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Nano Satellite Beacons for Space Weather Monitoring
WP 110. Analyse effects and requirements

Refinement of Requirements for Nano Satellite Beacons for Space Weather Monitoring

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TABLE OF CONTENTS

1 INTRODUCTION

1.1 Document change record

Issue	Date	Notes/remarks
Issue 0.1	02 Mar 2005	First issue
Issue 1.0	06 Apr 2005	Version for review by ESA
Issue 1.1	04 Jul 2005	• Section 3. Corrected data rate for refined solar imagery reqs 1.1, 1.2 & 1.3 as discussed at PM#3. • Section 3.1. Excluded requirement 6.1 for solar radio bursts as analysis shows antenna size too big for nanosats. • New section 5. Most requirements to measure fluxes of energetic particles constrained to high fluxes. • Changes above reflected in rest of document: e.g. Figure 1, Table 4, Table 5 and section 9.
Issue 1.2	05 Sep 2005	New section 5 added to record changes to requirements for upper atmosphere measurements. Subsequent section numbers incremented by one.
Issue 1.3	01 Oct 2005	Update section 5 to discuss auroral observations – focus on UV observations (req 11.1) and drop visible observations (req 11.3).

1.2 Purpose of Document

A set of requirements for space weather monitoring by nanosats [R1] have been established as part of the study of Nano Satellite Beacons for Space Weather Monitoring under ESTEC Contract No. 18474/04/NL/LvH. This document describes the refinement of those requirements in response to new ideas developed at a study team “Solutions Workshop” held at ESTEC on 7-11 February 2005.

1.3 Definitions, Acronyms and Abbreviations

AKR	Auroral Kilometric Radiation
ASPERA	Analyzer of Space Plasma and Energetic Atoms
CCD	Charged-coupled device
CCLRC	Council of the Central Laboratory of the Research Councils
CME	Coronal mass ejection
CRC	Corporate Research Centre
ENA	Energetic Neutral Atoms
ESA	European Space Agency
ESTEC	European Space Technology Centre
EUV	Extreme ultra-violet
GEO	Geosynchronous orbit
GPS	Global positioning system
GTO	Geosynchronous transfer orbit
HMF	Heliospheric magnetic field
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IRF	Swedish Institute of Space Physics
L1	Lagrangian point 1
LEO	Low Earth orbit

MIDI	Michelson Doppler Imager
MLT	Magnetic Local Time
MNT	Micro- and nano-technology
NUADU	Neutral Atom Detection Unit
RAL	Rutherford Appleton Laboratory
SOHO	Solar and Heliospheric Observatory
SW	Space Weather
SWARM	Space Weather Advanced Research Mission
TBC	To be confirmed
TBD	To be defined
TRACE	Transition Region and Coronal Explorer
UV	Ultra-violet

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
A4	Minutes from Negotiation Teleconference, 23/09/2004, SWNS-RAL-MN-0001

1.4.2 Reference documents

R1	Space weather effects and requirements analysis for space weather monitoring by nanosats, SWNS-RAL-TN-0001
R2	The Michelson Doppler Imager, http://soi.stanford.edu/
R3	European Space Weather Programme System Requirements Definition, ESWP-DER-SR-0001, available via http://www.wdc.rl.ac.uk/SWstudy/
R4	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
R5	Welcome to WAVES, The Radio and Plasma Wave Investigation on the WIND Spacecraft http://lep694.gsfc.nasa.gov/waves/waves.html
R6	STEREO/SWAVES home page, http://www-lep.gsfc.nasa.gov/swaves/swaves.html
R7	http://sec.noaa.gov/alerts/description.html#proton
R8	http://sec.noaa.gov/alerts/description.html#electron
R9	SPEE report, see http://www.ava.fmi.fi/spee/
R10	UCL Fabry-Perot programme, http://www.apl.ucl.ac.uk/research/earth_observation/FPI_Intro.html
R11	TIMED Doppler Interferometer (TIDI), http://tidi.engin.umich.edu/
R12	TIMED (Thermosphere Ionosphere Mesosphere Energetics and Dynamics) mission, http://stp.gsfc.nasa.gov/missions/timed/timed.htm

1.5 Overview of Document

Section 2 outlines the general principles that drive the refinement of requirements described in this document. These principles are applied to solar observations in section 3 and used to drive some major refinements. In section 4 we note how the requirements for radiation belt monitoring and in-situ monitoring of the plasmasphere can be combined into a single constellation and in section 5 we refine the requirements for upper atmosphere measurements. In section 6 we discuss how many of the requirements for measurements of energetic particles can be focussed on high fluxes. In section 7 we outline autonomy requirements for different constellations. In section 8 we summarise how the refinements were added to the database developed in the initial analysis. In section 9 we use the updated analysis to re-visit the nanosat solutions analysis performed in [R1] and show how the refinements change those groups in several significant ways, e.g. the inclusion of solar observations for flare location in the LEO group, the emergence of a well-focussed group of requirements for monitoring at L1. Finally section 10 summarises the conclusions of this work.

Annex A presents an updated table describing the different orbits that may be used for space weather monitoring by nanosats. These include the Solar-LEO orbit identified in the course of the refinement process.

2 Introduction

A set of service and measurement requirements for space weather monitoring by nanosats [R1] has been established as part of the present study. These requirements were a major input for a study team solutions workshop held at ESTEC in February 2005. That workshop generated some important ideas that have allowed us to refine the measurement requirements to better support the development of instrument and spacecraft solutions. The purpose of this note is to describe that refinement.

The key refinement issues are:

- It is very valuable to consider conversion of space weather measurements into useful parameters by processing on-board the spacecraft making the measurements. This approach has the potential to reduce data rates dramatically because we can use scientific knowledge to extract the minimum set of useful information. Thus we can always match, and often outperform, generic data compression techniques. This reduction could be highly advantageous for space weather operations because those operations need rapid and near-continuous downlink of useful information. However, we must note that data reduced on-board will be of limited use for science, as that generally requires access to the raw measurements. Thus this issue may be a basis for distinguishing the level 1 and 3 options described in the Statement of Work [A1]. Note also that downlink of raw data for science can be separated in time since science data does not require such urgent downlink; some or all raw data could be buffered on-board and downlinked when the spacecraft has high-speed access to a ground station.

- A holistic approach is important when developing space weather payloads. The combination of data from several sensors on the same spacecraft, when processed on-board, could be very valuable. For example on-board processing could combine data from solar flux measurements to detect flares with data from a solar imager to locate it. On-board processing could generate, and downlink, a flux value, a flare status flag (flare on, no flare) and a location code for the flare (null if no flare).

- It is important to explore how we can optimise instrument characteristics to suit the needs of space weather applications and not simply aim at the high performance associated with high-quality scientific research.

3 Solar observations

The existing measurement requirements [R1] focus solar observations on geosynchronous orbit or the L1 Lagrangian point. These offer advantages of good solar visibility (continuous at L1, small breaks for equinoctial eclipses in GEO) and good ground station visibility (a single station will suffice for GEO and three or four spread in longitude for L1). However these orbits have the disadvantage of greater range from the Earth so that it is more difficult to support the required data rates, especially the higher rates needed for imaging observations.

For scientific observations of the Sun, a third orbit is often used. This is the sun-synchronous low Earth orbit in the dawn-dusk plane - as used by solar missions such as TRACE and HESSI. This provides continuous solar visibility and has the advantage of short range from the Earth. But it has previously been rejected as a solution for space weather measurements because of the major difficulty of maintaining the near continuous ground-station contact essential for solar monitoring (e.g. flare onsets need to be detected within a minute). In the context of this nanosat study it is worth reconsidering this issue since we can consider flying a significant number of nanosats in this orbit. These can form a ring around the Earth such that (a) one spacecraft can always be in view of a polar ground station, and (b) inter-spacecraft links may be used to transfer data around the ring to the spacecraft currently handling downlink. Note that a similar of nanosat constellation is already required to monitor space weather conditions in the ionosphere (see Table 11 of [R1]).

Thus use of nanosat constellation can resolve the problem of ground station contact for this LEO. But what kind of solar instruments could be carried by a nanosat? The requirements for solar and heliospheric imagery were discussed in detail during the February 2005 workshop. They may be summarised in three groups:

1. **Whole disc solar imagery** (requirements 1.1 (EUV), 1.2 (H-alpha) and 1.3 (X-ray)). Here the discussion showed that the image sensor and signal are not a constraint on nanosat solutions. The constraint is the optical system needed to get the required resolution. For detection of CME/flare precursors (a developing but not yet mature space weather application) one would probably need science grade resolution (few arcseconds) and thus need an optical system with several cm aperture (as set by diffraction limits) and a focal length of about a metre (to fit resolution to CCD pixel size). But for flare location (a mature application) we require only coarse resolution – perhaps 90 arcseconds, giving 20 pixels across solar disc; thus the aperture and focal length could be reduced to scale much more appropriate for nanosat solutions. If this approach were combined with on-board processing, we can envisage the combination discussed in the previous section, whereby solar flux and image data are used to return data on flare detection and location. The location code for the flare would be a cell from a 20 x 20 matrix. Thus we conclude that requirements 1.1, 1.2 and 1.3 could be satisfied on a nanosat in respect of applications that need information on flare location - but applications to detect CME/flare precursors probably need a larger instrument that would be difficult to accommodate on a nanosat.
2. **Spectral imagery** (requirements 1.5 (helioseismology) and 7.1 (magnetograms)). This requires an imaging spectrometer to observe the Doppler shift of spectral lines from the Sun and thus deduce vertical motions in the solar photosphere (as done by the MDI instrument on SOHO [R2]). Such measurements can also be used observe Zeeman splitting of spectral lines and thus deduce photospheric magnetic fields. This requires a large optical system as for detection of CME/flare precursors and thus is difficult to accommodate on a nanosat.
3. **Heliospheric imagery** (requirements 1.4 (Stereo observations of CMEs), 1.6 (Lyman-alpha scattering) and 2.1 (Coronagraph). These instruments detect the small amounts of sunlight scattered by the tenuous plasma in the heliosphere. Thus they require optical systems which can eliminate both direct emissions from the Sun (i.e. by use of an occulting disc) and stray light scattered within the optical systems. The latter necessitates a sophisticated baffle system, which imposes the need for significant mass and volume, beyond what could be accommodated on a nanosat.

Thus we conclude that one group of requirement for solar and heliospheric imagery can clearly be satisfied on a nanosats – namely the requirement for flare location by EUV, H-alpha or X-ray imagery. However, this is a very important requirement since flare location data are critical for short-term predictions of solar proton events. The other requirements for solar and heliospheric imagery need a science-class instrument that would be hard to accommodate on a nanosat because of the need for a large (1 metre) optical system to provide adequate resolution and straylight suppression. Thus we exclude these from further consideration here.

This approach allows us to refine the requirements for solar and heliospheric observations from nanosats as follows:

1. A sun-synchronous low-Earth-orbit in the dawn-dusk plane (Solar-LEO) should be used for whole disc imagery at coarse resolution (90 arcseconds) in support of flare location (requirements 1.1, 1.2 and 1.3). This orbit provides continuous view of the Sun and has short range to ground station, which facilitates downlink. The concept relies of deployment of multiple nanosats in this orbit such that one is always in view from a polar ground station (e.g. Svalbard). In principle the spacecraft in view of the ground station could be the one providing real-time data and thus cross-links would not be needed. In practice use of cross-links would increase operational robustness by allowing more choice in the spacecraft to provide the real-time data. To ensure ground station and cross-link visibility a relatively high orbit (800 to 1000 km altitude) must be used. Note that this orbit can also be used for monitoring solar fluxes at X-ray, EUV and UV wavelengths (requirements 3.1, 4.1 and 4.2) since it is well above the levels (200-300 km) at which those wavelengths are absorbed. Note also that the reduction in image resolution greatly reduces the data rate compared to the previous requirements. We estimate that whole disc images at coarse resolution and 10 minute cadence require only 20 bps (compared with a previous value of 6000 bps). On-board processing to return a flare status flag and location code will reduce this below 1 bps. For the purposes of the present study we use the 20 bps value in further analysis.
2. The requirement for monitoring solar radio bursts (6.1) cannot be moved to LEO as the electron density at 1000km can rise to as much as 10^5 cm^{-3}. This will screen out solar radio bursts at frequencies below about 3 MHz, whereas the requirement is to observe down to 30 kHz. Thus these observations must be made at much greater distance from the Earth.
3. The requirements for high performance imagery (requirements 1.4, 1.5, 1.6, 2.1 and 7.1, plus requirements 1.1, 1.2 and 1.3 in respect of CME/flare precursors) are very difficult to satisfy on a nanosat because of the size of the optical systems needed. Thus they are not considered further here.

3.1 Impact on GEO solutions

The approach discussed above allows us to greatly reduce requirements for nanosats solutions in geosynchronous orbit. The solar observations can be eliminated entirely except for the monitoring of solar radio bursts (6.1).

The requirements for heliospheric particle monitoring (10.1, 10.2, 10.3) can be better done at L1 and those for radiation belt monitoring (17.1, 18.1, 19.1) are better done by the radiation belt constellation discussed in [R1], backed up by hitchhikers on GEO spacecraft.

Thus the only requirement that now needs a solution in geosynchronous orbit is that to monitor solar radio bursts (6.1). This may be done in GEO or at L1, but not close to the Earth (Solar-LEO) because the topside ionosphere and plasmasphere are dense enough to block the required frequencies (down to 30 kHz). This requirement is thus best satisfied in GEO because of the advantage of the much smaller range compared to L1. However, the feasibility of satisfying this requirement on a nanosat is unlikely in view of the need for a relatively large antenna (comparable to that needed to detect AKR (req 12.1) which was rejected in [R1]). Examination of the current state-of-the-art confirms that this measurement requires large antennae:

- The WAVES experiment on NASA’s WIND spacecraft (launched 1994) has three dipole antennae – one at 50 metres each side, a second at 7.5 metres each side and the third at 5 metres each side [R5].
- The SWAVES experiment on NASA’s STEREO spacecraft (to launched early in 2006) has 3 monopoles each six metres long and with a mass of 1.3 kg each (the total instrument mass is 10.8 kg) [R6].

It is unlikely that antenna size can reduced much further because the experiment seeks to detect natural radio emissions with wavelengths from a few metres up to several kilometres. Thus we conclude that this measurement requires an antenna that is unlikely to be accommodated on a nanosat and thus we reject it from further study.

3.2 Impact on L1/upstream solutions

The approach discussed above has also simplified the requirements for observations at L1. The removal of the requirements for high performance imagery allows us to focus on a small number of observations that are best made upstream of the magnetosphere (e.g. solar wind, heliospheric magnetic field and heliospheric particle fluxes) but have modest data rates (8.1, 8.2, 9.1, 10.1, 10.2, 10.3).

4 Combine plasmasphere and radiation belt orbits

The requirements established in [R1] include two (20.1, 20.2) to monitor electron densities in the plasmasphere on an equatorial elliptical orbit similar to the radiation belt solution, but with a reduced apogee around 20000 km. However the similarity of the plasmasphere and radiation belt orbits suggests that it would be advantageous to combine these two solutions. Thus we re-assign the plasmasphere requirements to the radiation belt orbit with the caveat that that plasmasphere measurements are not required above L=4. Thus the combined data rate may be considered to a function of distance from the Earth.

5 Upper atmosphere observations

The requirements include numerous observations of the upper atmosphere from low-earth orbit, e.g. of the ionosphere and of the neutral atmosphere (the thermosphere) in which it is embedded. Analysis of instrument solutions suggests that, with one exception, there is good potential to develop miniaturised instruments to satisfy these requirements. The exception is requirement 23.1, measurement of the neutral wind in the thermosphere. This is typically done using a Fabry-Perot interferometer to measure the Doppler shift of airglow emissions such as the atomic oxygen line at 630nm (e.g. as discussed in the study reports [R4]). This gives a direct measurement of the line-of-sight wind component. Fabry-Perot interferometers may be operated on the ground [R10] or on spacecraft [R11]. However, they are relatively large instruments because a large aperture is needed to collect photons and obtain good signal-to-noise, e.g. the TIDI instrument on NASA’s TIMED spacecraft [R12] has a mass of 42 kg and a power of 30 W. It is not expected that a Fabry-Perot interferometer could be miniaturised to fit on a nanosat without significant reduction of aperture size, thus compromising the measurement through reduction in signal strength. Thus we conclude that this measurement requires a sensor that is unlikely to be accommodated on a nanosat and thus we reject it from further study.

The requirements also include remote sensing of auroral activity from a Molnyia orbit using optical observations at both visible and ultra-violet wavelengths. However, the analysis of the instrument solutions suggests that observations at visible wavelengths are much less suitable:

a. visible light observations are subject to greater contamination by sunlight scattered from the Earth’s atmosphere. UV observations are simpler to make and thus more suitable for nanosat solutions.
b. ultra-violet observations are a more direct measure of auroral electron precipitation. Auroral UV lines arise from energy levels directly excited by that precipitation. Optical emissions (e.g. the green and red oxygen lines at 557.7 and 630.0 nm) are often the product of series of chemical reactions triggered by the electron precipitation and are a delayed response to electron precipitation (up to 100s for the red line of oxygen).

For these reasons we have dropped the requirement for optical observations (11.3) and focused on the requirement for ultra-violet observations (11.1. For example, we can add photometry to provide a simple way to monitor the auroral oval at UV wavelengths and thus one that may be very suitable for implementation on a nanosat.

6 Measure high particle fluxes only

Many of the requirements to measure energetic particles are related to the effect of particle impacts on people and on devices, e.g. through radiation damage and charge deposition. In these cases the space weather risk is significant only when there are high particle fluxes leading to a high impact rate on the affected systems. Thus we can constrain such requirements to detect only high fluxes that lead to risk and ignore lower fluxes that may be of scientific interest but do not result in a space weather risk. The table below shows the measurement requirements for energetic particles (as taken from [R1]) and indicates:

- Whether the requirement can be restricted to high fluxes
- An estimate of the threshold for high fluxes
- A rationale for that estimate

Table 1. Measurement requirements for energetic particles.

Requirement number	Sub-requirement number	Measurement sub-type	Location	Highflux only	Threshold	Source/ rationale for threshold
8	1	Solar wind bulk velocity	Upstream	N	n/a	
8	2	Solar wind bulk density	Upstream	N	n/a	
10	1	>100 MeV ions from heliosphere	Upstream	Y	10 particles $cm^{-2}s^{-1}sr^{-1}$	SEC solar proton limit [R6]
10	2	2-100 MeV ions from heliosphere	Upstream	Y	10 particles $cm^{-2}s^{-1}sr^{-1}$	SEC solar proton limit [R6]
10	3	2-20 MeV electrons from heliosphere	Upstream	Y	10^3 particles $cm^{-2}s^{-1}sr^{-1}$	as SEC electron limit? [R7]
11	2	Auroral particle precipitation	Ionospheric -LEO	Y	10^6 particles $cm^{-2}s^{-1}sr^{-1}$ keV^{-1}	SPEE report gives typical charging flux as 10^6 to 10^8 particles $cm^{-2}s^{-1}sr^{-1}keV^{-1}$ [R9]
15	1	1-10 keV electrons in magnetosphere	Rad belt	Y	10^6 particles $cm^{-2}s^{-1}sr^{-1}$ keV^{-1}	as SPEE charging issue [R9]
16	1	10-100 keV electrons in magnetosphere / radiation belt	Rad belt	Y	10^6 particles $cm^{-2}s^{-1}sr^{-1}$ keV^{-1}	as SPEE charging issue [R9]
17	1	High energy electrons in radiation belt	Rad belt	Y	10^3 particles $cm^{-2}s^{-1}sr^{-1}$	SEC solar electron limit (= daily fluence of 8.6 $\times 10^7$ electrons $cm^{-2}sr^{-1}$) [R7]
18	1	> 10 MeV protons in rad belt	Rad belt	Y	10 particles $cm^{-2}s^{-1}sr^{-1}$	SEC solar proton limit [R6]

This table shows that we can constrain all energetic particle measurements to a high flux regime, except for the solar wind particle measurements. These are not considered a high flux case as the associated space weather risk (increased geomagnetic activity and its consequences) is not directly related to solar wind particle fluxes. Furthermore, good measurements of solar wind particle fluxes are needed in order to derive accurate moments of the particle distribution, -namely the zero order moment (bulk density) and the first order moment (bulk flux, from which we derive velocity).

Thus we conclude that many of the requirements for measurements of energetic particle fluxes can focus on high fluxes in respect to solutions that support space weather services. Measurements to support scientific research may still require good measurements to lower flux levels that do not constitute a risk factor. The possibility of focussing on high fluxes is important in assessing nanosat solutions because it may allow the use of lower geometric factors within particle instruments and thus support sensor miniaturisation.

7 Autonomy

There is much scope for mission autonomy especially given an on-board awareness of position. This might be achieved quite simply by flying a good clock to measure time and uploading Keplerian elements as determined by classical tracking. A more sophisticated solution would be to fly a space-capable GPS system, which can now be done with modest mass requirements. This would of-course be restricted to orbits entirely inside the GPS constellation (20000 km altitude). Given awareness of position one can design an autonomous response in terms of control of communications to ground station and control of instruments with respect to location in the ionosphere and magnetosphere. We assess potential use of autonomy for the different constellations as follows:

Table 2. Autonomy options for space weather constellations

Platform	**Autonomy**
Ionospheric-LEO	Determine latitude and MLT and report in telemetry stream, determine if s/c is in view of ground station, interact with other s/c to select downlink node and telemetry routing to node
Molniya	Activate instruments and telemetry when spacecraft has view of auroral oval (altitude > TBD)
Rad belt	Identify the L value zone in which the spacecraft is operating and report in telemetry stream; switch off instrument telemetry while in outer zone (L>7 for rad belt, L>4 for plasmasphere measurements)
Solar-LEO	Determine if s/c is in view of ground station, interact with other s/c to select observation and downlink nodes, route telemetry from observation node to downlink node. Note that observation and downlink nodes may or may not be the same spacecraft.
Swarm orbit	Determine if s/c is in view of ground station and downlink data when in view. Use knowledge of distance from Earth to match magnetometer instrument mode to expected size of the magnetic field
Upstream	No options identified

8 Database update

To implement the results of analyses discussed above we have updated the database as follows:

- By adding new entries to the cross-reference table linking the sub-requirements to the orbits where the required measurements may be made. These entries record the solutions in Solar-LEO for requirements 1.1, 1.2, 1.3, 3.1, 4.1 and 4.2.
- By increasing the typical range of the Ionospheric-LEO solution to 1000 km.
- By changing 20.1 and 20.2 to the radiation belt orbit
- By adding new column to this cross-reference table. This column “Refined” takes logical values and is set false where a solution has been eliminated by this analysis, i.e. solar imagery and flux measurements in GEO, high performance imagery.
- Updating the query that maps sub-requirements into values of DR2 and multiplicity, so that it picks up only requirements with Refined=True in the cross-reference table.

9 Nanosat solutions revisited

In this section we re-visit the analysis performed in section 6 of [R1]. Updated values of DR^2 and multiplicity were calculated from the database. The values of R (typical range) are now as shown in Table 3 below. The orbits are described in detail in Annex A of this document, which is an updated version of Annex D of [R1].

Table 3. Measurement locations and ranges

Location	Typical range (km)	Notes
Ionospheric-LEO	1.00E+03	
Solar-LEO	1.00E+03	
Molniya	2.00E+04	Variable: a 1000 km at perigee to 39000km 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.
Solar-L1	1.50E+06	
Upstream	1.50E+06	

Figure 1 below shows a scatter plot of DR^2 versus multiplicity, which may be compared with Figure 3 of [R1]. As before the red points indicate the values for the various combinations of requirements and location. The four ovals coloured blue, green, magenta and red) indicate four groups of combinations with similar values; we will discuss these groups in more detail below, especially changes from the similar groups discussed in [R1]. The cyan Sun symbol indicates the location of solutions for L1 monitoring of the solar wind and HMF.

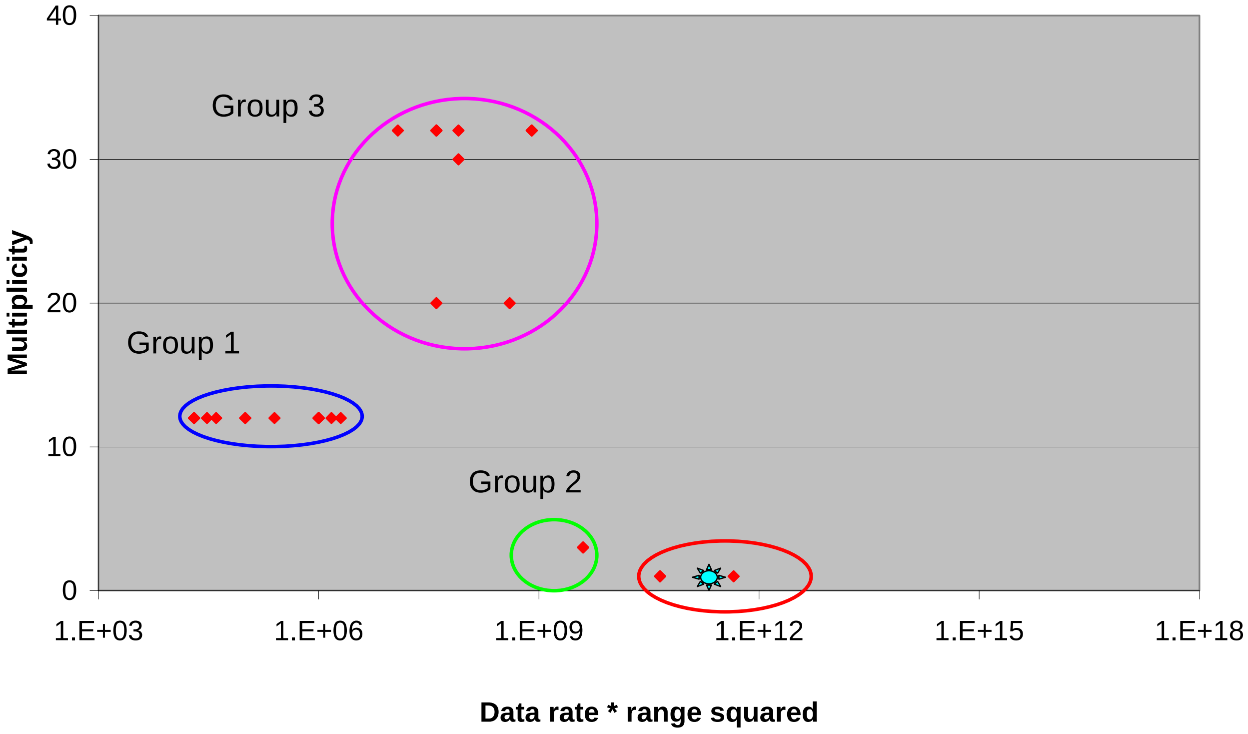

Figure 1. Nanosat combinations ordered by DR^2 (units=kbps km^2) and multiplicity

9.1 Group 1 – low data rate combinations

This group is now selected by $DR^2 < 1x10^7$ kbps km^2 (an increase with respect to [R1] reflecting the increased range assigned to LEO solutions. The group is shown in Table 4 below. It contains the LEO applications identified in [R1], which are mainly ionospheric measurements with sufficient number of satellites to ensure global coverage with cadence less than the typical orbit period of 90 minutes. But it also now contains the solar applications in LEO that were discussed in some detail in section 3 above.

Table 4. Group 1 - low data rate combinations

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
1	2	H-alpha images of Sun	Solar-LEO	2.00E+04	12
1	3	Soft X-ray images of Sun	Solar-LEO	2.00E+04	12
1	1	EUV images of Sun	Solar-LEO	2.00E+04	12
25	1	Microparticle measurements	Ionospheric-LEO	3.00E+04	12
3	1	Solar X-ray flux monitor	Solar-LEO	4.00E+04	12
19	1	Dosimetry	Ionospheric-LEO	1.00E+05	12
20	1	Total electron content of iono/plasmasphere	Ionospheric-LEO	1.00E+05	12
4	2	Solar UV flux	Solar-LEO	2.50E+05	12
4	1	Solar EUV full disc flux	Solar-LEO	1.00E+06	12
22	1	Neutral density in thermosphere	Ionospheric-LEO	1.00E+06	12
21	1	Plasma velocity in ionosphere	Ionospheric-LEO	1.00E+06	12
20	2	Electron density of iono/plasmasphere	Ionospheric-LEO	1.00E+06	12
14	1	In-situ magnetospheric E field	Ionospheric-LEO	1.50E+06	12
11	2	Auroral particle precipitation	Ionospheric-LEO	2.00E+06	12

9.2 Group 2 – medium data rate, low multiplicity

This group is selected, as in [R1], by DR^2 between 3x10^7 and 3x10^9 kbps km^2 and multiplicity < 12 and is shown in Table 5 below. Its content is reduced compared to [R1] because of the move of solar and radiation belt measurements away from geosynchronous orbit and the dropping of requirements for measurements of solar radio emissions and visible emissions from the aurora. It now contains:

- Auroral activity monitoring by UV observations from polar elliptical orbits

Table 5. Group 2 – medium data rate, low multiplicity.

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
11	1	Auroral UV imaging	Molniya	4.00E+09	3

9.3 Group 3 – medium data rate, high multiplicity

This group is selected, as in [R1], by multiplicity > 15 and is shown in Table 6 below. It is unchanged from [R1] and 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 6. Group 3 – medium data rate, high multiplicity

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
20	1	Total electron content of iono/plasmasphere	Rad belt	4.00E+07	20
20	2	Electron density of iono/plasmasphere	Rad belt	4.00E+08	20
13	1	Magnetospheric magnetic field	Rad belt	8.00E+07	32
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
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
25	1	Microparticle measurements	Rad belt	1.20E+07	32
13	1	Magnetospheric magnetic field	Swarm orbit	8.00E+07	30

9.4 L1 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 7 below. It is much changed from [R1]. The dropping of high performance imagery (because it is very difficult to do on a nanosat) has focused this group on measurements made at the L1 point and mainly on measurements that are best made there, i.e. monitoring of the solar wind, heliospheric magnetic field and heliospheric population of energetic particles. In view of this focus, the group has been renamed as L1 combinations (thus removing the negative connotation of the “low priority” name used in [R1]. 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 7. L1 combinations

Requirement number	Sub-requirement number	Measurement sub-type	Location	DR2	Multiplicity
10	3	2-20 MeV electrons from heliosphere	Upstream	4.50E+10	1
10	2	2-100 MeV ions from heliosphere	Upstream	4.50E+10	1
10	1	>100 MeV ions from heliosphere	Upstream	4.50E+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
6	1	Solar radio bursts	Solar-L1	2.25E+12	1

10 Conclusions

The refinement described in this document has allowed us to produce a much more focussed set of requirements for space weather monitoring by nanosats:

- It is demonstrated by solar monitoring for flare location is a distinct and important requirement that could be addressed by a nanosat solution that considerably reduces the size of the optical system and the data rate.
- The requirements for complex imaging systems are excluded as they require large optical systems that would be difficult to accommodate on a nanosat.
- Some further requirements are excluded because feedback from the instrument solutions indicates that the sensors are unlikely to miniaturised to fit on a nanosat: 6.1 solar radio bursts; 23.1, neutral winds in the thermosphere.
- There is now a well-focussed set of requirements for upstream monitoring at L1 – namely to monitor solar wind, the heliospheric magnetic field and heliospheric fluxes of energetic particles.
- The requirements for measuring energetic particle fluxes, other than the low energy particles in the solar wind, may be descoped to focus only the high fluxes that yield significant risks. This may allow sensor miniaturisation by accepting a lower geometric factor. Estimates of the high flux threshold are given in Table 1.
- The LEO constellation for ionospheric monitoring, already well-defined in [R1], is retained in full.
- The requirements for auroral imagery are now focussed on the stable and readily accessible Molnyia orbit and focus on UV wavelengths (100-300 nm) which provide a more direct measure of auroral particle precipitation. This focus is the great advantage of space-based auroral observations. Ground-based observations cannot access these wavelengths.
- The need for large constellations for monitoring the radiation belts is confirmed and can be combined with plasmaspheric monitoring
- The need for a SWARM-type orbit to measure the magnetospheric magnetic field is also confirmed.

The refinement has also identified a set of autonomy issues that may be considered in any design work.

11 Annex A: Orbits and multiplicity of space weather monitors

This is an updated version of Annex D from [R1]. The measurement requirements 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 8 below. 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 resolution.

Table 8. 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).
Solar-LEO	Low earth sun-synchronous orbit in dawn-dusk plane	12	Observation	Use 12 (tbc) spacecraft per orbit to ensure one is always visible from a polar ground station.
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.
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.
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.