements

2.2.1 RAL study - consolidated system measurements requirements

The RAL study established a set of consolidated system measurements requirements (CSMRs) that specified the measurements and models needed to generate the products given in the user requirements. These CSMRs were clearly traced from the user requirements as described in the detailed report [R4] and include information on the location and time resolution of the measurements.

The CSMRs are presented in Annex A; this includes changes (deletion of one CSMR and one new CSMR) to the results of the RAL study as recorded in R7, subsequent to the main requirements analysis. However, the CSMRs include a mix of space-based and ground-based measurements. For the purposes of the present study we have excluded all CSMRs that describe explicitly ground-based measurements. The excluded requirements are shown in Table 17 together with a rationale for exclusion.

2.2.2 Alcatel study – key parameters

The Alcatel study provided a detailed report on the measurement and system requirements for the space segment [R5]. This report includes an extensive list of the observations that might be made by a space weather programme (their Table 1). This is then consolidated into a list of the key parameters that must be measured (their table 2A). This table is cross-referenced to proposed instruments in their Table 3, which also gives important information on the required instrument performance, e.g. resolution in time, energy, wavelength, etc. In this report we have taken their table 2A as the main source of measurement requirements as shown in Table 18. This enables us to pick-up the all-important information on required measurement resolution, via the cross-references between their Tables 2A and 3.

2.2.3 User communities

Both the Alcatel and RAL studies identified the user communities whose needs would be addressed by the requirements reported by each study. The two studies used different, but overlapping, specifications of user communities; these have been consolidated into a single list as shown in Table 19. In the RAL study this identification was attached to the user requirements and has been used without change in the present study. In Alcatel study the user community identification was attached to the observation types listed in Table 1 of [R5]. To use these data in the present study we have re-interpreted this identification to associate them with the key parameters from Table 2A of [R5].

2.2.4 Requirements database

To support the synthesis of the RAL and Alcatel measurement requirements into a single dataset, much data from the RAL and Alcatel studies were ingested into a relational database running under Microsoft Access. This information was then available to provide traceability to the synthesised requirements and also to support checks on the completeness of the synthesised requirements. The generation of the synthesised requirement will be discussed in detail in the next section. Here we just summarise the database objects.

Table 1. Database tables containing information from RAL and Alcatel studies.

User groups: the consolidated list of user communities derived from both studies See table in Annex A.
User Requirements as discussed above. This table includes fields that identify: (a) whether the requirement relates to forecasts, nowcasts or post-event analysis, and (b) the topic area to which the requirement applies. See Annex A for a table showing these topic areas. These topic areas are related to user groups, but better visibility of the technical interest in cases where groups have diverse interests (e.g. satellite operators).
Cross-references between the user requirements and the consolidated set of user communities
The consolidated system measurements requirements identified in the RAL study
Cross-references between the CSMRs and the user requirements
The key parameters identified by the Alcatel study
Cross-references between the Alcatel key parameters and the consolidated set of user communities
The instrument types and attributes identified by the Alcatel study
Cross-references between the Alcatel study key parameters and instruments
Cross-references between the Alcatel study instruments and the instrument platform types discussed in that study – namely solar, upstream, magnetospheric and ionospheric monitors.

3 Synthesis of service requirements

As these are part of the common user requirements little synthesis is required. The three service requirements presented in the User requirements (Table 15) as items 23 and 25 and are as follows.

UR 23: continuous data availability during and after extreme events. This is the requirement that space weather sensors and any critical support systems should be designed to operate reliably when subjected to extreme space weather events. This is to ensure that space weather data will be available when needed to support nowcasting of trends during extreme events and also post-event analysis of problems arising during such events. The need for this requirement has been demonstrated by the well-known problem with the solar wind plasma sensor on NASA's ACE spacecraft, which has provided real-time solar wind monitoring at the L1 point since 1997. Unfortunately this instrument gives highly inaccurate data during strong solar proton events – presumably due to energetic protons penetrating shielding and contaminating the particle detectors. Fortunately, the SOHO spacecraft, also at L1, has a more robust plasma sensor and its data have proved to be an adequate backup during extreme events. For future space weather monitoring missions, it is important to ensure sensor robustness against extreme events as shown in the table below – and also to ensure the robustness of critical sub-systems supporting those measurements (e.g. commanding).

Table 2. Robustness requirements for space weather monitoring

Event	Robustness requirement
Solar protons	Particle sensors: suppress false particle counts due to penetrating radiation, e.g. by shielding or co-incidence counting; also need to avoid sensor saturation. Imagers: suppress trails in CCDs due to penetrating radiation? May be difficult.
Enhanced drag	If spacecraft position data are important (e.g. GPS sounding of ionosphere as on CHAMP) need frequent updates of orbit
Ionospheric scintillation	Downlink of data: avoid data loss due to signal fading during enhanced scintillation, e.g. use frequency less affected by scintillation, use ground stations outside major scintillation regions at equator and auroral zone, build redundancy into downlink data

UR24: Continued data availability in the event of premature failure or end-of-life of key space weather systems. This is the requirement for redundancy of space weather measurements. In the context of space-based measurements it is the ability to launch replacement spacecraft, e.g. through on-demand launches, in-orbit spares or the use of multiple spacecraft. The CDF study established a design lifetime of at least 5 years with provision of replacement spacecraft after that date. The present study must use a similar requirement – namely that each spacecraft and instruments be designed to operate for a suitable lifetime and but subject to replacement at the end of design life; this is in addition to the need for redundancy to deal with premature failures. The target lifetime should be of order of a few years but must be subject to trade-off during the design phase of the present study. That trade-off may be different for different orbit architectures, e.g. to respond to differences in radiation exposure.

UR25: Efficient distribution of data to users and continuous availability. This requirement reflects an important characteristic of space weather monitoring that is very different to scientific measurements. To be useful in space weather applications (especially nowcasting and forecasting) space weather data must be available in near-real time and without significant data gaps. This is a critical requirement as delays and gaps in data delivery will lead to a rapid deterioration in quality of service. In contrast, the provision of data from scientific measurements can be delayed by several days as detailed scientific analysis usually requires a period of months, often years, after the event (e.g. it is a common practice on ESA science missions to deliver data to scientists some days after collection on the spacecraft). The timeliness requirement for different measurements was extensively discussed in the RAL study – for example see [R7].

The CDF study raised a further service requirement that we consider here – namely that the space weather system should be independent of presently operational or planned scientific missions. This is important given the very different aims and need of scientific missions. As discussed above science missions do not have a requirement for timely return of measurement data. In addition, science missions are usually more tolerant about data gaps, including those caused by space weather effects on sensors and spacecraft. A trade-off between data coverage and mission cost is quite normal on a science mission. Finally and most important, science missions usually fly state-of-the-art instruments in order to provide novel data that addresses questions at the cutting-edge of science. This is very different driver to the need of space weather monitoring. It will sometimes lead to data which have secondary applications in space weather but certainly not to optimal data production for space weather needs. Given these major differences between the needs of space weather monitoring and of science missions, it is appropriate to have an explicit requirement that space weather monitoring should be independent of presently operational or planned scientific missions.

Discussions with ESA during the course of the present study identified three further service requirements:

- The importance of instrument calibration. Space weather monitoring provides values of physical parameters for use in models of the space environment and its effects on human beings and their technology. The accurate estimation of those effects requires that the model inputs are themselves accurate. Thus there is a clear requirement to ensure good calibration of space weather monitoring instruments. The calibration procedure will be specific to the instrument design but is likely to include a mix of pre-launch and in-flight activities. The latter may include execution of dedicated calibration activities and regular monitoring activities (to check for gradual trends and abrupt changes in instrument performance). Ground processing systems must provide efficient and reliable configuration control of items sensitive to instrument calibration.
- Monitoring of data quality. The requirement for accurate measurements also implies a requirement to monitor data quality. The quality of data returned by any instrument is likely to vary with time due to a number of factors including: temporary problems with instrument or spacecraft performance, interference from the space environment, variable sampling of target environment. An example of the latter is particle measurements at low fluxes, where there may be insufficient particle counts to yield statistically reliable results. Thus instrument measurements and their processing should include procedures to assess data quality. The form of that assessment will be specific to the instrument design but should result in a status flag that can be associated with each data record.
- Quality assurance. The development, deployment, commissioning and operation of space weather monitors should be subject to an appropriate level of quality assurance (e.g. through procedures to document and review activities). Well-known QA standards, such as ECSS and ISO9001, can provide a starting point, but the procedures must be tailored to address the specific needs of a space weather monitoring programme, e.g. the other service requirements discussed in this section. The tailoring must also ensure that the QA procedures are efficient so that they contribute value to the programme.

We summarise the synthesised service requirements as follows:

Table 3. Synthesised service requirements

N	Requirement	Main characteristics
1	The space and ground segments for a space weather monitor shall provide continuous data availability during and after extreme events.	Robust sensors and operations
2	The space and ground segments for a space weather monitor shall provide continued data availability in the event of premature failure or end-of-life of key space weather systems.	Redundancy in orbit and rolling replacement at end of design life
3	The space and ground segments for a space weather monitor shall provide efficient distribution of data to users and continuous availability	Prompt availability of data, design to ensure data gaps are below maximum acceptable gaps.
4	The space and ground segments for a space weather monitor shall support good calibration of that monitor	Dedicated calibration activities both pre-launch and in-flight; regular monitoring of instrument performance; configuration control
5	The space and ground segments for a space weather monitor shall provide a data quality flag for each data record	Assessment of data quality through on-board and on-ground procedures
6	The development, deployment, commissioning and operation of space weather monitors shall be subject to appropriate and effective quality assurance procedures	Document and review activities; avoid bureaucratisation of QA process by focusing on value to programme
7	The space and ground segments for a space weather monitor shall, to the greatest extent possible, be independent of presently operational or planned scientific missions.	Avoid unacceptable trade-off with science objectives

4 Synthesis of measurement requirements

To synthesise the requirements data from the previous studies, we have created a new tables of formal requirements within the Access database described in section 2.2.4 and have built tables of cross-references between the new tables and the previous data. This approach has given us the flexibility to reformulate the requirements to address the aims of the present study, while maintaining traceability from earlier work. The cross-reference tables allow us to instantiate traceability SQL queries that explore the consequences

In building the new requirements tables we have adopted a hierarchical approach. We first created a high level set of requirements that specify the distinct types of measurements needed but leaves details of measurement performance to lower level requirements (sub-requirements). This scheme has two advantages:

- It facilitates synthesis by allowing us to associate the previous requirements with their common measurement type. The details of previous requests can then be merged or distinguished, on a case-by-case basis, at the level of detailed sub-requirements.
- The hierarchical approach is a convenient framework for presenting requirements. The high level requirements provide a good overview while the sub-requirements ensure that detail is not lost.

4.1 Table design

The high-level requirement table has the following fields:

- Requirement number
- Requirement text

While the sub-requirement table has the following fields:

- Number of the high-level requirement to which the sub-requirement is associated
- Sub-requirement number
- Measurement sub-type – text description of what distinguishes the measurement in this sub-requirement, e.g. type of images to be taken, type of particles to be detected
- Time resolution required in units of minutes – two values are given, one from each of the RAL and Alcatel studies.
- Measurement resolution – numerical specification of measurement performance (e.g. pixel size for images)
- Measurement units – the units in which the measurement resolution is given
- Data rate – the raw data rate of measurement in kilobits per second - based on the finer of the two time resolutions above.
- Timeliness – the acceptable time interval, in minutes, between data acquisition and provision of product to user
- Solution level – a code indicating how the sub-requirement applies to the three levels of solutions required by ESA [A1 and described in Table 8]. The code values are shown in Table 4 below.
- General notes. Additional general information as appropriate in each case.
- Solution notes. Additional notes on the choice of solution level above.
- Timeliness notes. Additional notes on the choice of timeliness value.

Table 4. Solution level codes

Code	Applicable to solution level
0	The requirement does not apply to any of the three solution levels required by ESA
1	The requirement applies to all three solution levels
2	The requirement applies to second and third solution levels (data for full space weather operations and/or data model development; science data-taking)
3	The requirement applies only to the third solution level (science data-taking)

4.2 Initial population of the tables

The high-level requirements table was built by examining the consolidated system measurement requirements (RAL study – see Table 16) and the key parameters (Alcatel study – see Table 18) and manually identifying the distinct types of measurements within these inputs. The cross-reference table between the high-level requirements and the CSMRs was then built by examining each CSMR in turn and assigning it to one or more of the high-level requirements. An analogous process was used to build the cross-reference table between the high-level requirements and the key parameters. To check the completeness of each cross-reference table (and thus of the set of high-level requirements), we built queries that look for CSMRs and key parameters not in the appropriate cross-reference tables. The analysis was repeated until these queries returned no requirements relevant to the present study. At the end of the process, it was found that all CSMRs, and all bar one of the key parameters, had been mapped to high-level requirements. The one key parameter that was excluded from the high-level requirements was the boundaries parameter. This was excluded as it is not a measured parameter but rather a set of events derived from measurements. It is not considered further here as the present study focuses on the actual measurements which might be made by a nanosat.

To support initial population of the sub-requirements table, we have constructed a query that joins each high-level requirement to the CSMRs and key parameters recorded in the cross-reference tables and to the instrument details associated with each key parameter. Since these are relational (inner) joins, the query output has a record for every distinct combination (110 in total) of high-level requirement, CSMR, key parameter and instrument recorded in the cross-reference tables. This provides a set of combinations that can inform the production of the sub-requirements, e.g. providing:

- text description of the requirement
- cross-references to the CSMRs and key parameters
- the time and spatial resolution specified in the CSMRs
- the instrument type and attributes (e.g. time resolution) linked to the key parameters

These combinations were inspected manually to assess which provide valid data for the detailed sub-requirements. Where both the RAL and Alcatel studies provided a time resolution, we selected the finer value.

To facilitate this examination of the data we built an Access forms interface to display the query output – with one record per form. At first sight this process may seem cumbersome, but, in practice, it reduces the amount of data to be inspected and provides a degree of formalism that aids accuracy. The 110 records to be inspected must be compared to the million records that would arise if we inspected every possible combination of high-level requirement, CSMR, key parameter and instrument. This process uses the knowledge encoded in the cross-reference tables to provide a first iteration of the detailed data, which can then be efficiently refined by manual inspection.

The data rate value for each sub-requirements was derived by examining the values quoted in the Alcatel and RAL study reports on instruments ([R4] and [R7]); where two values were available the larger was used (reflecting our earlier choice of the finer time resolution where both study provided time resolution values).

While building the sub-requirements table we also populated three cross-reference tables linking the sub-requirements to (a) the CSMRs, (b) the key parameters, and (c) the orbits where the required measurements may be made. The sub-requirement orbits are placed in a separate table so that we can specify multiple orbits in which the required measurement may be made; this table also allows us to specify the multiplicity, the number of separate measurements (and thus spacecraft) required in that orbit. For example, solar observations at L1 require a single spacecraft but the equivalent observations at geosynchronous orbit will require two spacecraft (in order to maintain continuous observations during eclipse seasons). A full description of the orbits and multiplicity values used in this analysis is given in Annex D (Table 22) together with a rationale for the choice of multiplicity and a discussion of the impact of descoping that choice.

Finally to check the completeness of the sub-requirements, we built queries that look for CSMRs and key parameters not mapped to sub-requirements. The analysis was repeated until these queries returned no requirements relevant to the present study. At the end of the process, it was found that 1 CSMRs and 1 key parameter had not been mapped to sub-requirements. The key parameter was the boundary parameter, which was excluded as discussed above. The unmapped CSMR is number 73 which is associated with human spaceflight. This CSMR is not relevant to a nanosat programme and thus is not considered further in this study.

4.3 Initial results

The high-level requirements and subsequent sub-requirements are shown in Table 5 and Table 6 below.

Table 5. High level requirements

Requirement number	Requirement text
1	X-ray / EUV / UV/ optical images of solar disc
2	Solar coronagraph images
3	Solar X-ray flux and spectrum
4	Solar EUV/UV flux
5	Solar constant
6	Solar/interplanetary radio bursts
7	Solar magnetograms
8	Solar wind density and velocity
9	Heliospheric magnetic field
10	Solar energetic particles and cosmic rays
11	Aurora oval size and location
12	Wave emissions, especially AKR
13	Magnetospheric B-field
14	Cross-tail electric field
15	Low energy (1-10keV) electrons with good spectral information
16	Medium energy (10-100keV) electrons with good spectral information
17	High energy (>300keV) electrons with good spectral information
18	>10MeV protons
19	Radiation doses
20	Electron densities in plasmasphere and ionosphere
21	Ionospheric drift velocities
22	Neutral densities in thermosphere
23	Neutral winds in thermosphere
24	Neutral temperature in thermosphere
25	Micro-particle measurements

Table 6. The sub-requirements: initial time resolution and data rate

Requirement number	Sub-requirement	Measurement sub-type	Alcatel time resolution (mins)	RAL time resolution (mins)	Data rate (kbps)	Timeliness (mins)
1	1	EUV images of Sun	2.5	60	28	30
1	2	H-alpha images of Sun	0.5	NA	120	30
1	3	Soft X-ray images of Sun	1	60	70	5
1	4	Stereo images of Sun-Earth space	NA	60	10	360
2	1	Coronagraph	10	60	50	720
3	1	Solar X-ray flux monitor	1	5	0.2	5
4	1	Solar EUV full disc flux	NA	1440	1	1440
4	2	Solar UV flux	NA	60	0.25	60
6	1	Solar radio bursts	NA	60	1	720
7	1	Solar magnetograms	15	20	10	720
8	1	Solar wind bulk velocity	1	1	0.1	30
8	2	Solar wind bulk density	1	15	0.1	30
9	1	Heliospheric magnetic field	1	1	0.2	2
10	1	>100 MeV ions from heliosphere	1	60	0.1	5
10	2	2-100 MeV ions from heliosphere	1	30	0.1	5
10	3	2-20 MeV electrons from heliosphere	1	0	0.1	1440
11	1	Auroral UV imaging	NA	60	10	5
11	2	Auroral particle precipitation	NA	60	2	5
11	3	Auroral visible imaging	NA	60	10	5
12	1	Auroral kilometric radiation (AKR)	NA	1	2	5
13	1	Magnetospheric magnetic field	1	1	0.2	1440
14	1	In-situ magnetospheric E field	NA	180	1.5	5
15	1	1-10 keV electrons in magnetosphere	1	1	2	90
16	1	10-100 keV electrons in magnetosphere/rad belt	1	1	2	60
17	1	High energy electrons in rad belt	1	30	0.1	5
18	1	> 10 MeV protons in rad belt	1	30	0.1	5
19	1	Dosimetry	NA	5	0.1	5

Requirement number	Sub-requirement	Measurement sub-type	Alcatel time resolution (mins)	RAL time resolution (mins)	Data rate (kbps)	Timeliness (mins)
20	1	Total electron content of iono/plasmasphere	NA	5	0.1	5
20	2	Electron density of iono/plasmasphere	NA	1	1	5
21	1	Plasma velocity in ionosphere	NA	0.1	1	5
22	1	Neutral density in thermosphere	NA	30	1	60
23	1	Neutral wind in thermosphere	NA	30	1	60
25	1	Microparticle measurements	NA	1440	0.03	1440

Note: NA in the time resolution columns indicates no value available

4.4 Refinement of the tables

Table 6 shows that there are some cases where there are marked differences between the time resolutions specified by RAL and Alcatel. We have explored these differences by distinguishing the time resolution needed for a space weather service from that needed for scientific research of space weather phenomena. This is an important distinction because the service can often operate with coarser than are needed for research. This is an important issue for the requirements because the coarser time resolution implies a low data rate requirement, which may help in the design phase of the study.

To accommodate this additional analysis the sub-requirement table has been extended to include three extra fields as follows:

- Cadence for service - time resolution in minutes needed for a space weather service.
- Cadence for science – maximum acceptable time resolution in minutes for scientific research of space weather phenomena. Note that this is an indicative figure for purposes of these requirements and that finer resolution will always facilitate scientific research.
- Cadence notes – a short justification of the time resolution needed for a space weather service. This field is populated only

These fields were populated as follows:

- Where the Alcatel and RAL time resolutions are in good agreement, a common value was stored in the cadence for service and science fields – and the cadence notes were left empty.
- Where the Alcatel and RAL time resolutions were markedly different, we considered the distinction between the needs of service and science and placed appropriate values in the cadence for service and science fields. In practice, this involved placing a compromise value in the cadence for service field and the finer of the Alcatel and RAL time resolutions in the cadence for science field; a short rationale for the service cadence was placed in the cadence notes field. The data rate field was then adjusted to reflect the cadence for service. (The data rate for science is not separately recorded as it is equal to the data rate for service × cadence for service ÷ cadence for science.)

We found that there were 11 (out of 33) sub-requirements where the Alcatel and RAL time resolutions were markedly different. These are shown in the table blocks below together with the adjusted cadence values and the notes justifying the changes.

Req. 1.1	EUV images of Sun
Alcatel time resolution (mins)	2.5
RAL time resolution (mins)	60
Cadence for service (mins)	10
Cadence for science (mins)	2.5
Cadence notes	10 mins is ok to capture flares

Req. 1.2	H-alpha images of Sun
Alcatel time resolution (mins)	0.5
RAL time resolution (mins)	
Cadence for service (mins)	10
Cadence for science (mins)	0.5
Cadence notes	As EUV and X-ray

Req. 1.3	Soft X-ray images of Sun
Alcatel time resolution (mins)	1
RAL time resolution (mins)	60
Cadence for service (mins)	10
Cadence for science (mins)	1
Cadence notes	10 mins is ok to capture flares

Req. 2.1	Coronograph
Alcatel time resolution (mins)	10
RAL time resolution (mins)	60
Cadence for service (mins)	15
Cadence for science (mins)	10
Cadence notes	Set to get 10 obs over 30 Rs for a 2000 km s-1 CME - to allow good estimate of CME velocity

Req. 3.1	Solar X-ray flux monitor
Alcatel time resolution (mins)	1
RAL time resolution (mins)	5
Cadence for service (mins)	5
Cadence for science (mins)	1
Cadence notes	GOES 5-min resolution is fine

Req. 8.2	Solar wind bulk density
Alcatel time resolution (mins)	1
RAL time resolution (mins)	15
Cadence for service (mins)	1
Cadence for science (mins)	1
Cadence notes	Use same value as for velocity and magnetic field. 1 min resolution ensures shocks in density are seen between L1 passage and arrival at Earth.

Req. 10.1	>100 MeV ions from heliosphere
Alcatel time resolution (mins)	1
RAL time resolution (mins)	60
Cadence for service (mins)	5
Cadence for science (mins)	1
Cadence notes	5 minute resolution (as GOES) is fine for solar energetic particles. GOES data indicate timescale for flux changes is around 1 hour.

Req. 10.2	2-100 MeV ions from heliosphere
Alcatel time resolution (mins)	1
RAL time resolution (mins)	30
Cadence for service (mins)	5
Cadence for science (mins)	1
Cadence notes	5 minute resolution (as GOES) is fine for solar energetic particles. GOES data indicate timescale for flux changes is around 1 hour.

Req. 10.3	2-20 MeV electrons from heliosphere
Alcatel time resolution (mins)	1
RAL time resolution (mins)	
Cadence for service (mins)	5
Cadence for science (mins)	1
Cadence notes	5 minute resolution (as GOES) is fine for solar energetic particles. GOES data indicate timescale for flux changes is around 1 hour.

Req. 17.1	High energy electrons in rad belt
Alcatel time resolution (mins)	1
RAL time resolution (mins)	30
Cadence for service (mins)	1
Cadence for science (mins)	1
Cadence notes	Need cadence shorter than drift time around Earth (a few minutes)

Req. 18.1	> 10 MeV protons in rad belt
Alcatel time resolution (mins)	1
RAL time resolution (mins)	30
Cadence for service (mins)	1
Cadence for science (mins)	1
Cadence notes	Need cadence shorter than drift time around Earth (a few minutes)

4.5 Additional measurement requirements

The measurement requirements presented above have been based on analysis of the previous ESA studies that were completed at the end of 2001 (three years before the time of writing). Thus it is appropriate to consider whether any new requirements have emerged in those three years. To explore this, and in particular to focus on European needs, we examined the descriptions of the many service development activities that are participants in ESA's Space Weather Applications Pilot Project and extracted information on the measurements used as inputs to those activities. The descriptions used were those available on, and linked from, the SWPP server (http://www.esa-spaceweather.net/). The results are given in Table 21 in Annex C.

The measurements used by the SDAs include a variety of types including primary data from both spacebased and ground-based instruments, but also secondary data provided by third party processing of primary data. In the present analysis we focus on SDA use of primary data from space-based instruments as this is the area that overlaps with the objectives of this study. We have compared these primary data with the measurement requirements established above and determined that just one new measurement requirement is needed to satisfy SDA use of primary data. This is a requirement to monitor activity occurring on the farside of the Sun in order to locate active regions on the farside and predict when they will rotate into view and thus affect the Earth and its surroundings. Techniques to do this have been developed by two instrument teams on SOHO: (a) by the MDI instrument team [R8] using helioseismology measurements, and (b) by the SWAN instrument team [R13] using measurements of solar Lyman-alpha emissions back-scattered by the interplanetary medium. These farside data can improve the forecasting of solar activity at a lead time of about two weeks (i.e. half a solar rotation), which can be of value for supporting applications related to space weather applications such as spacecraft drag and GIC. Thus we have added a new requirements for (a) helioseismology measurements (as requirement 1.5) with attributes based on the SOHO/MDI instrument [R9], and (b) Lyman-alpha monitoring (as requirement 1.6) with attributes based on the SOHO/SWAN instrument [R13]. Note that, while helioseismology measurements can be made at either of the two locations specified here for solar observations (GEO and Solar-L1), Lyman-alpha monitoring must performed well away from the Earth (i.e. at Solar-L1 not GEO) to reduce contamination by resonant scattering of Lyman-alpha in the Earth's geocorona [R14].

Ongoing work within the Pilot Project (ESA, private communication) has raised the question of whether spacecraft magnetometer data could substitute for current us of ground-based magnetometer data (e.g. see entries in Table 17). This is not pursued in the present study as there are no mature requirements on use of spacecraft magnetometer data in space weather models. Some of the key problems are discussed in Annex F together with thoughts on future work.

This analysis has established a mapping from the SDA data inputs to the measurement requirements established in this study. This is also shown in Table 21.

4.6 Final results

The refinement described above leads to a final set of sub-requirements as shown in Table 7 below.

Table 7. The sub-requirements: time resolution and data rate

Requirement number	Sub-requirement number	Measurement sub-type	Cadence for service (mins)	Cadence for science (mins)	Service data rate (kbps)	Timeliness (mins)
1	1	EUV images of Sun	10	2.5	7	30
1	2	H-alpha images of Sun	10	0.5	6	30
1	3	Soft X-ray images of Sun	10	1	7	5
1	4	Stereo images of Sun-Earth space	60	60	10	360
1	5	Helioseismology	1	1	5	1440
1	6	Lyman-alpha monitoring	1440	1440	0.2	1440
2	1	Coronograph	15	10	33	720
3	1	Solar X-ray flux monitor	5	1	0.04	5
4	1	Solar EUV full disc flux	1440	1440	1	1440
4	2	Solar UV flux	60	60	0.25	60
6	1	Solar radio bursts	60	60	1	720
7	1	Solar magnetograms	15	15	10	720
8	1	Solar wind bulk velocity	1	1	0.1	30
8	2	Solar wind bulk density	1	1	0.1	30
9	1	Heliospheric magnetic field	1	1	0.2	2
10	1	>100 MeV ions from heliosphere	5	1	0.02	5
10	2	2-100 MeV ions from heliosphere	5	1	0.02	5
10	3	2-20 MeV electrons from heliosphere	5	1	0.02	1440
11	1	Auroral UV imaging	60	60	10	5
11	2	Auroral particle precipitation	60	60	2	5
11	3	Auroral visible imaging	60	60	10	5
12	1	Auroral kilometric radiation (AKR)	1	1	2	5
13	1	Magnetospheric magnetic field	1	1	0.2	1440
14	1	In-situ magnetospheric E field	180	180	1.5	5
15	1	1-10 keV electrons in magnetosphere	1	1	2	90

Requirement number	Sub-requirement number	Measurement sub-type	Cadence for service (mins)	Cadence for science (mins)	Service data rate (kbps)	Timeliness (mins)
16	1	10-100 keV electrons in magnetosphere/rad belt	1	1	2	60
17	1	High energy electrons in rad belt	1	1	0.1	5
18	1	> 10 MeV protons in rad belt	1	1	0.1	5
19	1	Dosimetry	5	5	0.1	5
20	1	Total electron content of iono/plasmasphere	5	5	0.1	5
20	2	Electron density of iono/plasmasphere	1	1	1	5
21	1	Plasma velocity in ionosphere	0.1	0.1	1	5
22	1	Neutral density in thermosphere	30	30	1	60
23	1	Neutral wind in thermosphere	30	30	1	60
25	1	Microparticle measurements	1440	1440	0.03	1440

5 Solution levels

5.1 Introduction

The Statement of Work requires that the study addresses three levels of nanosat solutions as described in Table 8 below. So we now map each sub-requirement identified in the previous section to one of the three levels. We do this before considering nanosat options because it is more straightforward to accomplish. Thus we leave the most uncertain part of the analysis (assessing requirements for suitability against nanosat solutions) until the last step. This has the great advantage that changes in the nanosat assessment can easily be traced into updated results – both in the course of the study and by readers after the completion of the study.

Table 8. Three levels of solutions

Solution level 1: Low level solution:	
the minimum measurements required for input to services geared at mitigating space weather effects on spacecraft operations	This is the core solution that will support a basic space weather service for users in space operations
Solution level 2: Medium level solution:	
incorporates all elements of the low level solution plus additional measurements of value for modelling aspects of the geospace environment and data of importance for services geared towards mitigating ground-based space weather effects (as opposed to focusing on spacecraft effects alone)	This is an extended solution that will provide a comprehensive space weather service and also support efforts to develop improved models of the geospace environment (and thus assist the future development of space weather services)
Solution level 3: High level solution:	
incorporates all elements of the low and medium level solution plus other space weather measurements of interest to the scientific community e.g. imaging data	This solution would extend the nanosat problem to address issues where the scientific community has requirements that go beyond those needed for space weather services.

5.2 Assessment against requirement details

We have assessed the sub-requirements against the solution levels by two routes:

- First we made a manual examination of each requirement, assessed it against the criteria above and recorded the selected solution level in the sub-requirements table, together with notes justifying the selected level.
- Second we made a more automated assessment using the database. The sub-requirements are already traced to CSMRs and key parameters, which are in turn traced to the user groups which they serve. The different groups recorded in the database are shown in Table 19. We have associated each group with an appropriate solution level: Level 1 is restricted to satellite operations (including the generic storm prediction group), Level 2 includes all other groups with practical applications, while Level 3 is restricted to research, policy support and outreach. To obtain one automated solution level we have built two queries: one traces each sub-requirement via the CSMRs to a set of user groups and thus solution levels, while the second summarises the first query by finding the minimum solution level for each sub-requirement. Since the definition of solution levels requires that each level includes all higher level, this summary is gives the required solution level. We obtain a second automated process by building analogous queries that trace via the key parameters.

The results of the manual and automated analyses are shown in Table 9 below. You can see that there is a wide measure of agreement. We take the manual solution as the result from this study because this is only one of the three values under control of the present study and thus the only one subject to adjustment in the light of judgements recorded in the study database.

Table 9. Sub-requirements: solution levels

Requirement number	Sub-requirement number	Measurement sub-type	CSMR solution	KP solution	Manual solution
1	1	EUV images of Sun	1	1	1
1	2	H-alpha images		1	1
1	3	Soft X-ray imager	1	1	1
1	4	Stereo images of Sun-Earth space	1		1
1	5	Helioseismology	NA	NA	1
1	6	Lyman-alpha monitoring	NA	NA	1
2	1	Coronagraph	1	1	1
3	1	X-ray flux monitor	1	1	1
4	1	EUV full disc flux	2	1	3
4	2	UV flux	1		1
6	1	Radio bursts	1	1	1
7	1	Solar magnetograms	2	1	1
8	1	Solar wind bulk velocity	1	1	1
8	2	Solar wind bulk density	1	1	1
9	1	magnetic field	1	1	1
10	1	>100 MeV ions	1	1	1
10	2	2-100 MeV ions	1	1	1
10	3	2-20 MeV electrons		1	2
11	1	Auroral UV imaging	1	1	2
11	2	Auroral particle precipitation	1	1	1
11	3	Auroral visible imaging	2	1	2
12	1	AKR	1	1	1
13	1	magnetic field	1	1	2
14	1	In-situ E field	1	1	1
15	1	1-10 keV electrons	1	1	1
16	1	10-100 keV electrons	1	1	1
17	1	High energy electrons	1	1	1
18	1	> 10 MeV protons	1	1	1
19	1	Dosimetry	2		1
20	1	Total electron content	2	1	2
20	2	Electron density	1	1	1
21	1	Plasma velocity	1	1	1
22	1	Neutral density	1	1	1
23	1	Neutral wind	1	1	1
25	1	Microparticle measurements	1		2

5.3 Assessment against cost

Another way to assess the solution levels is by examination of costs. Note that many of the requirements in Table 7 place a higher time resolution on measurements for scientific research (level 3) than on measurements to support space weather services (level 1 and 2). However, we shall not pursue this idea here as analysis of costs is beyond the scope of the requirements phase – and, furthermore, a premature judgement on costs could exclude creative ideas. Instead we flag that analysis of costs, as a criterion for differentiating solution levels, should be revisited later in the study, once it is possible to reliably assess the impact of instrument and nanosat innovation on costs.

6 Nanosat solutions

6.1 Selection criteria for nanosat solutions

A critical issue for this study is to develop criteria for selecting which of the measurement requirements are well-suited for implementation via nanosat solutions. Many of the advantages commonly ascribed to nanosat solutions are generic issues (e.g. reduced launch costs) and thus apply equally to all the requirements. Such advantages clearly apply to a space weather nanosat programme in general, but do not provide a means to distinguish the applicability of nanosats to the specific measurement requirements shown in Table 6.

Thus the aim here is to establish criteria, preferably based on objective data, that allow us to make such distinctions. As previously noted, this is speculative territory and therefore these criteria have been applied as the last step in the study. This has two advantages:

- the previous and more solidly-based results are independent of the nanosat selection criteria
- it should be straightforward to update the nanosat selection in response to changes in criteria

We have established two criteria for nanosat selection that can readily be based on objective data. They are as follows:

- Data rate. As a general rule we need to maintain the instrument data rates shown in the requirement tables (see Table 6). The miniaturisation of instruments can reduce their volume, mass and power consumption, but not at the expense of the information content that is encoded in the data downlinked to Earth. This information (and thus the data rate) is required to satisfy the measurement requirements. Given that a nanosat is likely to have limited downlink resources in terms of power and antenna size, we have used a criterion based on data rate to apply nanosat solutions to the measurement requirements s. Because the different measurement requirements apply at different locations (and some requirements apply at multiple locations), the selection criterion is taken as DR^2 where R is a typical distance from the Earth to the spacecraft. Lower data values of DR^2 imply higher priority for nanosat solutions. In principle we can derive two separate values of DR^2 - one using a data rate derived from the cadence for service and another using a rate derived from the cadence for science. In the rest of this section we focus on the former in order to give priority to service applications. We will later show that the difference between the two data rates does not alter the classification of solutions developed in this section.
- Multiplicity. Some measurement requirements require measurements to be made at multiple locations. In some cases this is just 2, 3 or 4 locations – but other requirements need, or would benefit from, measurements at ten of locations. In addition, multiple instances of a measurement provide in-orbit redundancy and thus serve to address part of service requirement 2 (see Table 3). Nanosats have the potential to facilitate multi-point measurements by reducing the costs of building multiple spacecraft. We therefore give priority to applying nanosat solutions to requirements that involve measurements at multiple locations.

We have considered whether instrument design could also be a selection criterion. There are two issues here. First do any of the measurements impose fundamental physical constraints that would rule out nanosat solutions, e.g. some aspect of the measurement is just too big to fit on a nanosat. Examination of Table 6 reveals just one possible case: requirement 12.1 is to monitor auroral activity by measuring auroral kilometric radiation. Good measurements require an antenna whose extent is greater than the Debye length of the plasma though which the spacecraft is travelling. For our application, this would mean an antenna tens of metres in length (e.g. Cluster measures AKR using a wire antenna 88 metres tip-to-tip). It is unlikely that a nanosat could carry and deploy an antenna of this kind and for this reason we have excluded requirement 12.1 from the final set in section 7. The second issue is the maturity of instrument miniaturisation. There is much activity and creativity in this area so it is difficult to make an objective assessment. Indeed, the progress and value of the present study would be put at risk if one were to exclude requirements (and thus inhibit later assessment of instrument designs) on the basis of perceived maturity of instrument development. For these reasons we have not used maturity as a selection criterion for *requirements*. This does not inhibit use of maturity as a criterion at the later design and recommendations stages of the study or for the setting of implementation priorities.

Finally we consider whether power could be a selection criterion. It is clear that power is a major design constraint on nanosats. If surface-mounted solar arrays are used for power generation, the small size of nanosats will limit the available power to a very few watts (e.g. a nanosat with dimensions of order 10 cm will intercept about 14 watts of sunlight, but this will be reduced down to a few watts after allowing for conversion efficiency and geometric constraints). The available power could be increased by deploying a larger array on a boom but this would have to traded off against the mass of the array and booms, which would be severely limited on a nanosat. Thus it is clear that the available power is low. This is a major constraint on instrument design, especially given the need to prioritise use of power for downlink. However, the high level of creativity in instrument design, already discussed above, suggests that it is difficult and probably undesirable to choose between *requirements* on the basis of power. But it is equally clear that the success of a nanosat programme will require innovative design of instruments to reduce mass and power.

6.2 Results

The values of DR^2 and multiplicity were calculated from the database and used to rank combinations of requirements and the location at which they may be satisfied. The values of R (typical range) are taken as shown in Table 10 below.

Table 10. Measurement locations and ranges

Location[1]	Typical range (km)	Notes
Ionospheric-LEO	5.00E+02	
Molniya	2.00E+04	Variable: a 1000 km at perigee to 39000km at apogee
Plasmasphere	2.00E+04	Variable: a few 100 km at perigee to 19000km at apogee
Rad belt	2.00E+04	Variable: a few 100 km at perigee to 36000km at apogee
Swarm orbit	2.00E+04	Variable: see detailed description in Annex D.
GEO	4.50E+04	
Solar-L1	1.50E+06	
Stereo	1.50E+08	
Upstream	1.50E+06	

The results are shown independently for DR^2 and multiplicity in Figure 2 and Figure 3 in Annex B. To use the two criteria together we generated a scatter plot of DR^2 versus multiplicity as shown in Figure 1 below. The red points indicate the values for the various combinations of requirements and location. The three ovals (coloured blue, green and magenta) indicate three groups of combinations with similar values; we will discuss these groups in more detail below. The yellow and cyan Sun symbol indicates the location of solutions for what we may regard as basic space weather monitoring – namely (a) solar imagery from geosynchronous orbit (yellow) and (b) L1 monitoring of the solar wind and HMF (cyan).

[1] See Annex D for a detailed description of the different orbits or locations.

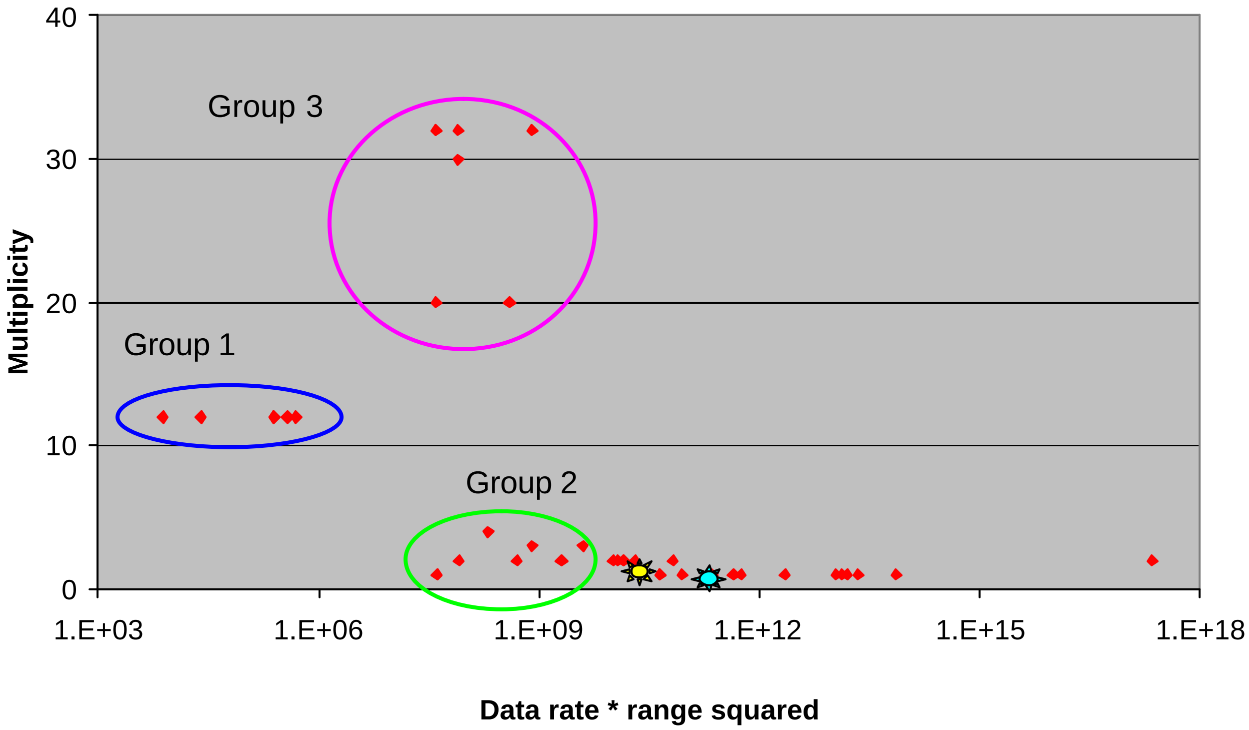

Figure 1. Nanosat combinations ordered by DR² (units=kbps km²) and multiplicity

6.3 Group 1 – low data rate combinations

This group is selected by $DR^2 < 1x10^6$ kbps km^2 and is shown in Table 11 below. Unsurprisingly it is entirely dominated by applications in LEO where a large number of satellites are desirable to ensure global coverage with cadence less than the typical orbit period of 90 minutes.

Table 11. Group 1 - low data rate combinations

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
25	1	Microparticle measurements	Ionospheric-LEO	7.50E+03	12
19	1	Dosimetry	Ionospheric-LEO	2.50E+04	12
20	1	Total electron content of iono/plasmasphere	Ionospheric-LEO	2.50E+04	12
23	1	Neutral wind in thermosphere	Ionospheric-LEO	2.50E+05	12
22	1	Neutral density in thermosphere	Ionospheric-LEO	2.50E+05	12
21	1	Plasma velocity in ionosphere	Ionospheric-LEO	2.50E+05	12
20	2	Electron density of iono/plasmasphere	Ionospheric-LEO	2.50E+05	12
14	1	In-situ magnetospheric E field	Ionospheric-LEO	3.75E+05	12
11	2	Auroral particle precipitation	Ionospheric-LEO	5.00E+05	12

The space weather measurements that can be made from this location are mainly monitoring of the thermosphere-ionosphere system, including auroral inputs at high latitudes. These support applications in areas such navigation, communications, GIC and satellite drag. The group also includes monitoring of direct space weather effects on spacecraft in these orbits through dosimetry and micro-particle impacts.

We note, in passing, that the design of an ionospheric nanosat constellation may draw ideas from the present Taiwan/US Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC) project [R11] which aims to launch six microsatellites into LEO late in 2005 and to use these to study the ionosphere and lower atmosphere by the GPS limb sounding (aka radio occultation) technique.

6.4 Group 2 – medium data rate, low multiplicity

This group is selected by DR^2 between $3x10^7$ and $3x10^9$ kbps km^2 and multiplicity < 12 and is shown in Table 12 below. It contains a number of different types of measurements including:

- Energetic particle measurements and dosimetry in key magnetospheric locations such as the radiation belts and geosynchronous orbit
- Auroral activity monitoring by imaging from polar elliptical orbits
- Measurements of solar radio emissions and total flux at several wavelengths from geosynchronous orbit

Table 12. Group 2 – medium data rate, low multiplicity.

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
10	3	2-20 MeV electrons from heliosphere	GEO	4.05E+07	1
10	2	2-100 MeV ions from heliosphere	GEO	4.05E+07	1
10	1	>100 MeV ions from heliosphere	GEO	4.05E+07	1
25	1	Microparticle measurements	GEO	6.08E+07	4
3	1	Solar X-ray flux monitor	GEO	8.10E+07	2
18	1	> 10 MeV protons in rad belt	GEO	2.03E+08	4
17	1	High energy electrons in rad belt	GEO	2.03E+08	4
19	1	Dosimetry	GEO	2.03E+08	4
4	2	Solar UV flux	GEO	5.06E+08	2
12	1	Auroral kilometric radiation (AKR)	Molniya	8.00E+08	3
6	1	Solar radio bursts	GEO	2.02E+09	2
4	1	Solar EUV full disc flux	GEO	2.02E+09	2
11	3	Auroral visible imaging	Molniya	4.00E+09	3
11	1	Auroral UV imaging	Molniya	4.00E+09	3

The measurements in this group have wide application – particularly in terms of radiation effects on spacecraft. There are also measurements relevant to applications for communications and GIC. The group includes some monitoring of the solar activity that is the driver for so many space weather effects.

6.5 Group 3 – medium data rate, high multiplicity

This group is selected by multiplicity > 15 and is shown in Table 13 below. It reflects the requirement for extensive measurements of key parameters:

- Energetic particle fluxes in the radiation belts – a key issue for spacecraft protection from radiation and charging effects, especially in the outer belt.
- Electron densities in the plasmasphere – an important issue for GNSS signals
- The magnetospheric magnetic field in order to improve magnetospheric magnetic field modelling, which is a major requirement for many space weather applications.

Table 13. Group 3 – medium data rate, high multiplicity

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
25	1	Microparticle measurements	Rad belt	1.20E+07	32
20	1	Total electron content of iono/plasmasphere	Plasmasphere	4.00E+07	20
19	1	Dosimetry	Rad belt	4.00E+07	32
18	1	> 10 MeV protons in rad belt	Rad belt	4.00E+07	32
17	1	High energy electrons in rad belt	Rad belt	4.00E+07	32
13	1	Magnetospheric magnetic field	Swarm orbit	8.00E+07	30
13	1	Magnetospheric magnetic field	Rad belt	8.00E+07	32
20	2	Electron density of iono/plasmasphere	Plasmasphere	4.00E+08	20
16	1	10-100 keV electrons in magnetosphere/rad belt	Rad belt	8.00E+08	32
15	1	1-10 keV electrons in magnetosphere	Rad belt	8.00E+08	32

6.6 Low priority combinations

These are the combinations not in the other three groups, i.e. $DR^2 > 10^{10}$ kbps km^2, and are shown in Table 14 below. It contains many important measurements including:

- Solar imaging from geosynchronous orbit
- Monitoring of solar activity, solar wind and energetic particles at L1
- Stereo monitoring of CME propagation

The low priority given here to these observations is purely a consequence of their need for high data rate (especially for image data) and the relatively large range from the Earth. It does NOT reflect the importance of these observations for very many space weather applications. Thus it will be useful to explore further whether the data rate demand can be mitigated to facilitate nanosat applications, e.g. by reducing cadence, using data compression or relay spacecraft.

Table 14. Low priority combinations

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
1	5	Heliosesimology	GEO	1.01E+10	2
1	2	H-alpha images of Sun	GEO	1.21E+10	2
1	3	Soft X-ray images of Sun	GEO	1.42E+10	2
1	1	EUV images of Sun	GEO	1.42E+10	2
7	1	Solar magnetograms	GEO	2.02E+10	2
10	3	2-20 MeV electrons from heliosphere	Solar-L1	4.50E+10	1
10	1	>100 MeV ions from heliosphere	Solar-L1	4.50E+10	1
10	1	>100 MeV ions from heliosphere	Upstream	4.50E+10	1
10	2	2-100 MeV ions from heliosphere	Upstream	4.50E+10	1
10	3	2-20 MeV electrons from heliosphere	Upstream	4.50E+10	1
10	2	2-100 MeV ions from heliosphere	Solar-L1	4.50E+10	1
2	1	Coronograph	GEO	6.68E+10	2
3	1	Solar X-ray flux monitor	Solar-L1	9.00E+10	1
8	2	Solar wind bulk density	Upstream	2.25E+11	1
8	1	Solar wind bulk velocity	Upstream	2.25E+11	1
9	1	Heliospheric magnetic field	Upstream	4.50E+11	1
1	6	Lyman-alpha monitoring	Solar-L1	4.50E+11	1
4	2	Solar UV flux	Solar-L1	5.63E+11	1
6	1	Solar radio bursts	Solar-L1	2.25E+12	1
4	1	Solar EUV full disc flux	Solar-L1	2.25E+12	1
1	5	Heliosesimology	Solar-L1	1.12E+13	1
1	2	H-alpha images of Sun	Solar-L1	1.35E+13	1
1	1	EUV images of Sun	Solar-L1	1.57E+13	1
1	3	Soft X-ray images of Sun	Solar-L1	1.57E+13	1
7	1	Solar magnetograms	Solar-L1	2.25E+13	1
2	1	Coronograph	Solar-L1	7.43E+13	1
1	4	Stereo images of Sun-Earth space	Stereo	2.25E+17	2

7 Detailed requirements

This section specifies the detailed requirements derived during the course of this study. There is a table block for each of the requirements with fields as follows:

- Requirement reference comprising the high level requirement number and sub-requirement number (as developed in previous sections) separated by a period symbol.
- A concise description of the space weather parameter needed
- Cadence of measurements in minutes
- Spatial coverage in terms of numbers of spacecraft in a particular location or orbit (as specified in Table 10)
- Timeliness – time interval between data acquisition and provision of product to user.
- Notes – providing additional information such as energy or wavelength ranges
- Solution level –the ESA solution level to which this requirement applies (codes as specified in Table 4). Each requirement is given a single solution level, but note that solution level N implies membership of all higher solution levels.
- Nanosat group. The classification of the requirement within the grouping scheme described in the previous section.

Req. 1.1	**EUV images of Sun**
Cadence (mins)	2.5
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	30
Notes	Alcatel: Narrow band EUV (195 and 304 Å) , full Sun, 5” pixels
Solution level	1
Nanosat group	0

Req. 1.2	**H-alpha images of Sun**
Cadence (mins)	0.5
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	30
Notes	Alcatel: Selectable narrow bands around H-a line +/- 2 Å centre, full Sun, 2” pixels. No RAL requirement for H-alpha.
Solution level	1
Nanosat group	0

Req. 1.3	**Soft X-ray images of Sun**
Cadence (mins)	1
Spatial coverage	2 s/c in GEO, or 1 s/c in Solar-L1
Timeliness (mins)	5
Notes	Alcatel: Broad band, full Sun, 5” pixels, pair of filters
Solution level	1
Nanosat group	0

Req. 1.4	**Stereo images of Sun-Earth space**
Cadence (mins)	60
Spatial coverage	2 s/c in Stereo
Timeliness (mins)	360
Notes	RAL-only requirement. Images may be UV or visible light. Take data rate as for coronagraph, but scaled for time resolution.
Solution level	1
Nanosat group	0

Req. 1.5	**Heliosesimology**
Cadence (mins)	1
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	1440
Notes	New measurement requirement not derived from parallel assessment studies but added in present study following analysis of SDA descriptions. Based on SOHO/MDI description - see http://soi.stanford.edu/science/obs_prog.html
Solution level	1
Nanosat group	0

Req. 1.6	**Lyman-alpha monitoring**
Cadence (mins)	1440
Spatial coverage	1 s/c in Solar-L1
Timeliness (mins)	1440
Notes	New measurement requirement not derived from parallel assessment studies but added in present study following analysis of SDA descriptions. Based on SOHO/SWAN description - see ESA SP-1104
Solution level	1
Nanosat group	0

Req. 2.1	**Coronograph**
Cadence (mins)	10
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	720
Notes	Alcatel: 1.5-30 Solar radii, 1024x1024 pixel CCD. Two coronagraphs (inner and outer)
Solution level	1
Nanosat group	0

Req. 3.1	**Solar X-ray flux monitor**
Cadence (mins)	1
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	5
Notes	Alcatel: Wide band flux monitors (SXR GOES-like). RAL: time res, 5min to 1 hr (according to application). Need samples at several wavelengths.
Solution level	1
Nanosat group	2

Req. 4.1	**Solar EUV full disc flux**
Cadence (mins)	1440
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	1440
Notes	Alcatel: Absolute EUV flux (full disc), no time res from Alcatel
Solution level	3
Nanosat group	2

Req. 4.2	**Solar UV flux**
Cadence (mins)	60
Spatial coverage	1 s/c in Solar-L1, or 2 s/c in GEO
Timeliness (mins)	60
Notes	No requirement from Alcatel
Solution level	1
Nanosat group	2

Req. 6.1	**Solar radio bursts**
Cadence (mins)	60
Spatial coverage	2 s/c in GEO, or 1 s/c in Solar-L1
Timeliness (mins)	720
Notes	Alcatel: 30 kHz to 400 MHz. Space-based essential to track bursts far from Sun (frequencies down to 30 kHz).
Solution level	1
Nanosat group	0

Req. 7.1	**Solar magnetograms**
Cadence (mins)	15
Spatial coverage	2 s/c in GEO, or 1 s/c in Solar-L1
Timeliness (mins)	720
Notes	Alcatel: Full Sun, 2” pixels
Solution level	1
Nanosat group	0

Req. 8.1	**Solar wind bulk velocity**
Cadence (mins)	1
Spatial coverage	1 s/c in Upstream
Timeliness (mins)	30
Notes	Data rate is for moments only. Alcatel attributes: 0-40 keV ions and electrons, For ions measure 45° cone with 5 ° resolution, for electrons measure all 4p with 45° resolution
Solution level	1
Nanosat group	0

Req. 8.2	**Solar wind bulk density**
Cadence (mins)	1
Spatial coverage	1 s/c in Upstream
Timeliness (mins)	30
Notes	Data rate is for moments only. Alcatel attributes: 0-40 keV ions and electrons, For ions measure 45° cone with 5 ° resolution, for electrons measure all 4p with 45° resolution
Solution level	1
Nanosat group	0

Req. 9.1	**Heliospheric magnetic field**
Cadence (mins)	1
Spatial coverage	1 s/c in Upstream
Timeliness (mins)	2
Notes	Measure 0-±64nT or 0-±256 nT
Solution level	1
Nanosat group	0

Req. 10.1	**>100 MeV ions from heliosphere**
Cadence (mins)	1
Spatial coverage	1 s/c in Solar-L1, or 1 s/c in GEO
Timeliness (mins)	5
Notes	Need energy spectra
Solution level	2
Nanosat group	2

Req. 10.2	**2-100 MeV ions from heliosphere**
Cadence (mins)	1
Spatial coverage	1 s/c in Solar-L1, or 1 s/c in GEO
Timeliness (mins)	5
Notes	RAL <30 mins time res
Solution level	1
Nanosat group	2

Req. 10.3	**2-20 MeV electrons from heliosphere**
Cadence (mins)	1
Spatial coverage	1 s/c in GEO, or 1 s/c in Upstream
Timeliness (mins)	1440
Notes	No CSMR
Solution level	2
Nanosat group	0

Req. 11.1	**Auroral UV imaging**
Cadence (mins)	60
Spatial coverage	3 s/c in Molniya
Timeliness (mins)	5
Notes	UV, 130-190 nm
Solution level	2
Nanosat group	2

Req. 11.2	**Auroral particle precipitation**
Cadence (mins)	60
Spatial coverage	12 s/c in Ionospheric-LEO
Timeliness (mins)	5
Notes	0-40 keV ions and electrons
Solution level	1
Nanosat group	1

Req. 11.3	**Auroral visible imaging**
Cadence (mins)	60
Spatial coverage	3 s/c in Molniya
Timeliness (mins)	5
Notes	
Solution level	2
Nanosat group	2

Req. 12.1	**Auroral kilometric radiation (AKR)**
Cadence (mins)	1
Spatial coverage	3 s/c in Molniya
Timeliness (mins)	5
Notes	1 Hz-100 kHz, 1 electric antenna
Solution level	1
Nanosat group	2

Req. 13.1	**Magnetospheric magnetic field**
Cadence (mins)	1
Spatial coverage	30 s/c in Swarm orbit, or 32 s/c in Rad belt
Timeliness (mins)	1440
Notes	0-±64, 0-±256 nT, 0-±65536 nT,
Solution level	2
Nanosat group	3

Req. 14.1	**In-situ magnetospheric E field**
Cadence (mins)	180
Spatial coverage	12 s/c in Ionospheric-LEO
Timeliness (mins)	5
Notes	For conventional probe measurements use 3 orthogonal pairs if possible. In long-term Cluster/EDI approach may be better for nanosat approach (no antenna needed).
Solution level	1
Nanosat group	1

Req. 15.1	**1-10 keV electrons in magnetosphere**
Cadence (mins)	1
Spatial coverage	32 s/c in Rad belt
Timeliness (mins)	90
Notes	Need good spectral resolution
Solution level	1
Nanosat group	3

Req. 16.1	**10-100 keV electrons in magnetosphere/rad belt**
Cadence (mins)	1
Spatial coverage	32 s/c in Rad belt
Timeliness (mins)	60
Notes	4p coverage, 45° resolution,
Solution level	1
Nanosat group	3

Req. 17.1	**High energy electrons in rad belt**
Cadence (mins)	1
Spatial coverage	4 s/c in GEO, or 32 s/c in Rad belt
Timeliness (mins)	5
Notes	2-20 MeV
Solution level	1
Nanosat group	3

Req. 18.1	**> 10 MeV protons in rad belt**
Cadence (mins)	1
Spatial coverage	4 s/c in GEO, or 32 s/c in Rad belt
Timeliness (mins)	5
Notes	
Solution level	1
Nanosat group	3

Req. 19.1	**Dosimetry**
Cadence (mins)	5
Spatial coverage	32 s/c in Rad belt, or 4 s/c in GEO
Timeliness (mins)	5
Notes	No requirement from Alcatel
Solution level	1
Nanosat group	2

Req. 20.1	**Total electron content of iono/plasmasphere**
Cadence (mins)	5
Spatial coverage	20 s/c in Plasmasphere, or 12 s/c in Ionospheric-LEO
Timeliness (mins)	5
Notes	Local and global sounding
Solution level	2
Nanosat group	1

Req. 20.2	**Electron density of iono/plasmasphere**
Cadence (mins)	1
Spatial coverage	20 s/c in Plasmasphere, or 12 s/c in Ionospheric-LEO
Timeliness (mins)	5
Notes	
Solution level	1
Nanosat group	1

Req. 21.1	**Plasma velocity in ionosphere**
Cadence (mins)	0.1
Spatial coverage	12 s/c in Ionospheric-LEO
Timeliness (mins)	5
Notes	
Solution level	1
Nanosat group	1

Req. 22.1	**Neutral density in thermosphere**
Cadence (mins)	30
Spatial coverage	12 s/c in Ionospheric-LEO
Timeliness (mins)	60
Notes	
Solution level	1
Nanosat group	1

Req. 23.1	**Neutral wind in thermosphere**
Cadence (mins)	30
Spatial coverage	12 s/c in Ionospheric-LEO
Timeliness (mins)	60
Notes	
Solution level	1
Nanosat group	1

Req. 25.1	**Microparticle measurements**
Cadence (mins)	1440
Spatial coverage	32 s/c in Rad belt, or 4 s/c in GEO
Timeliness (mins)	1440
Notes	
Solution level	2
Nanosat group	2

8 Conclusions

This report describes work done to produce a synthesis of the requirements for space weather measurements developed in the course of previous ESA space weather studies performed in 2000-2001 -namely the two parallel assessment studies led by RAL [R1] and Alcatel [R2] plus the design study performed by the ESTEC Conceptual Design Facility [R3].

The synthesis of a set of service requirements was straightforward. These describe general constraints on all measurements in terms of the need for speed of data delivery, continuity, quality and reliability. They were easily retrieved from the common user requirements used by the RAL- and Alcatel-led studies, supplemented by material from the CDF study and discussion with ESA.

The synthesis of a set of measurements requirements was more difficult. Some experimentation was required to bring RAL and Alcatel data into a common framework. This has now been achieved and provides a firm basis for traceability from the new synthesis back to the requirements established by the prior studies. This includes traceability to attributes of the old requirements and has proved helpful in the further analysis of the synthesised requirements. Some disagreements between the RAL and Alcatel data were identified and resolved by distinguishing the needs of space weather services from those of research on space weather phenomena. This synthesis includes only measurement requirements which must be or can be space-based.

The requirements were compared with the service development activities within ESA's Space Weather Applications Pilot Project. With the addition of one new measurement requirement (helioseismology observations to detect farside sunspot activity), it can be shown that the measurement requirements in this study can satisfy SDA needs for space-based measurements.

The synthesised requirements have been assessed in terms of the three solution levels required by ESA (Table 8). This analysis was greatly aided by the traceability to the previous studies, because those had identified the likely users of their requirements. Thus we could associate the synthesised requirements with potential users reported by the RAL and Alcatel studies as well as an independent manual assessment performed as part of this study. These three results showed a high level of consistency, which builds confidence in the result. This demonstrated that the three levels of solutions are not a useful scheme for distinguishing or prioritising the synthesised requirements because most are associated with the first solution level – namely effects that impact spacecraft operations. In hindsight, this result is not surprising. It reflects the fact that most space-based measurements address phenomena that have either a direct impact on spacecraft or are generic precursors of space weather effects (e.g. monitoring activity on the Sun and in the solar wind). The exclusion of explicitly ground-based measurements excludes many that would be associated with the second solution level (i.e. data for services that mitigate ground-based space weather effects).

The synthesised requirements have also been assessed in terms of priorities for nanosat solutions. The key issue here is the development of objective criteria for setting such priorities. The report is very cautious about using instrument constraints as a criterion because this field is evolving quickly in response to the high creativity shown by instrument developers. We only exclude requirements where the physics of measurement requires large structures unsuitable for nanosats. The one known example is wave measurements, such as AKR, where the plasma Debye length in the magnetosphere mandates large (~100m). antennae for good measurements. Instead this assessment focuses on more objective criteria such as data rate and the number of spacecraft needed to make measurements. The data rate for a measurement must keep its size in order to maintain the needed information content. However, when weighted by the square of the range from Earth, it is a measure of the demand placed on the spacecraft for downlink. In view of the limited capability of nanosats a low value of this criterion indicates greater appropriateness for nanosat solutions. One of the generic advantages of nanosats is the ease of producing multiple copies. Thus requirements that require larger numbers of spacecraft are also considered as more appropriate for nanosat solutions. These two main criteria have allowed us to classify requirements into several groups with different levels of appropriateness. The two highest priority groups are requirements to measure parameters relevant to the thermosphere-ionosphere system from LEO (Group 1) and to make global measurements of key parameters such as radiation belt particle fluxes and the magnetospheric magnetic field (Group 3). At intermediate priority (Group 2) we find requirements to make non-imaging solar measurements from GEO, to monitor radiation belt fluxes in GEO and to image the aurora oval from polar elliptical orbits. The lowest priority group includes most solar and solar wind monitoring. The low priority of this last group may seem strange but just reflects a low appropriateness for nanosat solutions because of higher data rates (solar imagery) or greater range (upstream monitoring at L1).

Finally we present a summary of all requirements appropriate for nanosat solutions tagged with their appropriateness to the solution levels prescribed by ESA (Table 8) and the prioritised groups of nanosat solutions developed in this report. The summary also includes the data requirements prescribed by ESA namely the space weather parameters needed, the cadence of measurements, energy and wavelength ranges, spatial coverage and timeliness.

9 Annex A. Requirements data from the previous studies

9.1 The common user requirements

The table below shows the common user requirements developed during the course of the RAL and Alcatel space weather studies in 2000-2001. Source is Table 4 of the Final Report of the RAL study [R6].

Table 15. The common user requirements.

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)
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)

UR no	User requirement	Timeliness	Potential Users
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

9.2 RAL study: consolidated system measurement requirements

The consolidated system measurement requirements (CSMRs) were developed in the course of the RAL-led study and described in detail in [R4]. The table below summarises the CSMRs and includes thee main changes with respect to the tables in R4:

- CSMR 18 has been removed as it was rendered obsolete in the course of the RAL study. See section 2.5 of [R7].
- Requirements for ground-based measurements have been removed as discussed in section 2.2. The excluded CSMRs are shown in Table 17 below.
- One additional space-based requirement was identified in the course of the RAL study and is appended to the table below; it is given CSMR number 100 in order that it is clearly distinguished from the original CSMRs which have numbers 1 to 75. The origin of this extra CSMR is discussed in R7, section 2.3.3.

Table 16. Space-based CSMRs.

CSMR number	Parameter	Spatial sampling	Temporal sampling
1	Solar EUV / X-ray images	Single point measurement in space	1 hour
2	Solar coronagraph 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
6	Auroral oval, size, location and intensity	Single point measurement	1 hour
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
23	Vsw	Single point measurement in IMF, e.g. at L1 point	1 minute
24	Vsw	Single point measurement at L1	15 minutes
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
33	AE index (alternatively AKR)	Global index	1 minute
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 magnetosphere	1 minute
40	Magnetospheric B-field	Multi-point measurements in magnetosphere	5 minutes
41	Magnetospheric B-field	Multi-point measurements in magnetosphere	< 30 minutes
42	Magnetospheric B-field	Multi-point measurements in magnetosphere	30 minutes
43	Magnetospheric B-field	Multi-point measurements in magnetosphere	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

CSMR number	Parameter	Spatial sampling	Temporal sampling
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 hour
56	>10MeV ions (SPE/SEPE)	Single point measurement in interplanetary space	
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	
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	
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 day
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
100	Solar magnetograph measurements	Single measurement from space or ground	20 mins

Table 17. Ground-based CSMRs

CSMR number	Parameter	Notes
5	Auroral imaging	Explicit ground-based product
7	Auroral equatorward boundary	Explicit ground-based product
14	F10.7	Standard ground-based product under IUGG auspices
15	F10.7	
16	F10.7	
17	F10.7	
19	Secondary neutron flux	Must be measured in lower atmosphere
20	Secondary neutrons (GCR)	
21	Secondary neutrons (GCR)	
22	Secondary neutron flux	
28	Kp	Must be measured below ionospheric current layer, also standard ground-based product under IUGG auspices
29	Kp*	
30	Ap	
31	Dst	
32	Dst*	
34	SSN	Standard ground-based product under IUGG auspices
35	SSN	
44	Terrestrial B-field (hence dB/dt)	Explicit ground-based product
45	Interplanetary radio scintillation	Explicit ground-based product
46	f0F2 from ionosonde (also E1 and F1)	Explicit ground-based product, also foE and foF1 must be measured from below 100 km.
47	f0F2 from ionosonde	

9.3 Alcatel study: key parameters for space-based monitoring

The key parameters (KPs) were developed in the course of the Alcatel-led study and described in detail in [R5]. The table below summarises these key parameters. To ensure traceability of the KPs within the present study they have been assigned numerical parameter codes as shown below.

Table 18. Key parameters.

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

9.4 User groups for space weather applications

The table below shows the user groups used in the present study. These are derived from the previous studies. The groups with source R are derived from the RAL-led study [R4] and preserve the group codes from [R4]. The groups with source A have been added to cover the full range of groups covered by the Alcatel study [R5] (but note that the Alcatel study also covers many of same groups as the RAL study). To ensure traceability, the groups with source A have been assigned their own distinct group codes.

The solution level shows how we have mapped each user group to the three solution levels required in the Statement of Work [A1] and described in Table 8.

Table 19. User groups.

Group code	Group description	Group source	Solution level
A	Airlines and air safety organisations	R	2
B	Electric power transmission organisations (also pipeline operators and railways and telephone companies)	R	2
C	Geological prospectors	R	2
D	Drilling industry	R	2
E	Military (target detection and tracking)	R	2
F	RF systems (civil and military)	R	2
G	GNSS location systems and radar systems (civil and military)	R	2
H	Satellite operators (civil and military)	R	1
I	Insurance and financial services (for satellite operations)	R	1
J	Tourism	R	2
K	Space Agencies	R	2
L	Launch providers	R	2
O	Outreach	A	3
P	Policy (e.g. climate change)	A	3
R	Research	A	3
S	Storm predictors	A	1

9.5 CDF study instruments

Table 20 below shows how the space weather instruments discussed in the CDF study [R3] are be related to the detailed requirements produced in the present study. This takes account of both the nature of the instruments and the locations at which they would operate.

Table 20. CDF instruments

Name	Mission and Main Objective	Instruments	Requirement
IMM	Inner Magnetospheric Monitor - to provide near-real-time monitoring of Earth's magnetic field and particles	Thermal Plasma Monitor (TPM)	15.1, 20.1
		Mid-Energy particle Monitor (MEM)	16.1
		High-Energy particle Monitor (HEM)	17.1, 18.1
		Magnetometer (MAG)	13.1
		Waves Instrument (WAVE)	12.1
		GPS Receiver Ionospheric Sounder (GRIS)	20.1
SWM	Solar Wind Monitor - to provide near-real-time monitoring of the solar wind upstream from Earth	Thermal Plasma Monitor (TPM)	8.1, 8.2
		Mid-Energy particle Monitor (MEM)	10.3
		Magnetometer (MAG)	9.1
		Coil Radio Spectrograph (CRS)	6.1
SAM	Solar Activity Monitor - to provide near-real-time monitoring of the solar disc (for solar flare detection) and corona	White Light Coronagraph (WLC)	2.1
		Extreme UltraViolet Imager (EUVI)	1.1
		X-Ray Photometer (XRP)	3.1
		Cosmic Ray Monitor (CRM)	10.1, 10.2

10 Annex B - Nanosat selection criteria

The figures on the following pages show the ordering of the measurement requirements in terms of different selection criteria as discussed in section 6.1:

- Data rate. The instrument data rate multiplied by the square of the typical range – which gives an estimate of the demand that the instrument will place on the spacecraft in terms of data downlink.
- Multiplicity. The minimum number of sensor locations (= separate spacecraft) needed to make the measurements.

Both these criteria require knowledge of the measurement location, so we actually order combinations of the measurement requirement and the location (as shown on the left of each figure). Some measurement requirements may be satisfied in more than one location – and thus have multiple entries in the priority lists. This allows us to assess the relative merits of the different locations.

The horizontal bars show the size of the selection criterion for each combination. The combinations are ordered with best case at the bottom of the diagram and worst case at the top.

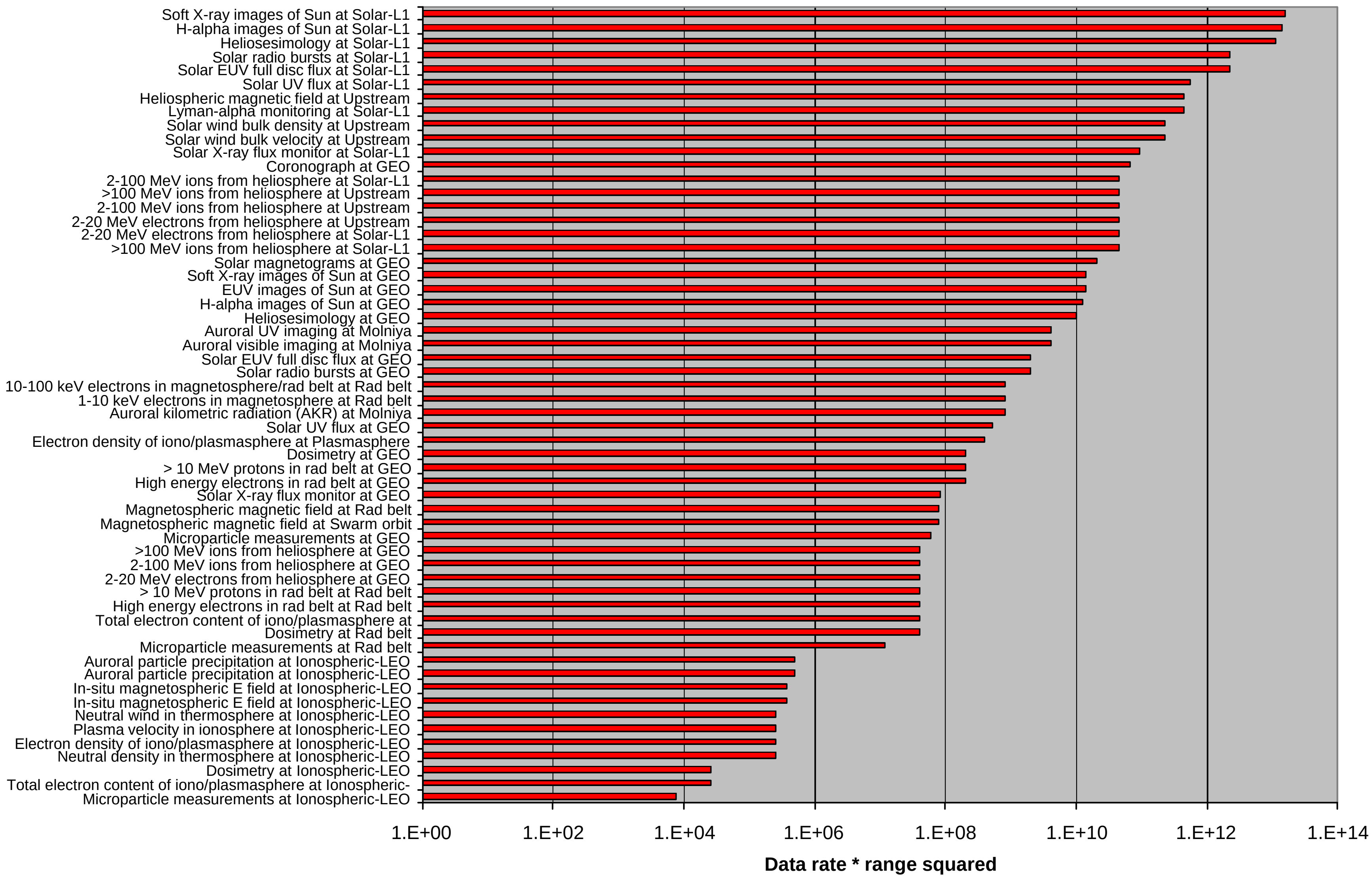

Figure 2. Requirements ordered by data rate criterion

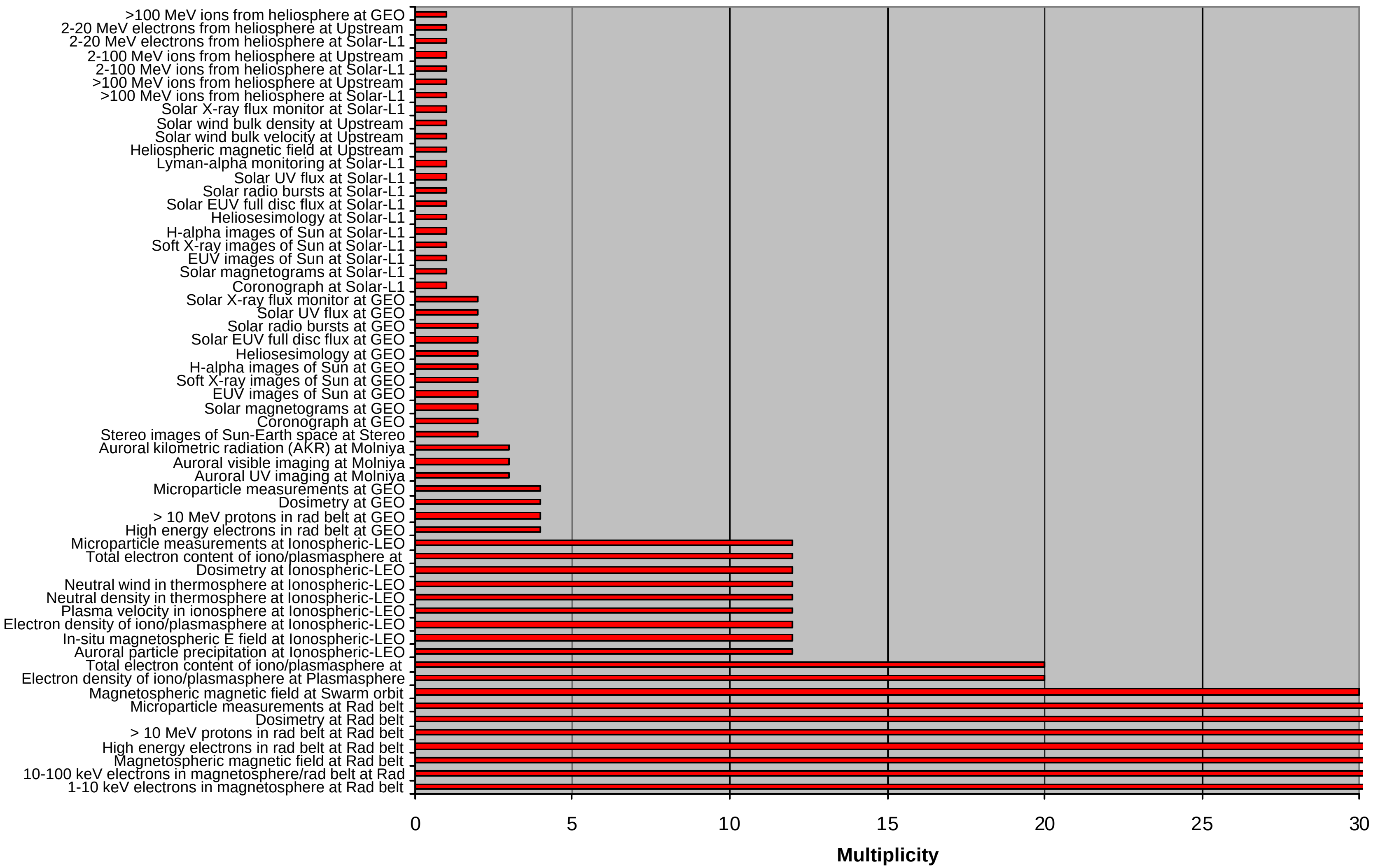

Figure 3. Requirements ordered by multiplicity criterion

11 Annex C. Measurements used by Service Development Activities

The table below lists the Service Development Activities that form part of ESA's Space Weather Applications Pilot Project. For each SDA we provide:

- The acronym, title and name of the service operator
- A short description of the measurements used by that service as deduced from analysis of the SDA description available on, and linked from, SWENET web site (http://www.esa-spaceweather.net/).
- The ids of the measurement requirements (from Table 7) that will provide measurement types used by the SDA. This field is left blank where the SDA does not use space-based data, e.g. many SDAs used only ground-based (GB) data.

Table 21. SDA inputs and the measurement requirements

Acronym	**Full title**	**Operator**	**Measurements used**	**Measurement requirements**
Auroras Now!	Auroras Now!	FMI (Fin)	Uses GB data (MIRACLE)	
BINCAST	F10.7, DRX (Lerwick), sunspot number (SSN) and Geomagnetic Activity Forecast (Ap) Real Time Monitoring of Global Magnetic Activity: the Ap(est) index *	BGS (UK)	Uses GB data plus "conditions on the Sun and in interplanetary space"	1.1, 1.2, 1.3, 2.1, 8.1, 8.2, 9.1
CORRENG	Space Weather Service for Pipeline Operations *	NRCan (Cdn)	ACE data, solar observations (active regions, coronal holes, flares, filaments, CMEs)	1.1, 1.2, 1.3, 2.1, 8.1, 8.2, 9.1
DIFS	Daily Ionospheric Forecasting Service	BAE Systems (UK)	Data inputs unclear; "plethora of available data sources"	

Acronym	Full title	Operator	Measurements used	Measurement requirements
GAFS	Geomagnetic Activity Forecast - A Service for Prospectors and Surveyors	DMI (Dk)	remote sensing of the sun and solar corona data sources: SOHO spacecraft and ground-based solar observatories in-situ sensing of the solar wind and interplanetary magnetic field data sources: ACE and SOHO spacecraft in-situ sensing of solar X-ray and energetic proton flux in the magnetosphere data sources: GOES satellites in-situ sensing of the magnetic variations at ground level data sources: DMI ground-based magnetometers	1.1, 1.2, 1.3, 2.1, 3.1, 8.1, 8.2, 9.1, 10.2
Gasum Now!	Gasum Now!	FMI (Fin)	GB data	
GEISHA	Geosynchronous Environment for Identification of Satellite Hit Anomalies	ONERA (F)	GEO medium/high energy particle (e-) data (GOES/LANL)	16.1, 17.1
GIC Forecast	Real Time Forecast Service for Geomagnetically Induced Currents	IRF Lund (Swe)	ACE (but flags SOHO/MDI for spots on far side)	1.5, 8.1, 8.2, 9.1
GIC Simulator	Real-Time GIC Simulator	NRCan (Cdn)	GB data	
GIFINT	Geomagnetic Indices Forecasting and Ionospheric Nowcasting Tools	IFSI (I)	ACE, GB data	8.1, 8.2, 9.1
GPS Validation	Validation of Near-Real-Time GPS Occultation Data Products for Meteorological Services	DMI (Dk)	GPS occultation data from s/c	
Ionosfera	Ionosfera	AMSAT Italia (I)	Uses third party predictions of classic indices, not primary data	
ISGI	International Service of Geomagnetic Indices *	CETP (F)	GB data	
SAAPS	Spacecraft Anomaly Analysis and Prediction System *	IRF Lund (Swe)	ACE mag/swe, GOES xray & part (p+,e-), LANL e-, OMNI	3.1, 8.1, 8.2, 9.1, 10.2, 16.1, 17.1

Acronym	Full title	Operator	Measurements used	Measurement requirements
Scintillation quickmaps	Quickmaps and History of the Effects of Ionospheric Scintillations on GPS/GLONASS Signals	CLS (F)	GB GPS data	
SEIS	Space Environment and Information System *	Uninova (P)	SEC (GOES/ACE), SOHO/Celias+Lasco, irradiance data	2.1, 3.1, 4.1, 4.2, 8.1, 8.2, 9.1, 10.2, 17.1
SFC	Daily Solar Activity Parameter Calculation and Forecast *	CLS (F)	SOHO, ACE, GB data (uses solar farside monitoring by SOHO/SWAN to improve 10.7 cm predictions)	1.1, 1.2, 1.3, 2.1, 8.1, 8.2, 9.1
SHAFT	A Pilot Space Weather Service Employing the Spacecraft Hazard and Anomaly Forecasting Tool	QinetiQ (UK)	GEO medium/high energy e- data (GOES)	16.1, 17.1
SIDC	Solar Influences Data Centre	SIDC, Royal Obs. Belgium (B)	SOHO, ACE, GOES, GB data	1.1, 1.2, 1.3, 2.1, 3.1, 8.1, 8.2, 9.1
SOARS	Space Weather Operational Airline Risks Service	MSSL-UCL (UK)	Data inputs unclear	
SPECTRE	Operational Distribution Service of 2D TEC maps over Europe for Natural Hazard Studies	Noveltis (F)	GB GPS data	
STIF	Short Term Ionospheric Forecasting Facilities for Radio Communications Unit *	CLRC - RAL (UK)	GB ionospheric data, ACE	8.1, 8.2, 9.1
SWIMIC	Solar Wind Monitoring and Induction Modelling for GICs	BGS (UK)	ACE	8.1, 8.2, 9.1
SWIPPA	Space Weather Impact on Precise Positioning Applictions of GNSS	DLR (D)	GB ionospheric & magnetic data, ACE	8.1, 8.2, 9.1
TSRS	Radio Surveillance of the Solar Corona for Communication Service Providers	INAF - OAT (I)	GB radio obs of Sun	

12 Annex D. Orbits and multiplicity of space weather monitors

The measurement requirements specified in Table 7 are associated with one or more orbits from which the measurements may be made and a multiplicity value for each orbit, i.e. how many separate measurements are required in that orbit. The orbits, and associated multiplicity values, are shown in Table 22 below. Note that the GEO orbit has several multiplicity solutions and these are shown as separate records in the table. The table also provides a rationale for the choice of multiplicity and an indication of how performance will respond to changes in the multiplicity. A descope type of Observation indicates that loss of a spacecraft will lead to loss of data coverage (as there will be times when no spacecraft is available to make an observation). In contrast a descope type of Resolution indicates that loss of a spacecraft will just lead coarser resolutuion.

Table 22. Orbits and multiplicity of space weather monitor

Location	Description	Multiplicity	Descope type	Rationale
Ionospheric-LEO	Low earth orbit suitable for ionospheric and thermospheric observations, both in-situ and remote-sensing	12	Resolution	Use two orbits separated by 90 degrees in right ascension to sample four local times (one LEO samples two local times). Use 6 spacecraft per orbit to obtain a time separation of 15 minutes which is standard time for ionospheric sampling. Increasing or decreasing numbers will improve or degrade resolution. An increase to 18 spacecraft per orbit (multiplicity of 36) will allow better resolution of dynamical phenomena such as acoustic gravity waves (e.g. as generated by auroral activity).
Molniya	High inclination elliptical orbit (1470 x 38900km, 63.4°). This orbit is suitable for remote-sensing observations of the polar ionosphere and thermosphere. The orbit period of 12h facilitates ground station coverage. This orbit is relatively stable against luni-solar perturbations.	3	Observation	To ensure that one spacecraft is always near apogee to make observations. Increasing numbers just improve redundancy. Decreasing numbers will add risk of missing observations.

Location	Description	Multiplicity	Descope type	Rationale
Rad belt	GTO-like orbit for in-situ observations of the radiation belts over a range of L value	32	Resolution	This multiplicity gives a resolution of 6 hours in MLT and 1 in L value - see detailed analysis in Annex E below. Increasing or decreasing numbers will improve or degrade resolution.
Plasmasphere	Ecliptic orbit with apogee at 4 Re near equator, suitable for in-situ and remote sensing observations of the plasmasphere	20	Resolution	This multiplicity gives a resolution of 6 hours in MLT and 1 in L – based on adaptation of radiation belt analysis in Annex E to orbit with 4 Re apogee. Increasing or decreasing numbers will improve or degrade resolution.
Swarm orbit	Set of orbits for global study of magnetosphere as in SWARM proposal by Schwartz et al [R10]	30	Resolution	The SWARM orbit is a set of orbits designed to explore the Earth's magnetosphere. It comprises a set of five highly elliptical orbits with apogee in the range 15 to 20 Re and perigee just above the atmosphere. Four of the orbits lie in the equatorial plane and are equally spaced in local time (thus giving 6 hours resolution in local time). The fifth orbit is highly inclined thus giving access to high latitudes. There would be six spacecraft spaced around each orbit to give resolution over a range of geocentric distances. And hence a total of 30 satellites. For more information, see web page on [R10] and documents available from that link.
GEO	Solar observations from geosynchronous orbit	2	Observation	2 spacecraft needed to ensure continuous visibility of Sun during equinoctial eclipse season. Descope will lead to loss of observations.
GEO	Radiation belt observations from geosynchronous orbit	4	Resolution	4 spacecraft will gives a resolution of 6 hours in MLT. Increasing or decreasing numbers will improve or degrade resolution
GEO	Heliospheric energetic particle observations from geosynchronous orbit	1	Observation	Only one sampling point required as energetic particles can penetrate all parts of GEO orbit. Descope will lead to loss of observations.
Solar-L1	Solar observations from L1	1	Observation	Only one sampling point required as L1 provides continuous view of Sun. Descope will lead to loss of observations.
Stereo	Observations of heliospheric phenomena between Sun and Earth – viewed away from Sun-Earth line	2	Observation	Two sampling points required for stereo view. Descope will lead to loss of observations.
Upstream	In-situ solar wind and HMF observations from L1	1	Observation	Only one sampling point required as L1 provides access to solar wind. Descope will lead to loss of observations.

13 Annex E. Multiplicity of radiation belt measurements

The number of spacecraft required to monitor the radiation belts has been analysed in some detail as part of this study so that: (a) we can explore the possibility of deploying large numbers of nanosats for radiation belt monitoring and research, and (b) we can understand how we could adjust the ideal situation to match funding opportunities.

The number of spacecraft used for this task is determined by the required resolution of monitoring in terms of magnetic local time and McIlwain L value. Our aim is to quantify this relationship. We assume that the monitoring will by done from a geosynchronous transfer orbit (GTO) as in the previous studies [R1, R2, R3]. For purpose of modelling we take GTO as 600 by 35700 lm altitude. The resolution in local time is then set by using a number of different GTO orbits separated in right ascension, as discussed in previous studies. If we have M such orbits spread equally around all 360 degrees of right ascension, the local time resolution is 24/M hours. We propose to use M=4 to get a resolution of 6 hours. Other values will improve or degrade resolution as M is increased or decreased.[2]

The resolution in L value is complex. We have modelled this by assuming that (a) we have N spacecraft spread evenly in time around each GTO orbit and (b) the orbit is close to the equatorial plane. We also assume a dipole geomagnetic field (a good assumption for L>4), so that for our equatorial orbit we can take the L value to be equal to the geocentric distance in Earth radii. We then set up a simple Kelperian model of the spacecraft orbits around the Earth and determine the time variation of L value for each spacecraft over a single orbital period (10.6 hours). The result for N=8 is shown in Figure 4 below. (Note: the small kinks in some orbit curves are artefacts arising from use of a simple two-stage solution to Kepler's equation.)

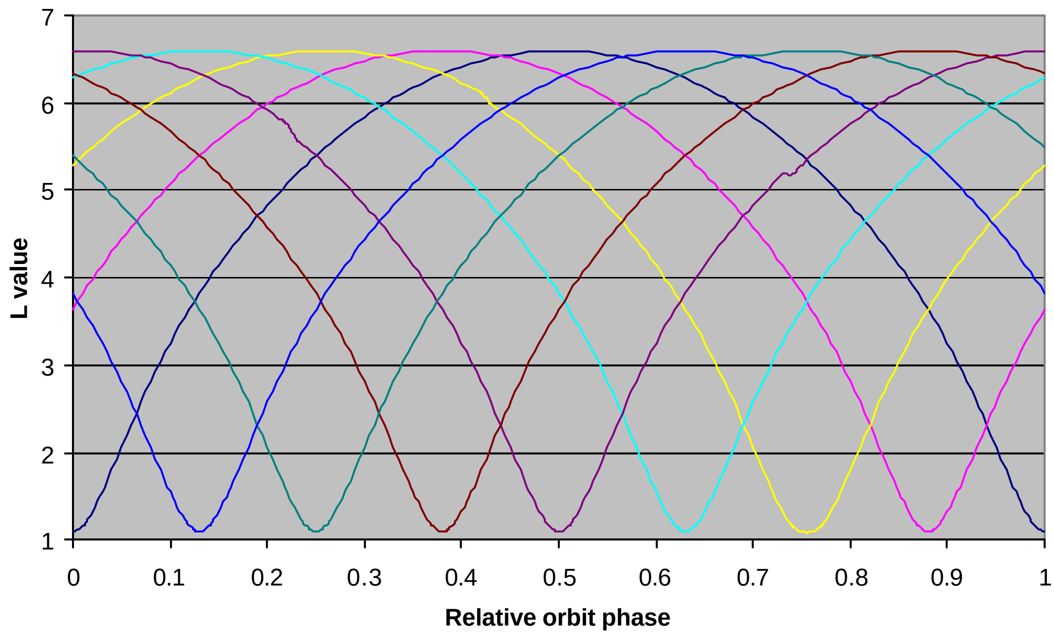

Figure 4. L values for 8 radiation belt monitors spread evenly around GTO orbit

This figure shows eight overlapping orbits with each spacecraft sampling different L-values at different times. The next step is to convert this plot into a form which shows the resulting resolution in L-value. At each time step, we rank the spacecraft in order of increasing L value. We then plot the time variation of L

[2] This assumes that it is possible to launch into GTO orbits with their lines of apsides distributed in right ascension. This requires further work, beyond the scope of present study, but we note that the normal launch configuration is to enter an orbit with apogee towards the Sun. Thus a range of right ascension could be achieved by launches at different seasons.

value for each rank, i.e. the identity of the spacecraft changes when the ranking changes. The result is shown in Figure 5 below. Note how the curves in Figure 5 can join up to demonstrate their derivation from Figure 4.

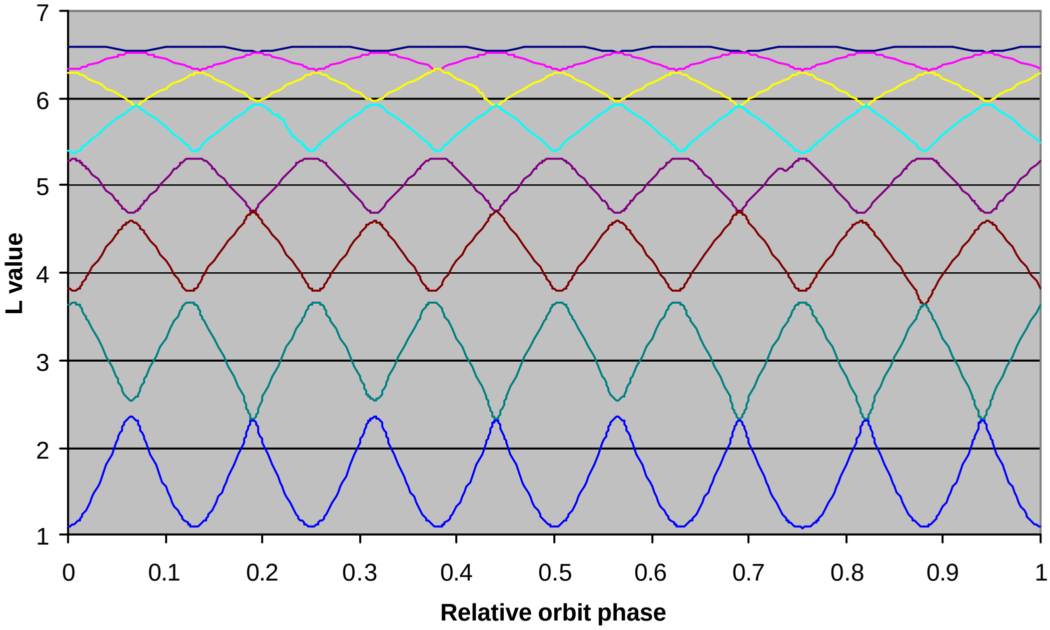

Figure 5. Radiation belt monitors in GTO ranked by L value

The great advantage of Figure 5 is that the ranking gives us a clear sequence of measurements across the full range of L values. Each ranked position spans a well-defined sub-range, e.g. L=2.6 to 3.6 for the second ranked position. The temporal changes of spacecraft identity for each sub-range is a simple operational matter and will not concern us further here. The example shown (N=8) has been chosen as our preferred solution as it gives a resolution of about 1 in L value. Other solutions will simply degrade or improve this resolution as the number of spacecraft is decreased or increased.

Note that our N=8 solution has two outer positions that do not contribute significantly to L value resolution. This is a simple consequence of Kelperian orbits; the spacecraft near apogee will be close-spaced and contribute little to the resolution. The resolution is set by the spacecraft distribution away from apogee. Thus the number of spacecraft needed is greater (say 30%) than the number of L value sub-ranges to be resolved.

Thus we must accept that each spacecraft will have a period around apogee when its measurements are of limited value. During the design phase, it may be worth considering whether to stop data-taking and downlink during this period in order to reduce power consumption and data volume downlinked.

14 Annex F – Use of spacecraft magnetometer data for index generation

Geomagnetic indices play a critical role in many space weather applications by providing a quantitative estimate of the state of the magnetosphere. The indices used for this purpose are those established over the past 60-70 years, e.g. the mid-latitude indices Ap/Kp and aa, the equatorial index Dst and the auroral electrojet index AE. These are all derived from analysis of ground-based magnetometer data drawn from networks at the appropriate latitudes. The coverage of those networks is not ideal but rather has evolved historically in response to the availability of land on which to place magnetometers and the scientific capability and interest of different countries to operate magnetometers. These technical factors are then vulnerable to economic and political considerations.

Despite these deficiencies the ground-based indices lie at the heart of much space weather modelling. The reasons are straightforward:

1. The ground-based indices are readily available. Their statistical properties and limitations are well understood. There is now a reasonable understanding of their relationship to magnetospheric and ionospheric current systems.
2. There is a huge body of research knowledge that characterises space weather in terms of these indices.

Ongoing work within the Space Weather Applications Pilot Project (ESA, private communication) has raised the question of whether it would be better for space weather applications to use geomagnetic indices derived from spacecraft magnetometers. This offers the advantage of being able to design coverage without the topographic and political constraints inherent in ground-based systems and thus has the potential to obtain more consistent data. However, the requirements for such measurements are poorly understood. A key issue here is that space-based magnetometers will usually pass inside the current circuits of magnetospheric and ionospheric current systems and thus obtain a very different view that obtained by ground-based magnetometers, which necessarily sit outside those current circuits.

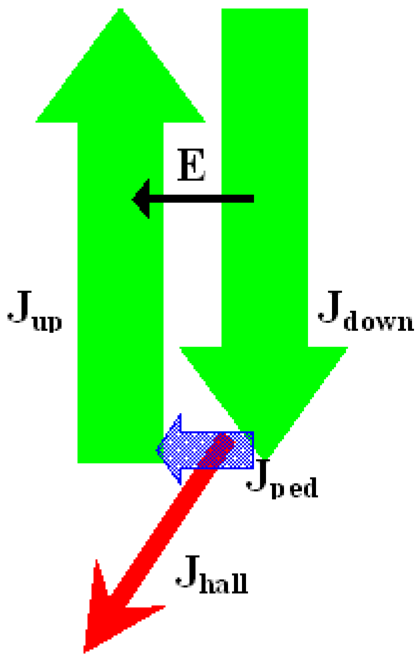

Figure 6. Auroral zone current systems

This is illustrated in Figure 6 above. This shows the typical configuration of currents in the auroral zone, which is a major site of space weather activity. There are two field-aligned (Birkeland) current systems slightly separated in latitude (J_{up} and J_{down}). These currents link the auroral ionosphere to the magnetosphere. The upward current corresponds to downward electron flow and thus is the site of intense electron precipitation into the atmosphere. The two current sheets are linked by a horizontal meridional current flowing in the conductive region of the ionosphere (100-150 km), where the electrons can move freely into response to electric fields but ion motion is inhibited by ion-neutral collisions. This linking current usually flows parallel to the electric field imposed by the magnetosphere and is thus a Pedersen current (J_{ped}). But given the presence of the geomagnetic field, there is also a Hall current flowing perpendicular to the electric (J_{hall}). The relative orientation of these currents depends on the magnetic field orientation (down in northern hemisphere, up in the southern hemisphere) and the local time (e.g. in the evening sector J_{up} is poleward of J_{down} in the evening sector and J_{hall} flows east; in the morning sector these are all reversed).

How are these current systems viewed by ground-based and space-based magnetometers? The main set of field-aligned and meridional currents (J_{up}, J_{down}, and J_{ped}) form a solenoidal current system whose magnetic field will be confined largely inside the current circuit. As a result an LEO spacecraft passing through the field-aligned currents will see a east-west magnetic perturbation (e.g. see Figure 5.55 of [R12]) but a ground-based magnetometer will not see any significant part of this field. All that the ground-based magnetometer sees is the field from the Hall current (the auroral electrojet), which appears as a north-south magnetic perturbation, traditionally termed a "magnetic bay" (e.g. see figure 8.27 of [R12]).

The key conclusion is that ground-based and space-based magnetometers can have very different responses to magnetospheric and ionospheric current systems. Thus the use of space-based magnetometer data as a substitute for ground-based data is not at all straightforward. Significant work is needed to explore how space-based magnetometer data could address the space weather measurement requirements currently covered by ground-based data. There are several possible approaches:

- To establish relationships between ground-based and space-based geomagnetic data such that existing models inputs could be generated from space-based data.
- To re-characterise space weather models in terms of space-based geomagnetic data. This is a major undertaking but would offer the opportunity to develop new geomagnetic indices firmly based on our modern understanding of magnetospheric physics.

In summary, a space-based magnetometer network has the potential to provide a more consistent set of geomagnetic data but significant work is needed to understand how space-based data could address the requirements on inputs for space weather models. Space-based data is not a simple substitute for ground-based data.