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WP421. Payload Definition

A definition of instruments needed for space weather measurements

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1 Preface

1.1 Document change record

Issue	Date	Notes/remarks
0.1	29 May 2001	Draft for internal review
1.0	30 Jun 2001	Revised in response to comments from RAL, Astrium and DERA
1.1	17 Jul 2001	Update costs in instrument attributes table
1.2	23 Jul 2001	Change CSMR 3 to coronagraph, obsolete CSMR 18, change CSMR 72 to set of pin diodes following comments from D. Rodgers, QinetiQ.
1.3	04 Aug 2001	Various changes to address comments from ESA, D. Rodgers and R. Gendrin: • clarify overall study logic with extra text, as appropriate, throughout the report • change minimum telemetry gap for CSMR 51 from 1s to 0s, i.e. it is more realistic to have no gap in this case • add further information on dose monitor instrument • add H-alpha imaging as a future ground-based technique • note that ground-based measurements of CME radio emissions and of meteoroids only sample a particular range of parameters
1.4	18 Nov 2001	Various changes following discussions at Intermediate Review, SWWT and by email: • added text on derivation of time resolution from user requirements • added discussion of instrument data sizing ("number of channels"). This is added to instrument description in section 2.6.2 as the detail of that discussion in instrument-specific.

1.2 Purpose of the document

This document is the output from the ESWS workpackage on payload definition (WP421). It comprises a single chapter to be incorporated in the overall space segment report (WP420) to be produced by Astrium. It is presented here as a separate document for ease of review and to provide a clear delivery.

1.3 Definitions, acronyms and abbreviations

CIR	Corotating interaction region
CME	Coronal Mass Ejection
CSMR	Consolidated System Measurement Requirement
ESWS	ESA Space Weather programme Study
EUV	Extreme ultra-violet
GEO	Geosynchronous (orbit)
GOES	Geosynchronous orbiting environment satellite
GTO	Geosynchronous transfer orbit
HTML	Hypertext Markup Language
IAGA	International Association for Geomagnetism and Aeronomy
IPS	Interplanetary scintillation
LEO	Low earth orbit
NASA	National Aviation and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PDF	Portable Document Format
SOHO	Solar and Heliospheric Observatory
TBD	To be done
TEC	Total electron content

1.4 Important Documents

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 test and this is indicated by a series of characters enclosed in square brackets, e.g. [ITT].

[ACE] The Advanced Composition Explorer Mission, Space Science Reviews, Vol 86 , Nos 1-4 (1998). Pages 1-663.

[CLUSTER] The Cluster and Phoenix Missions. Space Science Reviews, Vol 79, Nos 1-2 (1997), pages 1 to 658.

[CREEP] Columbus Radiation Environment & Effects Package http://www.estec.esa.nl/wmwww/wma/creep/index.htm

[GOES1] http://www.ngdc.noaa.gov/stp/GOES/goes_mission.htm

[GOES2] http://rsd.gsfc.nasa.gov/goes/text/goes.databook.html

[GOES3] SPIE VOL 2812, GOES-8 and beyond. Proceedings, 7-9 August 1996, Denver, Colarado. Washwell ER (ed).

[IMAGE] Imager for Magnetopause-to-Aurora Global Exploration, home page on http://image.gsfc.nasa.gov/

[IMPACT] STEREO IMPACT instrument, http://sprg.ssl.berkeley.edu/impact

[IPS1] R.A. Harrison, M.A. Hapgood, V. Moore and E.A. Lucek, (1992) "An Interplanetary Scintillation activity index", *Ann. Geophysicae* **10**, 519-526.

[IPS2] Mike Hapgood and Elizabeth Lucek, (1999) "Interplanetary Scintillation and Space Weather Monitoring", *Proceeding of the Workshop on Space Weather* - held at ESTEC, 11-13 November 1998, **ESA WPP-155**, 487-490.

[MODELS] http://www.expi.net/space/tools.html

[MRM] Miniature Radiation Monitor
http://www.estec.esa.nl/wmwww/wma/research/mrm.html

[PLASTIC] STEREO PLASTIC instrument,
http://atlas.sr.unh.edu/tof/Missions/Stereo/

[POLAR] Polar UVI hardware pages, http://wwwssl.msfc.nasa.gov/uvi/default.htm
Polar VIS hardware pages,
http://www-pi.physics.uiowa.edu/www/vis/description.html
Polar PIXIE pages, http://www.fi.uib.no/Spacephysics/PIXIE_mirror/

[SCHUMANN] K. Schlegel and M. Füllekrug,' Schumann Resonance Parameter Changes During High Energy Particle Precipitation,", *Journal of Geophysical Research*, Vol. 104, No. A5, p. 10111, 1999.

[SECCHI] STEREO SECCHI instrument, http://www.pxi.com/SECCHI/index.html

[SOHO] The SOHO Mission. Scientific and Technical Aspects of the Instruments. ESA SP-1104. November 1988.

[SOLO] Solar Orbiter Assessment Study Report, ESA-SCI(2000)6, July 2000. Download from ftp://star.mpae.gwdg.de/pub/SolarOrbiter/solo.pdf.

[SREM] Standard Radiation Environment Monitor,
http://www.estec.esa.nl/wmwww/wma/research/srem.html

[STEREO] The NASA STEREO mission
http://stp.gsfc.nasa.gov/missions/stereo/stereo.htm

[STORMS] STORMS Assessment Study Report ESA-SCI(2000)7, July 2000

[SURF] SURF - Compact charging & radiation monitor for spacecraft
http://www.space.dera.gov.uk/space_env/surf.html

[SWARM] SWARM : A Fleet of Microsatellites to Explore the Magnetosphere,
http://sprg.ssl.berkeley.edu/ConstellationClassMissions/Schwartz.pdf

[SWAVES] STEREO SWAVES instrument,
http://www-lep.gsfc.nasa.gov/swaves/swaves.html

[SWR_CAT] ESWS-RAL-RP-0001 Catalogue of European Space Weather Resources

[TIMED] TIMED SEE pages, http://lasp.colorado.edu/see/

[UARS] UARS SOLSTICE pages,
http://uarsfot08.gsfc.nasa.gov/UARS_INSTS/Obs_Inst_SOLSTICE.html

[WP300] ESWS-FMI-RP-0002, Rationale for European Space Weather Programme

[WP410] ESWP-DER-SR-0001, System Requirements Definition

2 Instrument Definition

2.1 Objectives

The main aim of this chapter is to define a set of instruments that will satisfy the system measurement requirements specified in [WP410]. The implementation of that set will then be discussed further in subsequent work packages.

The primary input to this chapter is the set of Consolidated System Measurement Requirements (CSMRs) given in Appendix C of [WP410]. The rest of that report, in particular, the other tables and the notes on the tables, have been widely used as a source of background material to aid in interpreting the CSMRs. Note, in particular, that the time resolutions cited in the present document are those given in [WP410]. These time resolutions are the finest values considered necessary to satisfy the underlying user requirements. Finer resolution could be used but will place unnecessary demands on the design of instruments and the supporting infrastructure (especially downlink telemetry for space-based instruments) and thus drive costs upwards.

The measurements specified in the CSMRs fall into two naturally distinct parts – namely space-based and ground-based measurements. These are described in two separate sections of the chapter. The section on space-based instrumentation then forms an input into the other space segment work packages (WP422 onwards), whilst the section on ground-based instrumentation is used as an input to the work package on programme structure and organisation (WP500). These two sections reference some large tables that provide the detailed lists of instruments and their various attributes. For convenience, those tables are consolidated in a single section at the end of the chapter. However, before we discuss space and ground-based instruments separately we should first discuss the underlying principles that determine whether any particular measurement should be performed in space or on the ground. This is the subject of the next section.

To maintain traceability from the earlier requirements work (WP120 and 410), the instruments to be specified in this Chapter will be cross-referenced to the numbered CSMRs in Appendix C of [WP410].

2.2 Space versus Ground instrumentation

This is an important issue for any programme of space weather measurements. Many space weather relevant parameters can be measured from the ground (as demonstrated by the CSMRs discussed above). Furthermore the scope of ground-based measurements is likely to increase in the future as advances in scientific understanding and technological capability bring new remote-sensing techniques into play (we will discuss this issue in more detail later).

Ground-based measurements have many practical advantages over space-based measurements. First and foremost, the total cost of bringing a space-based instrument into operation is much greater than that for a similar ground-based instrument. This follows simply from the extra costs of qualifying the instrument for space flight and an appropriate share of the costs of launching and operating the platform which hosts the space-based instrument. A second and equally important factor is the vastly greater ease with which ground-based instruments can be maintained and upgraded. Thus, in cases where one has a choice between measuring a parameter on the ground or in space, the presumption must be to measure it on the ground. Space-based measurements can only be justified by some overriding factor related to the practicability or quality of the measurements. For example:

- Some observations cannot be made from the ground, e.g. ground-based solar UV and X-ray images are impossible because of atmospheric absorption. A very important example of an essential space-based measurement is the upstream monitoring of the solar wind, e.g. at the L1 point. This must be carried out in-situ and at an adequate distance upstream of the Earth in order to obtain early warning of interplanetary disturbances before they hit the Earth.
- Some observations can be made from the ground but much greater sensitivity is possible in space, e.g. coronagraph images of CMEs are much clearer when taken in space because of the absence of stray light from atmospheric scattering (indeed CMEs were not recognised prior to their observation with the Skylab coronagraph).

2.3 Space Instrumentation

2.3.1 Methodology

1. As a first step we identified the CSMRs that should be addressed by space-based instruments. These are summarised in the following table:

CSMR number(s)	*Measurement type*	*Also ground*
1 to 3	Solar images	
4, 6	Auroral images	
8 to 13	Solar X-ray and UV fluxes	
23 to 27	Solar wind plasma properties	
36 to 38	Interplanetary magnetic field	
39 to 43	Magnetospheric magnetic field	
50	Cross-tail electric field	*
50 to 52	Bulk plasma properties	
53 to 67	Electron and ion fluxes	
69 to 71	Debris and meteoroid properties	*
72 and 73	Dose measurements	
75	Interplanetary radio emissions	*

The " *Also ground"* column indicates cases in which particular CSMRs might also be well-satisfied by ground-based measurements.

2. We next identified a set of preferred orbits to make the measurements that satisfy the above CSMRs. These are discussed in detail below (see also the figure below).

- Ln = Lagrangian point N. L1 is the traditional upstream location for solar and solar wind monitors since it allows continuous observations; L4 and L5 are off the Earth-Sun line and thus may have advantages for monitoring Earth-directed solar ejecta; L2 is a potential location for future astronomy missions and may thus be suitable for hitchhiker payloads to monitor very energetic particles (where the outer magnetosphere has no significant impact on particle motions) or to monitor the behaviour of the distant magnetotail.
- GEO = Geo-synchronous orbit. This is a traditional position for monitoring solar X-ray emissions and very energetic particles. It is also of major interest as an important applications orbit so monitoring of the local space environment, e.g. outer radiation belt, is of direct relevance,
- RB = radiation belt monitor. This is a set of elliptical, near equatorial orbits (similar to geosynchronous transfer orbit, GTO) such that the spacecraft passes through the full range of the radiation belt on each outbound and inbound pass. For global monitoring of the radiation belts at least three RB orbits, separated in longitude by 120 degrees, would have to be populated.
- SS = sun-synchronous low-Earth orbit. This is an alternative location for solar monitoring. Like L1 it allows continuous monitoring with the advantages in terms of bit rate and disadvantages in terms of ground station visibility.
- LEO = Low earth orbit (not shown in figure). This allows monitoring of global phenomena such as secondary neutrons from cosmic rays. LEOs with high inclination give access to the polar ionosphere, which is directly coupled to the magnetosphere, and is thus has potential

for measurements of parameters related to the magnetosphere (e.g. electric fields, energetic particles). Note that SS is a subset of polar LEO.

- Molniya (not shown in figure). This is a class of elliptical highly-inclined orbits with a 12-hour period such that the spacecraft spends much time at apogee over two high-latitude locations 180 degrees apart in longitude (e.g. Northern Scandinavia and Alaska). It is a good orbit for remote sensing of high-latitude regions. For continuous monitoring we require at least one spacecraft always near apogee, so at least a pair of Molniya orbits would have to be populated.
- PEO = Polar Earth orbit (not shown in figure). These are a more general class of highly-inclined orbits which allow monitoring of the polar regions. Elliptical orbits with apogee over one of the poles provide a good viewpoint for imaging extended regions such as the auroral oval or the plasmasphere. Note that Molniya is a subset of PEO.
- Magnetosphere. In this context we refer to a set of orbits that allow simultaneous sampling in many different regions of the Earth's magnetosphere, e.g. as in the SWARM proposal [SWARM].

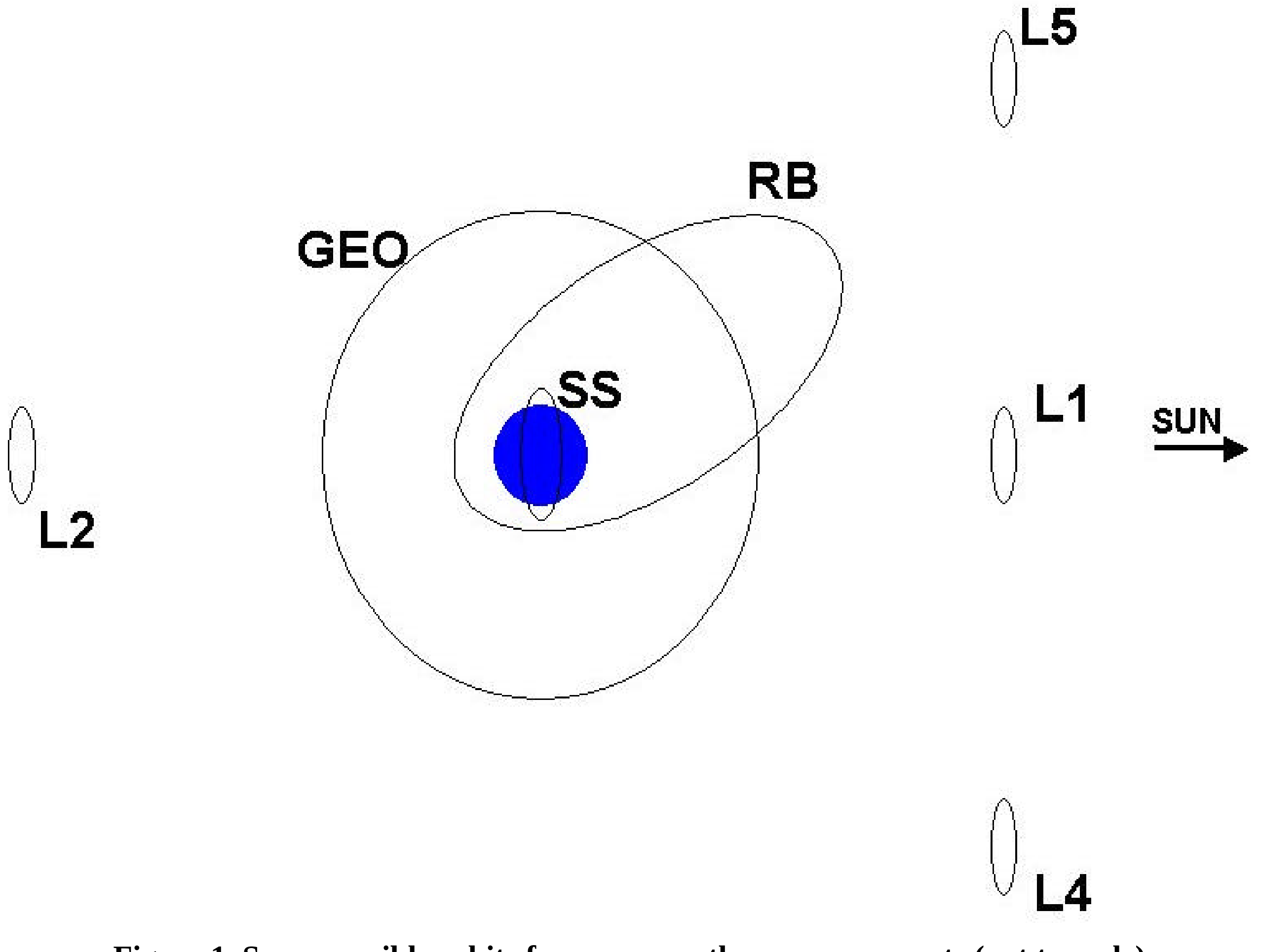

Figure 1. Some possible orbits for space weather measurements (not to scale)

3. We then identified a set of generic instruments and established which CSMRs they would satisfy and the orbits in which they should be located.

4. Finally we developed a common set of attributes for each instrument type in the generic set. These include:
   - A description giving a general outline of the instrument and giving details not easily included in the common set of attributes.
   - The data products to be derived from the instrument. These may include reduced products generated on-board to minimise telemetry downlink. For example, the raw product from an energetic particle sensor is typically a set of counts at various energies; there is now considerable flight experience in Europe and elsewhere (e.g. with AMPTE-IRM, ACE and Cluster) in using on-board processing to reduce these to a set of uncalibrated moments of the particle distribution. At least the first two moments must be downlinked to derive plasma bulk density and velocity.
   - Data rate (raw and reduced)
   - Dimensions and mass
   - Power
   - The instrument cost is shown where known. This attribute is fairly sparsely populated as information about costs of existing instruments is much less readily available than are technical specifications. This may reflect a degree of financial and political sensitivity concerning those costs and the basis on which they are calculated.
   - Examples of such instrument. Here we identify similar instruments that have flown on previous missions, are in preparation for flight or have been the subject of a detailed study as part of a mission proposal.
   - The European heritage in these examples. We regard an instrument as having European heritage if there was major participation in instrument development by a European institute, e.g. as principal investigator or as a co-investigator supplying hardware or software for the instrument or its ground support. Many NASA-led instruments have European participation and are therefore included in this heritage.

The information collected through these steps is presented as a set of tables at the end of this chapter.

2.3.2 Data sources

A wide variety of sources were reviewed to derive information on appropriate space instruments. These include reports on existing missions (GOES, SOHO, Cluster, UARS, Polar, ACE, IMAGE), assessment studies for new mission proposals (Solar Orbiter, Storms) and reports on missions now in preparation (TIMED, STEREO). References to these sources are given in the Important Documents section. They include traditional scientific papers (hardcopy format), documents downloadable over the web (e.g. PDF format) and references to web pages (i.e. HTML format).

2.3.3 Other space-based instruments

We note that some of the measurable parameters given in CSMRs can also be derived by prediction from other measurements. These are shown in the table below:

CSMR number(s)	*Measurable parameter*	*Predicted from*	*Measured by*
36 to 38	Interplanetary magnetic field	Solar surface magnetic field	Solar magnetograph (space or ground-based)

2.4 Ground instrumentation

2.4.1 The role of ground-based measurements

We now return to the consolidated system measurement requirements (Appendix C of [WP410]) and identify those that should be addressed by ground-based instruments. These are summarised in the following table:

CSMR number(s)	*Measurement type*	*Network*	*Index*
5 and 7	Auroral image/intensity		
14 to 17	Solar 10.7 cm radio emission (Penticton index)		Y
19 to 22	Secondary neutron fluxes	Y	
28 to 33	Geomagnetic indices	Y	Y
34 and 35	Sunspot number	Y	Y
44	Geomagnetic variations	Y	
45	Interplanetary scintillation		
46 and 47	Ionospheric critical frequencies	Y	Y
48 and 49	Ionospheric total electron content	Y	
68 and 74	Spacecraft tracking		

The third column indicates measurements that require a global network of measurements and not just one or two spot measurements. This is an important aspect of many ground-based measurements. Their value lies in a co-ordinated international network of observations - with exchange of data between participants – so that a global picture of the measured quantity can be derived. For many of the measurement types listed above there are already well-established international arrangements to do this. This will be discussed in detail in WP500.

The last column indicates measurements from which internationally-recognised indices are derived. These include the sunspot number (available as a monthly value from 1759), various geomagnetic indices (Kp/Ap from 1932, AE and Dst from 1957) and solar 10.7 cm radio emission (from 1947). Thus there has been a long history of maintaining support for the measurements behind these indices and for their processing through to the level of indices. This will also be discussed in detail in WP500.

Note also that the interplanetary scintillation (IPS) technique has been included as a potential ground-based technique for monitoring the propagation of interplanetary disturbances. This technique was explored as space weather measurements in the early 1990s (e.g. see [IPS1]), but proved disappointing in that role (though a number of good scientific papers did result). However, advances in the understanding of IPS over more than a decade since that attempt indicate that we could now build a much better hardware for IPS observations (A. Breen, private communication) as well as better software for reducing those observations [IPS2]. This will be discussed in more detail in the tables below and in WP500.

A more detailed description of the ground-based instruments is given as a table at the end of this chapter.

2.4.2 Data sources

A wide variety of sources were reviewed to derive information on ground instruments. These include the Catalogue of European Space Weather Resources [SWR_CAT] prepared in WP500 and the many references in that catalogue. References to these sources are given in the Important Documents section. They include traditional scientific papers (hardcopy format), documents downloadable over the web (e.g. PDF format) and references to web pages (i.e. HTML format).

2.4.3 Other ground-based instruments

We note that some of the CSMRs formally mapped to space-based measurements can also be addressed by ground-based measurements. These are shown in the table below:

CSMR number(s)	*Measurement type*	*Ground-based technique*
36 to 38	Solar surface magnetic field	Solar magnetograph
50	Cross-tail electric field	HF backscatter radar network (SuperDARN)
69 to 71	Debris and meteoroid properties	Optical and radar tracking of meteor trails
75	Interplanetary radio emissions	Radio astronomy

The use of a HF backscatter radar network to measure the cross-tail electric field (via the cross-polar cap potential) is a well-established example of a modern ground-based technique that can be applied to replace a space-based measurement. It relies on both advances in scientific understanding and technological capability. The radar network simply measures the pattern of ionospheric motions via the Doppler effect. It is modern scientific understanding that allows us to interpret this in terms of the electrodynamics of the coupled ionosphere-magnetosphere system. Technological advances have made it possible to deploy a suitable radar network and to collect and interpret data in near-real-time. This is demonstrated by the existing SuperDARN system. A more detailed discussion of the technique and its present limitations is given in the table at the end of the chapter. A similar functionality might also be provided by a magnetometer network, which can measure the pattern of electric currents associated with ionospheric motions.

The interplanetary radio emission technique is another interesting ground-based technique. It is based on the measurement of radio emissions thought to be characteristic of coronal mass ejections and offers the possibility to remotely-sense CMEs as they move away from the Sun. Such ground-based measurements are used in some state-of-the-art models used to predict CME arrival at the Earth (and thus the possible onset of geomagnetic activity) [MODELS]. However, these emissions are detectable from the ground only when the CME is close to the Sun (as the CME moves away from the Sun its emission frequency drops below the ionospheric cut-off frequency). Thus this technique is greatly improved if measurements are made above the ionosphere. A French-led demonstration of the technique is planned as part of NASA’s STEREO mission [SWAVES].

Looking more into the future, there is evidence that other ground-based techniques could be developed to remotely sense space weather phenomena:

- CME launches by monitoring coronal filaments using ground-based H-alpha imaging. These filaments observed as dark filamentary structures in H-alpha images of the Sun. They are thought to be closed flux tubes filled with relatively cool dense material and seen in silhouette against the photosphere. The disappearance of filament indicates as a reconfiguration of the coronal magnetic field, which is typically a consequence of a CME launch.
- Solar proton events through their effect on Schumann resonances (by way of energetic particle precipitation into the upper atmosphere) [SCHUMANN]
- Earth's radiation belt through natural radio emissions from the belt particles.

2.4.4 Attributes and heritage for ground-based instruments

There is considerable European expertise in terms of the ground-based techniques listed above. This has already been described in the Catalogue of European Space Weather Resources [SWR_CAT] produced in WP500. Thus the attributes and heritage of ground-based instruments will not be discussed further in this report.

2.5 Obsolete CSMRs

During the progress of this workpackage, and following the finalisation of the System Requirements Definition document [WP410], one of the CSMRs was determined to be unnecessary. This is shown in the table below. Obsolete CSMRs are not traced further in this document.

CSMR number(s)	*Measurement type*	*Rationale*
18	Secondary neutron fluxes	User requirement is for energetic protons rather than neutrons. CSMR 18 is deleted and the user requirement subsumed into CSMR 57.

2.6 Detailed tables

This section contains the detailed tables of instruments and their attributes. They comprise the following tables:

1. Instruments and Orbits. This table maps various CSMRs to space instrument types and orbits.
2. Instrument Description. This gives a detailed text description for each space instrument type.
3. Instrument Attributes. For each space instrument type this gives various common attributes such as the required time resolution, raw data product, raw data rate, dimensions, mass and power. We also give the number of data channels generated by the instrument within a single time resolution, e.g. number of energy channels for a particle instrument, pixel dimensions for an imager. Where an instrument addresses CSMRs with several different time resolutions, the finest required time resolution is cited. Where applicable (e.g. moments from thermal plasma measurements) we also give a reduced data rate for an instrument. Finally, where possible, we provide a cost estimate for each instrument.
4. Instrument Examples. For each space instrument type this gives information on a specific example of that instrument. The table gives the specific name of that example, mission name, lead agency, launch date and indicates if the instrument is currently operational in space.
5. European Heritage/Expertise. This lists European institutes that have been involved in some of the space instrument examples above. It also includes development projects for which there is as yet no flight heritage. The table gives the country, institute name and acronym, the instrument type and specific name. It is ordered by country.
6. Ground-based Systems. This lists the CSMRs that can be addressed by ground-based measurements. For each CSMR we present a short discussion on how those measurements might be made.

2.6.1 Instruments and Orbits Table

This table lists the CSMRs from [WP410]. For each CSMR we give (a) the space instrument type needed to make the required measurement, (b) the orbits from which those measurements may be made (where a "/" separates alternatives and a "+" indicates combinations), (c) the maximum gap in telemetry coverage that can be tolerated, (d) the number of instruments that must be placed in the orbit of interest, and (e) reference to a note at the end of the table that explains this number (if not 1).

In some cases several options are given for one CSMR, e.g. CSMR 1 can be addressed from two different orbits. These options require different space architectures so their advantages and disadvantages will be explored in WP423.

Note that the maximum gap in telemetry is typically taken as one-third the time resolution since we do not want to significantly increase the delay in access to the data (compared with that imposed by time resolution). But in the case of L1 in-situ measurements we take the maximum gap as 10% of the typical propagation time of a major interplanetary disturbance from L1 to the Earth (since we do not wish to significantly delay delivery compared with that propagation time).

CSMR no	Instrument type	Orbit.	Maximum TM gap	Number	See note
1	Whole disk imager	L1	20 min	1	
1	Whole disk imager	SS	20 min	2	
2	Coronograph	L1 / L4 / L5	20 min	1	
2	Coronograph	SS	20 min	2	
3	Coronograph	L4 + L5	20 min	1 each	1
4	Auroral imager	PEO / Molniya	20 min	2	2
6	Auroral imager	PEO / Molniya	20 min	2	3
8	X-ray photometer / spectrometer	L1	20s	1	
8	X-ray photometer / spectrometer	SS / GEO	20s	2	
9	X-ray photometer /spectrometer	L1	100s	1	
9	X-ray photometer /spectrometer	SS / GEO	100s	2	
10	X-ray photometer / spectrometer	L1	20 min	1	
10	X-ray photometer / spectrometer	SS / GEO	20 min	2	
11	X-ray photometer / spectrometer	L1	20 min	1	
11	X-ray photometer / spectrometer	SS / GEO	20 min	2	
12	UV photometer	L1	8 hours	1	
12	UV photometer	SS / GEO	8 hours	2	
13	UV photometer	L1	8 hours	1	

CSMR no	Instrument type	Orbit.	Maximum TM gap	Number	See note
13	UV photometer	SS / GEO	8 hours	2	
23	Thermal energy ion spectrometer	L1	3 min	1	
24	Thermal energy ion spectrometer	L1	3 min	1	
25	Thermal energy ion spectrometer	L1	3 min	1	
26	Thermal energy ion spectrometer	L1	3 min	1	
27	Thermal energy ion spectrometer	L1	3 min	1	
36	Magnetometer	L1	3 min	1	
37	Magnetometer	L1	3 min	1	
38	Magnetometer	L1	3 min	1	
38	Magnetograph	L1/ L4 / L5	20 min	1	
39	Magnetometer	Magnetosphere	20s	4 to 100	4
40	Magnetometer	Magnetosphere	100s	4 to 100	4
41	Magnetometer	Magnetosphere	10 min	4 to 100	4
42	Magnetometer	Magnetosphere	10 min	4 to 100	4
43	Magnetometer	Magnetosphere	20 min	4 to 100	4
50	Electric field	Tail	1 hour	1	
50	Thermal energy ion spectrometer	Tail	1 hour	1	
51	Electric field	Polar LEO	0s	5 to 10	5
51	Thermal energy ion spectrometer	Polar LEO	0s	5 to 10	5
52	Thermal energy ion spectrometer	Elliptical eg GTO	20s	4	6
52	Ionosonde	Elliptical eg GTO	20s	2	6
52	UV imager	Elliptical eg GTO	20s	2	6
53	Thermal energy electron spectrometer	GTO / Polar LEO / GEO	20s	4 or more	7
54	Medium energy electron spectrometer	GTO / Polar LEO / GEO	20s	4 or more	7
55	Medium energy electron spectrometer	GTO / Polar LEO / GEO	20 min	4 or more	7
56	High energy ion detector	GEO / L1 / L2	10 min	1	
57	High energy ion detector	GEO / L1 / L2	20 min	1	
58	High energy ion detector	GEO / L1 / L2	8 hours	1	
59	High energy ion detector	GTO / Polar LEO	10 min	3 or more	7
60	High energy ion detector	GTO / Polar LEO	20 min	3 or more	7

CSMR no	Instrument type	Orbit.	Maximum TM gap	Number	See note
61	High energy ion detector	GTO / Polar LEO	8 hours	3 or more	7
62	High energy ion detector	GEO / L1 / L2	20 min	1	
63	High energy ion detector	Any	20 min	1	
64	High energy ion detector	Any	8 hours	1	
65	High energy ion detector	GEO / L1 / L2	10 days	1	
66	High energy electron spectrometer	GEO, GTO	10 min	3 or more	7
67	High energy electron spectrometer	GEO, GTO	20 min	3 or more	7
69	Debris monitor	LEO	2 months	1	
70	Debris monitor	Any	2 months	1	
71	Debris monitor	Any	8 hours	1	
72	Dose monitor	Onboard s / craft	100s	1	8
75	Radio wave detector	L4 / L5	20 min	1	9

Notes
1. One needed at each of L4 and L5
2. Need two separated by half an orbit to ensure one has good view from polar elliptical orbit.
3. 1 in polar LEO is ok since it crosses north and south auroral ovals each orbit, i.e. approximately half orbit = 45 mins between crossings.
4. Need measurements in many different regions of the magnetosphere - similar to [SWARM]/
5. We need a set of spacecraft spaced around a polar orbit. Given the typical extent of the two polar caps, 5 to 10 spacecraft equally spaced around a polar LEO should yield 1 or 2 in the caps at any one time.
6. Need 4 if using direct ion measurements, remote sensing (UV imager/ionosonde) could reduce need to 2
7. Need measurements at several different longitudes
8. But should be carried on all manned missions
9. Measurements of solar bursts should be made away from the Earth to allow stereoscopic comparison with ground-based observations.

2.6.2 Instrument Description Table

Instrument type	Description
Auroral imager	This is an instrument to take images of the auroral oval - the near continuous ring of aurora around each magnetic pole. The aurora emits over a wide range of wavelengths from visible wavelengths to X-rays. Images can be taken at wavelengths throughout this range. For a space-borne instrument, a UV imager at 100 to 200 nm is probably best - because it detects auroral emissions that are directly produced by electron bombardment of the upper atmosphere. Thus a UV image is a direct indicator of the location and intensity of the auroral electron precipitation. In contrast, most visible emissions from the auroral are secondary emissions that result from chemical processing of the excited states produced by the electron bombardment and the decay of metastable states produced by that processing. The effect is that visible emissions (in particular, the red line at 630.0 nm) are delayed with respect to the auroral electron precipitation and thus the image is less good as an indicator of that precipitation. There are a number of important issues for an imager: (a) the handling of apparent image motion due to spacecraft spin and motion, (b) screening of straylight (e.g. from the Sun), and (c) adequate field of view. The image motion due to spin may be handled in a number of ways included de-spun platforms (as on Polar), stepping CCD pixels in synchronism with spacecraft spin (as on the Swedish-led Viking spacecraft) or location-tagging of individual photons (in a photon-counting system). The field of view should be such as to capture the whole auroral oval (~ 5000 km diameter) at as low an altitude as possible. In previous missions this has typically been done with observations from spacecraft on highly elliptical polar orbits with apogee distances of several Earth radii, so that the spacecraft spends many hours around apogee with a good view of the oval. The required spatial resolution is 50km, so given the auroral oval scale size of 5000 km and a margin of 20%, a pixel size of 120 by 120 is adequate.
Coronograph	This is an instrument to take images of the solar corona out to several solar radii. Only a single instance is required subject to visibility and a cadence of one hour is adequate for current space weather requirements. The LASCO instrument on SOHO is a well-known example but is perhaps a more sophisticated device than needed for space weather monitoring. Note that LASCO is not a single coronagraph but comprises three coronagraphs viewing a series of concentric fields at differing angular distances from the Sun. For space weather monitoring a single or perhaps double coronagraph would be adequate. The key issue is the ability to detect Earth-directed ejecta, especially coronal mass ejections. For platforms at L1 or in Earth orbit this implies the ability to detect halo events. For platforms at L4 and L5 or similar, the requirement is less severe. For L1 observations a resolution approaching that of LASCO (11 arc-seconds) is required; to view out to say three solar radii this implies a pixel size of 500 by 500. For L4 or L5 observations, a resolution of 30 arc seconds is required and the viewing window may be offset to the Earthward side of the Sun, so a pixel size of 120 by 120 may be adequate.

Instrument type	Description
Debris monitor	This is an instrument to detect tiny particles from spacecraft debris and cosmic dust. Typical particle masses to be detected are 10^{-16} to 10^{-6} grams. The typical output of this instrument is a series of events when particles are detected. For each event we return a parameter that can be used to derive particle mass; a time-tag may also be returned or this may be implicit in the telemetry packetisation.
Dose monitor	This is an instrument to measure dose rates and linear energy transfer spectra due to energetic particles. Typically these are based measuring the response of electronic devices. The use of several such sensors behind different levels of shielding allows resolution by particle energy. We assume that 5 energy channels are required for the linear energy transfer spectra.
Electric field	This is an instrument to measure the ambient electric field at the spacecraft location. Ideally all three components should be measured but reduced coverage may be acceptable in some cases. The conventional technique for measuring electric fields is by deploying opposed pairs of long booms and measuring the tip-to-tip voltage. The electric field is then essentially this voltage divided by the tip-to-tip distance. The main issue for this technique is the size and deployment of the booms. The boom length must be greater than the Debye length of the plasma. This is the distance over which individual ions and electrons interact in a plasma and is typically of order several tens of metres in the Earth's outer magnetosphere. Thus for electric field measurements in the magnetosphere, the booms are huge - those on Cluster are nearly one hundred metres tip-to-tip. The construction and deployment of such large booms is a major challenge - especially as asymmetric deployment can lead to problems with the stability of the spacecraft. An alternative technique that is being pioneered in Europe is the use of low energy (keV) electron beams to probe the plasma and observe the electron drift due to the ambient electric field. This technique has been used on several missions and is currently in use on ESA's Cluster mission. The technique is in principle much simpler than the boom measurements - but is still very much in a development phase in which the instrument scientists are learning to control the instrument and extract useful data from the results. We assume in both cases that the instrument returns a three-component vector or equivalent data.
High energy particle detector	This is an instrument to detect electrons and ions with high energies. For ions measurements from 10 MeV up to 5 GeV are required with resolution in mass (say 5 channels covering protons, alphas, CNO, Si and Fe) and in energy (5 logarithmic steps across the range). For electrons measurements are required from 300 KeV to 5 MeV but with resolution in energy (10 logarithmic steps across the range). It is important to be able to sample particles coming from all 4 PI of solid angle but resolution of particle directions is significant only if the local magnetic field direction is also measured (either directly or by determining the axis of symmetry of the electron distribution).

Instrument type	Description
Ionosonde	This is an instrument to measure the location of the plasmapause, the usually sharp gradient in plasma number density that marks the outer edge of the plasmasphere. The technique involves sweeping the frequency of a simple radar and observing the strength and phase of echoes from the plasma. These come from locations where the natural plasma frequency (which is a simple function of plasma density) matches that of the radar signal. By measuring the time delay of the echo as a function of frequency it is possible to determine the distance and direction from the spacecraft to sharp density gradients such as the plasmapause (but note that the transmitter must be on the low density side of the gradient). This technique is identical to that used in ground-based ionospheric sounding, so what is required is a space-qualified ionosonde. Such instruments were operated in space during the 1960s and 1970s to study the topside ionosphere (e.g. Alouette) but the technique then fell into disuse because of the high costs of processing complex data in analogue form. It has now been revived, in a form producing digital data, and applied to new regions by the RPI instrument on NASA's IMAGE mission (see http://image.gsfc.nasa.gov/rpi/). RPI is simply a space-qualified version of the very successful Digisonde instrument developed by the University of Lowell in Massachusetts. The output of this instrument is an ionogram - a measurement of returned signal amplitude and phase as a function of frequency and time delay. This is effectively an image. A pixel size of 1024 by 1024 should be considered.
Magnetograph	This is an instrument to take measure the magnetic field at the visible surface of the Sun (photosphere). The technique involves measuring the Zeeman effect splitting of spectral lines, e.g. through use of an imaging spectrometer. Only a single instance is required - subject to provision of continuous solar visibility at the required cadence. For the latter, a value of one hour is adequate for current requirements for space weather. Magnetograph data taken prior to CME launches (and at the site of the launch) are essential if one is to predict the orientation of the interplanetary magnetic field when the CME hits the Earth. To obtain a resolution similar to the whole disc imager as pixel size of 400 by 400 is required.

Instrument type	Description
Magnetometer	This is an instrument to measure all three components of the magnetic field at the spacecraft location. A time resolution of no more than one minute is recommended for current space weather requirements (in particular, to catch the natural variability of the interplanetary magnetic field). Magnetic field measurements are a very well-established technique in space science with heritage dating back to the very first years of spaceflight. Recent European missions with magnetometer measurements include Cluster, Equator-S, Ulysses, AMPTE-IRM, AMPTE-UKS, Astrid-2 and Oersted. The fields to be measured typically have strengths ranging from a few nanoteslas (outer magnetosphere and solar wind) to around 50 microteslas (LEO). The main challenge for magnetometer measurements is that of eliminating magnetic interference from other items on the spacecraft, e.g. electrical systems and structures with magnetic properties. One aspect of this is that the sensors for a magnetometer are usually placed outboard on a boom several metres long - thus reducing interference from the spacecraft. The data processing unit can be placed on the main spacecraft. Another important issue is that it is essential to eliminate time-varying interference, e.g. from structures whose magnetic properties change with temperature or age. A small level (~ 1 nT) of static interference is acceptable as it can be handled as a fixed offset to be removed in ground processing of the magnetometer data. A related issue that is sometimes neglected is that the handling of the spacecraft by launch services must not alter the magnetic cleanliness. An example of this problem is that experienced by AMPTE-UKS following its launch by NASA in August 1984; a large magnetic offset was discovered in orbit and was attributed to magnetic material attached to the spacecraft during launch preparations in order to balance the stack of three spacecraft that comprised the AMPTE mission. The returned data are a series of three component vectors.
Medium energy electron spectrometer	This is an instrument to measure electrons at energies of 10 to 100 keV (and perhaps to 300 keV). Spectral resolution is required in order to derive the distribution of flux with energy (10 logarithmic steps across the range). It is important to be able to sample particles coming from all 4 PI of solid angle but resolution of particle directions is significant only if the local magnetic field direction is also measured. For a spinning spacecraft this may be achieved by sampling all directions in a meridian plane of the spin axis and then sampling all directions as the spacecraft spins; in this case, it is essential to measure spacecraft spin phase, e.g. through a sun sensor. For a non-spinning spacecraft the instrument should have sufficient sensors to sample all directions.
Medium energy ion spectrometer	This is an instrument to measure ions at energies of 10 to 300 keV. Spectral resolution is required in order to derive the distribution of flux with energy energy (10 logarithmic steps across the range). Resolution of mass is also required. . It is important to be able to sample particles coming from all 4 PI of solid angle but resolution of particle directions is significant only if the local magnetic field direction is also measured. For a spinning spacecraft this may be achieved by sampling all directions in a meridian plane of the spin axis and then sampling all directions as the spacecraft spins; in this case, it is essential to measure spacecraft spin phase, e.g. through a sun sensor. For a non-spinning spacecraft the instrument should have sufficient sensors to sample all directions.

Instrument type	Description
Radio wave detector	This is an instrument to detect the natural radio emissions that are thought to originate from electron acceleration in the vicinity of coronal mass ejections. These emissions are generated at the local plasma frequency and thus vary with plasma density - from frequencies of 10 MHz close to the Sun to frequencies of about 40kHz at 1AU. This is a new technique being taken forward by the WAVES instrument on NASA's STEREO mission (see http://www-lep.gsfc.nasa.gov/swaves/swaves.html). It offers the possibility of remote sensing the progress and properties of CMEs as they travel to the Earth and hence predicting their time of arrival and their geoeffectiveness. The instrument must measure wave amplitude in perhaps 100 steps across a range of frequencies.
Thermal electron spectrometer	This is an instrument to measure the velocity distribution of electrons up to about 20 keV (perhaps 20 logarithmically spaced steps). For most space weather environments a two-dimensional velocity distribution (i.e. with respect to pitch angle) is probably adequate. In some cases, only the moments of the pitch angle distribution are required, but in others the distribution of fluxes with energy is needed. It is important to be able to sample particles coming from all 4 PI of solid angle but resolution of particle directions is significant only if the local magnetic field direction is also measured. For a spinning spacecraft this complete sampling may be achieved by sampling all directions in a meridian plane of the spin axis and then sampling all directions as the spacecraft spins; in this case, it is essential to measure spacecraft spin phase, e.g. through a sun sensor. For a non-spinning spacecraft the instrument should have sufficient sensors to sample all directions. To derive bulk electron plasma properties (e.g. number density, bulk velocity, temperature and heat flux), the basic moments of the velocity distribution can be computed on-board (there is much heritage from Cluster, AMPTE-IRM and other missions) and converted to physical quantities on the ground. This greatly reduces the amount of data to be downlinked. Traditionally, the plasma bulk velocity (e.g. the solar wind velocity at L1) is derived from ion moments rather than electron moments. This is because the typical thermal velocities of ion are much less than those of the electrons. Thus the plasma bulk velocity has a much larger effect on the ion velocity distribution than on the electron distribution. However, the effect of the plasma bulk velocity on the electron distribution can still be detected with ease - at least in the solar wind and magnetosheath.

Instrument type	Description
Thermal energy ion spectrometer	This is an instrument to measure the distribution of ions up to about 20 keV (perhaps 20 logarithmically spaced steps). For most space weather environments a two-dimensional distribution (i.e. with respect to pitch angle) is probably adequate, but resolution of different ion species is also required. In some cases, only the moments of the pitch angle distribution are required, but in others the distribution of fluxes with energy is needed. It is important to be able to sample particles coming from all 4 PI of solid angle but resolution of particle directions is significant only if the local magnetic field direction is also measured. For a spinning spacecraft this may be achieved by sampling all directions in a meridian plane of the spin axis and then sampling all directions as the spacecraft spins; in this case, it is essential to measure spacecraft spin phase, e.g. through a sun sensor. For a non-spinning spacecraft the instrument should have sufficient sensors to sample all directions. To derive bulk ion plasma properties (e.g. number density, bulk velocity, temperature and heat flux), the basic moments can be computed on-board (there is much heritage from Cluster, AMPTE-IRM and other missions) and converted to physical quantities on the ground. This greatly reduces the amount of data to be downlinked. An important issue for thermal ion measurements is that measurements in the solar wind require special care. The bulk solar wind velocity is larger than the typical thermal velocities of ions in the solar wind. Thus the velocity distribution is greatly displaced from zero velocity; the distribution will be observed as a beam moving away from the Sun and not as a quasi-isotropic distribution filling all 4 PI of solid angle around the spacecraft.
UV imager	This is an instrument to image the shape and size of the plasmasphere (a region of relatively dense plasma above the ionosphere, but still close to (2 to 4 Re) the Earth and co-rotating with it) by observing resonant scattering of sunlight in the line of singly ionised helium (He+) at 30.4 nm. This is new technique being pioneered by the EUV instrument on NASA's IMAGE mission (see http://euv.lpl.arizona.edu/euv/). It offers the possibility of remote sensing the extent of the plasmasphere and hence predicting the size of the phase shift experienced by GPS signals during passage through that region. Note that the size of the plasmasphere can change dramatically during magnetic storms. The field of view should be such as to capture the whole plasmasphere (~ 8 Earth radii diameter) at as low an altitude as possible. In the IMAGE mission this has been done with observations from spacecraft on a highly elliptical orbits with an apogee distances of 7.2 Earth radii, so that the spacecraft spends many hours around apogee with a good view of the plasmasphere. An image size of 120 by 120 pixels should be adequate (allowing 1% resolution on the size of the plasmasphere).

Instrument type	Description
UV photometer	This is an instrument to monitor the global UV flux from the Sun at one or more wavelengths. A good target may be to measure at 5 channels covering 25 to 200 nm - say 25, 50, 100 and 200 nm plus Lyman-alpha at 121.5 nm.. Only a single instance is required subject to visibility. A time resolution of five minutes or less is recommended for current space weather requirements. An example is the SEE instrument that has been developed for NASA's TIMED mission (see http://lasp.colorado.edu/see/). The field of view should be such as to capture the whole photosphere of the Sun.
Whole disk imager	This is an instrument to take images of the whole disc of the Sun in various EUV or X-ray emission lines – similar to EIT on SOHO. Only a single instance is required - subject to provision of continuous solar visibility at the required cadence. For the latter, a value of one hour is adequate for current requirements for space weather. A resolution approaching that of EIT (5 arc-seconds) is required; which implies a pixel size of 360 by 360.
X-ray photometer/spectrometer	This is an instrument to monitor the global X-ray flux from the Sun at one or more wavelengths. Only a single instance is required subject to visibility. A time resolution of one minute or less is recommended for current space weather requirements (in particular, to catch the sharp rise of solar flares). A simple example is the XRS instrument that has long formed part of the space environment monitor on the NOAA GOES series of spacecraft and has more than adequate time resolution. XRS provides some spectroscopic capability by monitoring flux in two wavelength bands. A new instrument to monitor X ray flux could take a similar form or could equally well introduce a direct spectroscopic capability. The field of view should be such as to capture the whole Sun out to some distance in corona (2 solar radii?).

2.6.3 Instrument Attributes Table

Instrument type	Time resolution	Raw data product	Data Rate, raw (Kbit/sec)	Data Rate, reduced (Kbit/sec)	Dimensions (cm)	Mass (kg)	Power (W)	Cost (MEuro)
Auroral imager	1 min	image	11		60x70x25	29	30	10
Coronograph	60 min	image	5		80x30x30	17	25	17
Debris monitor		event series	0.03		3x20x20	0	0	4
Dose monitor	5 min	time series	<0.1?		400cm^3	0.5	1	0.4
Electric field	5 sec	time series	1		15x15x10	10	5	4
High energy particle detector	5 sec	time series	2		20x20x10	8	6	7
Ionosonde		image	38.4			50	134	TBD
Magnetograph	1 min	image	20		110x40x30	26	25	26
Magnetometer	1 sec	time series	0.2		20x10x16	3	3	5[1]
Medium energy electron spectrometer	5 sec	time series	0.2		17x8x7	6	4	3
Medium energy ion spectrometer	5 sec	time series	0.5		17x8x7	6	4	7
Radio wave detector			0.5			11	6	5
Thermal electron spectrometer	5 sec	time series	2	0.3	15x10x10	3	4	4
Thermal energy ion spectrometer	1 min	time series	6	0.1	25x20x20	5	4	4
UV imager		image				16	16	10
UV photometer	1 hr	spectra	0.25			27	27	2.5
Whole disk imager	60 min	image	5	0.5	200x25x40	10	3	14
X-ray photometer/spectrometer	2 sec	time series			26x14x11	0	0	5

[1] A magnetometer will also drive up spacecraft costs by imposing a requirement for design and verification of magnetic cleanliness.

2.6.4 Instrument Example Table

Instrument type	Instrument name	Mission	Agency	Launch	Operational
Coronograph	LASCO	SOHO	ESA	1995	Yes
Coronograph	SECCHI/COR1	Stereo	NASA	2004	No
Coronograph	SECCHI/COR2	Stereo	NASA	2004	No
Coronograph	UVC	SOLO	ESA	2011	No
Debris monitor	DUD	SOLO	ESA	2011	No
Dose monitor	CREAM/CREDO	ISS	ESA	2002	No
Dose monitor	DDM	STRV-1c	QINETIQ	2000	No
Electric field	DC-EFI	STORMS	ESA	N/A	No
Electric field	EFW	Cluster	ESA	2000	Yes
Electric field	EDI	Cluster	ESA	2000	Yes
Thermal electron spectrometer	SELA	STORMS	ESA	N/A	No
Thermal electron spectrometer	SWEPAM-E	ACE	NASA	1997	Yes
Thermal electron spectrometer	PEACE	Cluster	ESA	2000	Yes
Thermal electron spectrometer	SURF	TBD		N/A	TBD
Thermal electron spectrometer	SWA/EAS	SOLO	ESA	2011	No
High energy particle detector	EPT	STORMS	ESA	N/A	No
High energy particle detector	MRM	TBD		N/A	No
High energy particle detector	SURF	TBD		N/A	TBD
High energy particle detector	EPT	STORMS	ESA	N/A	No
High energy particle detector	SEM/EPS	GOES	NOAA	1986	Yes
High energy particle detector	COSTEP	SOHO	ESA	1995	Yes
High energy particle detector	SIS	ACE	NASA	1997	Yes
High energy particle detector	SREM	STRV-1c	QINETIQ	2000	No
High energy particle detector	SREM	Integral	ESA	2002	No
High energy particle detector	SREM	ISS	ESA	2002	No
High energy particle detector	CREAX	ISS	ESA	2002	No
High energy particle detector	SPICA	ISS	ESA	2002	No

Instrument type	Instrument name	Mission	Agency	Launch	Operational
High energy particle detector	IMPACT	Stereo	NASA	2004	No
Ion mass spectrometer	CELIAS	SOHO	ESA	1995	Yes
Ion mass spectrometer	PLASTIC/Solar Wind Sector	Stereo	NASA	2004	No
Ion mass spectrometer	PLASTIC/Wide Angle Partition	Stereo	NASA	2004	No
Ion mass spectrometer	SWA/MIS	SOLO	ESA	2011	No
Ion spectrometer	SIMA	STORMS	ESA	N/A	No
Ion Spectrometer	SWEPAM-I	ACE	NASA	1997	Yes
Ion spectrometer	CIS/HIA	Cluster	ESA	2000	Yes
Ion Spectrometer	PLASTIC/Solar Wind Sector	Stereo	NASA	2004	No
Ion spectrometer	SWA/PAS	SOLO	ESA	2011	No
Ionosonde	RPI	IMAGE	NASA	2000	Yes
Magnetograph	VIM	SOLO	ESA	2011	No
Magnetometer	DC-MFI	STORMS	ESA	N/A	No
Magnetometer	MAG	GOES	NOAA	1986	Yes
Magnetometer	MAG	ACE	NASA	1997	Yes
Magnetometer	FGM	Cluster	ESA	2000	Yes
Magnetometer	MAG	SOLO	ESA	2011	No
Medium energy electron spectrometer	RIS	STORMS	ESA	N/A	No
Medium energy electron spectrometer	EPAM	ACE	NASA	1997	Yes
Medium energy ion spectrometer	RES	STORMS	ESA	N/A	No
Medium energy ion spectrometer	RAPID	Cluster	ESA	2000	Yes
Radio wave detector	WAVES	Stereo	NASA	2004	No
UV imager	EUV	IMAGE	NASA	2000	Yes
Whole disk imager	EIT	SOHO	ESA	1995	Yes
Whole disk imager	SECCHI/EUV1	Stereo	NASA	2004	No
Whole disk imager	EUI/FSI	SOLO	ESA	2011	No

Instrument type	Instrument name	Mission	Agency	Launch	Operational
X-ray photometer/spectrometer	SEM/XRS	GOES	NOAA	1986	Yes

2.6.5 European Heritage/Expertise Table

Country	Institute	Acronym	Instrument type	Name
Austria	Institut fuer Weltraumforschung	IWF	Magnetometer	FGM
Belgium	Centre Spatiale de Liège		Whole disk imager	EIT
Belgium	Centre Spatiale de Liège		Whole disk imager/Coronograph	SECCHI
Belgium	Observatoire Royale de Belgique	ORB	Whole disk imager	EIT
Belgium	Observatoire Royale de Belgique	ORB	Whole disk imager/Coronograph	SECCHI
Canada	Thomson & Nielsen Electronics Ltd		Dose monitor	DDM
ESA	Space Environment and Effects Analysis Section	TOS-EMA	High energy particle detector	MRM
ESA	Space Science Department	SSD	Electric field	EFW
ESA	Space Science Department	SSD	High energy particle detector	IMPACT
France	Centre d'Etude Spatiale des Rayonnements	CESR	High energy particle detector	IMPACT
France	Centre d'Etude Spatiale des Rayonnements	CESR	Ion spectrometer	CIS
France	Institut d'Astrophysique Spatiale	IAS	Whole disk imager	EIT
France	Institut d'Astrophysique Spatiale	IAS	Whole disk imager/Coronograph	SECCHI
France	Institut d'Optique Théorique et Appliqueé	IOTA	Whole disk imager	EIT
France	Institut d'Optique Théorique et Appliqueé	IOTA	Whole disk imager/Coronograph	SECCHI
France	Laboratoire d'Astronomie Spatiale	LAS	Coronograph	LASCO
France	Laboratoire d'Astronomie Spatiale	LAS	Whole disk imager	EIT
France	Laboratoire d'Astronomie Spatiale	LAS	Whole disk imager/Coronograph	SECCHI
France	Observatorie de Meudon		High energy particle detector	IMPACT
France	Observatorie de Meudon		Radio wave detector	WAVES
France	Observatorie de Meudon		Whole disk imager/Coronograph	SECCHI
France	Office National d'Etudes et de Recherches Aérospatiales	ONERA	High energy particle detector	SPICA
Germany	Max-Planck-Institut für Aeronomie	MPAe	Coronograph	LASCO
Germany	Max-Planck-Institut für Aeronomie	MPAe	High energy particle detector	IMPACT
Germany	Max-Planck-Institut für Aeronomie	MPAe	Ion mass spectrometer	CELIAS
Germany	Max-Planck-Institut für Aeronomie	MPAe	Medium energy ion spectrometer	RAPID
Germany	Max-Planck-Institut für Aeronomie	MPAe	Whole disk imager/Coronograph	SECCHI

Country	Institute	Acronym	Instrument type	Name
Germany	Max-Planck-Institut für Aeronomie	MPAe	Whole disk imager/Coronograph	SECCHI
Germany	Max-Planck-Institut für extraterrestrische Physik	MPE	Electric field	EDI
Germany	Max-Planck-Institut für extraterrestrische Physik	MPE	Ion mass spectrometer	PLASTIC
Germany	Max-Planck-Institut für extraterrestrische Physik	MPE	Ion mass spectrometer	CELIAS
Germany	Max-Planck-Institut für extraterrestrische Physik	MPE	Ion spectrometer	CIS
Germany	Technische Universität Braunschweig	TUB	Ion mass spectrometer	CELIAS
Germany	Technische Universität Braunschweig	TUB	Magnetometer	FGM
Germany	Technische Universität Braunschweig	TUB	Medium energy ion spectrometer	RAPID
Germany	University of Kiel		High energy particle detector	IMPACT
Germany	University of Kiel		High energy particle detector	COSTEP
Germany	University of Kiel		Whole disk imager/Coronograph	SECCHI
Hungary	KFKI Research Institute for Particle and Nuclear Physics	RMKI	Magnetometer	FGM
Italy	Istituto di Fisica dello Spazio Interplanetario	IFSI	Ion spectrometer	CIS
Norway	Norwegian Defence Research Establishment	NDRE	Electron spectrometer	PEACE
Norway	University of Bergen		Medium energy ion spectrometer	RAPID
Sweden	Royal Institute of Technology	KTH	Electric field	EFW
Sweden	Swedish Insititute of Space Physics	IRF	Electric field	EFW
Switzerland	Paul Scherrer Institute	PSI	High energy particle detector	SREM
Switzerland	University of Bern		Ion mass spectrometer	PLASTIC
Switzerland	University of Bern		Ion mass spectrometer	CELIAS
Switzerland	University of Bern		Ion spectrometer	CIS
UK	Qinetiq (formerly DERA)		Dose monitor	CREAM/ CREDO
UK	Qinetiq (formerly DERA)		High energy particle detector	CREAX
UK	Qinetiq (formerly DERA)		Thermal energy electron detector	SURF
UK	Qinetiq (formerly DERA)		High energy particle detector	SURF
UK	Imperial College	ICSTM	Magnetometer	FGM
UK	Mullard Space Science Laboratory	MSSL	Electron spectrometer	PEACE
UK	Mullard Space Science Laboratory	MSSL	Whole disk imager/Coronograph	SECCHI
UK	Rutherford Appleton Laboratory	RAL	Electron spectrometer	PEACE

Country	Institute	Acronym	Instrument type	Name
UK	Rutherford Appleton Laboratory	RAL	Medium energy ion spectrometer	RAPID
UK	Rutherford Appleton Laboratory	RAL	Whole disk imager/Coronograph	SECCHI
UK	University of Leicester	RSPP	Auroral imager	
UK	University of Birmingham	DSR	Coronograph	LASCO
UK	University of Birmingham	DSR	Whole disk imager/Coronograph	SECCHI

2.6.6 Ground-based systems

CSMR	Description	Time res	Notes
5	Auroral imaging	1 hour	This requirement is to monitor the location and intensity of the aurora. The req is couched in terms of imaging but it is possible that a meridian scanning photometer could also satisfy the requirement.
7	Auroral equatorward boundary	3 hours	This requirement is to monitor the equatorward boundary of the diffuse aurora which is an optional input to the US Magnetospheric Specification and Forecasting Model (MSFM). Currently determined from particle measurements on polar orbiting s/c. Auroral monitoring could be a substitute, e.g. meridian scanning photometer.
14	F10.7	5 mins	This is a requirement for more frequent measurements of the F10.7 index to complement the Penticton index and would require many more observations around the world. A satellite-based receiver, e.g. at L1, might be more effective if justified as a piggyback on some other mission.
15	F10.7	1 hour	This is a requirement for more frequent measurements of the F10.7 index to complement the Penticton index and would require many more observations around the world. A satellite-based receiver, e.g. at L1, might be more effective if justified as a piggyback on some other mission.
16	F10.7	1 day	This is the standard Penticton index (solar radio flux at 10.7 cm) measured daily at 17:00UTC by Dominion Radio Observatory, Ottawa since 1947. This requirement is effectively a support for continuation of those observations, which have occasionally come under threat through budget pressure.
17	F10.7	1 month	This is the monthly running mean of the Penticton index.
19	Secondary neutron flux	1 hour	This is effectively a requirement to continue the current ground-based neutron monitoring network and to expand and modernise it. Note that the network has been significantly cut-back in recent years.
20	Secondary neutron flux	1 day	This is a requirement to average the previous measurements to 1 day values.
21	Secondary neutron flux	1 month	This is a requirement to average the previous measurements to 1 month values.
22	Secondary neutron flux (aircraft)	5 mins	This is a requirement to carry neutron monitors on aircraft that are in regular use on routes vulnerable to neutron radiation effects (e.g. between Europe and North America). If a significant number of aircraft carried such monitors and with the capability to relay results in real-time to some centre, it would be possible to provide real-time warnings. The data relay would require a low-bit rate channel piggybacked on an existing comms channel - perhaps akin to systems used by to relay digital data to/from taxis.

CSMR	Description	Time res	Notes
28	Kp	3 hours	This is the standard IAGA mid-latitude planetary index, which has been produced since 1932 using a network of 13 magnetometers in Europe, North America and Australia. The real issue here is the provision of indices in near real-time - rather than with some significant time delay as at present. NOAA Boulder produces a provisional value - but, since the end of the Cold War, that is now based only on magnetometers in North America (prior to 1994 the NOAA value also used values from a magnetometer at Upper Heyford in England).
29	Kp*	5 mins	As 28 with higher time resolution. However, note that Kp is a measure of variability within the time bin, specifically the maximum deviation from the quiet-time (tidal) variation in the magnetic field. Thus one must consider whether Kp remains physically meaningful for the higher time resolution. This will depend on the application for which it is required.
30	Ap	1 day	This is a derivative product of Kp. The three-hourly Kp index is converted to a linear equivalent value - termed ap (little a). Ap is the mean of the eight ap values in each day.
31	Dst	1 hour	This is the standard IAGA low-latitude planetary index, which has been produced since 1957 using a network of 4 magnetometers in the tropics. The real issue here is the provision of indices in near real-time - rather than with some significant time delay as at present.
32	Dst*	5 mins	As 31 but reduced at higher time resolution
33	AE index	1 minute	This is the standard index of high-latitude magnetic activity and has been produced since 1957 using a ring of 11 magnetometers in the auroral zone. The real issue here is the provision of indices in near real-time - rather than with some significant time delay as at present. Note that an index similar to AE, but based on three rings at different latitudes (corresponding to a small, normal and large auroral ovals), has been developed at RAL to support Cluster science studies.
34	SSN	1 day	This is the standard index produced by the Sunspot Index Data Centre (SIDC) at the Royal Observatory of Belgium in Brussels (also known as World Data Centre C1 for Sunspots). The index is based a weighted average of data from a network of ground-based solar observatories around the world. It is the continuation of a series of index data originally developed in Zürich but taken over by ROB in 1981. Its great strength is the length of the series - with daily values from 1818, monthly values back to 1749 and yearly values back to 1700. Thus this requirement is effectively a requirement to encourage continued operation of SIDC and the observatory network that supplies the data. Identification of European contributions is important given the context of the study. But it is important to remember that this is a global index so contributions from outside Europe are also important.

CSMR	Description	Time res	Notes
35	SSN	1 month	This is just the monthly average of the daily value. Twelve month running means of monthly values are also widely used, e.g. as the prime indicator of the solar cycle.
44	B-field	1 min	This is a requirement for ground-based magnetometer data to monitor fluctuations in the geomagnetic data. There are already several well-established networks of magnetometers - and with rapid access to those data. Thus this is effectively a requirement to continue those observations, to fill any holes in present networks and to provide rapid access to their data.
45	IPS	1 hour	This requirement addresses the possibility of using measurements of interplanetary scintillation (IPS) to monitor the appearance and motion of heliospheric disturbances such as CMEs and CIRs. The technique uses ground-based radio telescopes to monitor natural radio sources outside the solar system. The signals from these sources are subject to scintillation as they pass through plasma density fluctuations in the inner heliosphere (akin to the twinkling of starlight caused by density fluctuations in the Earth's atmosphere). However, the fluctuations are thought to be proportional to the total density. Thus the scintillation gives a measure of the column density of plasma along the line of sight. Hence, by observing the scintillation in a large number of radio sources, one can build a skymap of column density - in which one can detect density structures propagating through the inner heliosphere. The potential of IPS technique has been known for about forty years but has never been subjected to the extensive engineering analysis and development that could convert into a truly useful technique. For the most part IPS observations have been carried out on systems designed for radio astronomical observations. This imposes many limitations with respect to limits on sampling in space and time, rejection of additional scintillation from the Earth's ionosphere and so on. The potential exists to develop a modern IPS system with good sampling (perhaps via use of a phased-array to actively steer beams onto selected sources), good rejection of ionospheric scintillation through examination of the spectra of the returned signals. Given the much lower cost of ground-based systems and their innate potential for on-going development, an advanced IPS system could compete effectively with space-based coronagraphs for the detection of heliospheric disturbances.

CSMR	Description	Time res	Notes
46	foF2, foE, foF1	5 mins	This is a requirement for routine ionosonde measurements as for CSMR47 (below) but at higher than usual time resolution. Technically it is straightforward to run an ionosonde at 5 minute resolution - but the improved resolution does raise regulatory and financial issues. The regulatory issue is that of obtaining a licence to transmit. An ionosonde is an active instrument that transmits radio waves over a swept spectrum - typically from about 1 to 20 MHz (the upper limit depends on season and solar cycle phase) - and thus has great potential to interfere with nearby electronic systems. Thus to make high resolution observations it is important to use modern ionosondes that can operate efficiently at low power and to chose an operating site with few neighbours and/or good screening. The financial issue is that of ensuring that the equipment is sufficient robust to sustain five minute observations and of increased maintenance costs due to greater wear and tear on the ionosonde.
47	foF2	1 hour	This is a requirement for routine ionosonde measurements and the derivation (scaling is the traditional term in the ionospheric community) of the F2 region critical frequency (foF2). This type of observation has been widely carried out since the International Geophysical Year in 1957 and at some sites for up to 26 years before that. Modern digital ionosondes normally include software for automatic derivation of foF2 and other ionospheric parameters and the automatic dissemination of parameters and ionograms via the Web. Thus this requirement is effectively a requirement to encourage continued operation of the international ionosonde network. Unfortunately, government support for ionosonde networks has weakened dramatically in recent years - often as a result of a perception that ionospheric propagation is of little importance for modern communications. One example of this is the fate of the French ionosonde network. This was long operated by the Centre National pour Etudie Telecommunications (CNET) but has been closed as part of the recent (1999) reconfiguration of CNET as the more commercially-orientated France Telecom R&D. Another example is the precarious situation of the UK ionosonde network. This was long supported by dual funding from science budgets and from government support of radio applications. The reduction of the latter line has already forced the closure of one station and now threatens the whole programme (which now comprises the two sites with the longest ionosonde observation series in the world).

CSMR	Description	Time res	Notes
48	TEC	5 mins	This is a requirement to measure total electron content by monitoring satellite transmissions and looking for effects (e.g. phase delay, Faraday rotation) due to the total electron content along the path from the spacecraft to the monitoring station. This is most commonly performed using GPS signals, which now provide worldwide coverage and thus the opportunity for monitoring TEC worldwide. Some research groups have long exploited satellite transmissions to measure TEC along a range of lines of sight and then apply tomographic techniques to convert this into a height-resolved map of electron density. Methods for two-dimensional reconstruction (latitude and height) are well established. The research community is now addressing the more challenging problem of three-dimensional reconstruction (latitude, longitude and height).
49	TEC	5 mins	as 48
50	Cross-tail electric field	3 hours	This is a requirement to measure the electric field in the magnetotail or the total electric potential that this field imposes across the tail. That potential maps down the geomagnetic field to the ionosphere where is termed the polar cap potential. This is the electric potential across the noon to midnight channel of anti-sunward plasma flow in high-latitude ionosphere. In principle that flow can be measured, with time resolution of a few minutes, using the SuperDARN network of HF backscatter radars, converted to an equivalent electric field using the ideal magnetohydrodynamics equation ($\mathbf{E} = - \mathbf{v} \times \mathbf{B}$) and the electric field integrated to obtain the polar cap potential. In practice, SuperDARN data coverage is rarely ideal because of the incompleteness of the network (e.g. lack of stations in Russia) and poor backscatter signals when and where flow speeds are low. Thus the polar cap potential is actually derived by fitting a model to the data, where the model “fills in the gaps” in data coverage. Hence the measured potential has some dependence on existing models but that dependence decreases with increasing data quality. In summary, the HF backscatter provides an excellent means of monitoring the polar cap potential at good time resolution. But users should understand its limitations as a measurement independent of existing models.
68	Atmospheric scale height	1 day	This may be obtained through analysis of drag effects on satellite orbits.

CSMR	Description	Time res	Notes
70	Meteoroid size and velocity distribution	6 months	Meteoroid size and velocity distribution for masses above about 10^{-8} kg can be monitored from the ground by observing the meteors produced on entry into the Earth's atmosphere. The meteors are produced by ablation of the meteoroid material and produce both light and ionisation. The light emission is usually only observable in night-time conditions and may be recorded using low-light television equipment. The brightness of the meteors may be taken as a measure of the size of the meteoroid; velocity may be determined by observing the meteor from two well-separated sites. The ionisation can be detected using radar techniques and thus may be applied in both day- and night-time. The strength of the radar return may be taken as a measure of the size of the meteoroid; velocity may be determined from analysis of the signal two well-separated sites. The two techniques are complementary in that optical methods are better for studying larger objects (mass > 10^{-5} kg) whereas radar is better for smaller mass (down to 10^{-8} kg). Meteoroids with masses below 10^{-8} kg are best detected through in-situ measurements in space.
71	Meteoroid size and velocity distribution	1 day	As 70

CSMR	Description	Time res	Notes
74	Satellite position	30 mins	Traditionally satellite positions are rarely measured directly. Instead one maintains a mathematical model of the satellite's orbit and repeatedly refines this against radio-wavelength tracking data, e.g. the distance from the ground station (ranging) and the velocity relative to the ground station (Doppler). Thus spacecraft position is a key product of ground-station tracking. Optical methods provide more accurate tracking data. For example, optical observations of satellite motion provide accurate measurements of satellite direction from the ground station (whereas conventional radio observations are limited by the finite beam width of the antenna). Another example is laser ranging which can provide very accurate measurements of spacecraft distance. Optical tracking was a major activity in the 1960s and 1970s (including much interest in manual observations) when there was intense scientific interest in using satellite orbits to study the upper atmosphere and the shape of the Earth. There is much less interest in optical tracking today – presumably because of the costs of maintaining an adequate tracking network and its sensitivity to weather. The main user of optical tracking is the US military for whom accuracy is a key requirement. The advent of GPS has provided a new means of monitoring spacecraft position – at least in low orbits (below the GPS constellation). Several missions have now flown and successfully used GPS receivers.
75	Interplanetary radio emissions	1 hour	Like its space-based cousin discussed above, this is an instrument to detect the natural radio emissions that are thought to originate from electron acceleration in the vicinity of coronal mass ejections. These emissions are generated at the local plasma frequency and thus vary with plasma density - from frequencies of 10 MHz close to the Sun to frequencies of about 40kHz at 1AU. At the high end of this frequency range these emissions will penetrate the Earth's ionosphere and thus be observable from ground-based radio telescopes. Thus ground-based observations can also contribute to this measurement. However, their efficacy will vary significantly from time to time as the ionospheric cut-off frequency (foF2) changes with the seasons and the solar cycle.