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WP431. Spacecraft Interface

Ground segment interface with space-based space weather measurements

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1 Preface

1.1 Document change record

Issue	Date	Notes/remarks
0.1	08 July 2001	Draft for internal review
1.0	03 Sep 2001	First formal version
1.1	04 Sep 2001	Minor editorial changes - including doc number on cover page
1.2	25 Nov 2001	Changes in response to comments on v1.1: • various editorial changes throughout • added methodology figure from Intermediate Review presentation • added discussion on redundancy at various points in sections 4 and 5 • added text in section 4.2 to note that ground-station capital costs may not be charged when using a public sector facility • updated costs for orbit determination and prediction, changes traced through all tables

1.2 Purpose of the document

This document is the output from the ESWS workpackage on spacecraft interface (WP431). It comprises a single chapter to be incorporated in the overall ground segment report (WP432) to be produced by RAL. It is presented here as a separate document for ease of review.

1.3 Definitions, acronyms and abbreviations

CERT	Computer Emergency Response Team
COTS	Commercial Off The Shelf
CPU	Central Processing Unit (computer)
CSMR	Consolidated System Measurement Requirement
ESWS	ESA Space Weather programme Study
FTP	File transfer protocol
GEO	Geosynchronous (orbit)
GOES	Geosynchronous orbiting environment satellite
GTO	Geosynchronous transfer orbit
HTML	Hypertext Markup Language
HTTP	Hypertext transfer protocol
L1	Lagrangian point 1 - 1.5 million km sunward of the Earth
LEO	Low earth orbit
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NORAD	North American Air Defence Command
PC	Personal Computer

PDF	Portable Document Format
SS	Sun-synchronous (orbit)
SY	Staff-year
TBC	To be confirmed
TBD	To be done

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 text 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.
GS_INT	ESWS-RAL-TN-0002, Interface between spacecraft ground segment and space weather service
SOW	Statement of Work for ESA Space Weather Programme, Appendix 1 to AO/1-3533/99/NL/SB
SWR_CAT	ESWS-RAL-RP-0001 Catalogue of European Space Weather Resources
WP410	ESWP-DER-SR-0001, System Requirements Definition

2 Introduction

2.1 Objectives and scope

The aim of this chapter is to specify ground-segment elements required to control and collect data from the various options developed in the space segment architecture (WP422). In particular, we discuss:

- options for telemetry reception (ground stations, networks, …)
- options for telemetry uplink
- telemetry processing at ground station(s) and operations centre(s)
- options for spacecraft and payload commanding
- ground systems for monitoring the payload and the spacecraft

Note that the above scope is limited to the ground segment activities required to operate space-based instruments and convert their output into calibrated physical parameters (e.g. the conversion of particle counts to fluxes). The subsequent use of that data to provide a service for end users is discussed in the companion report on the Space Weather Service (WP432). The interface between these two services is discussed in [GS_INT]. This structure is illustrated in the following figure.

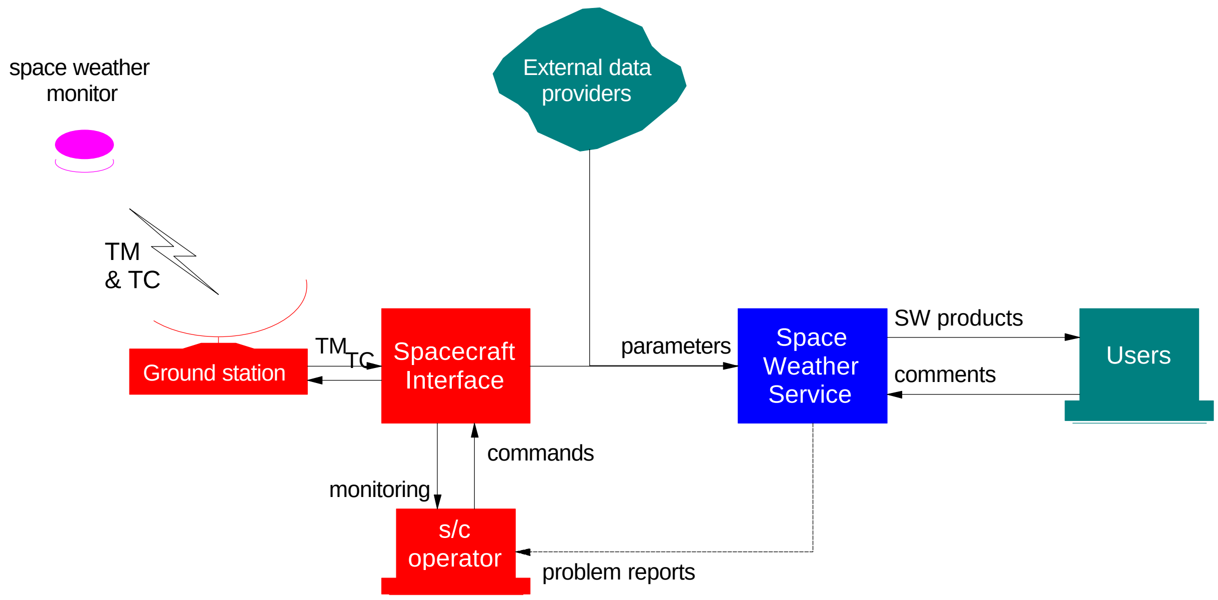

Figure 1. Ground segment for a space weather programme

2.2 Methodology

In section 3 we discuss the three space segment options that are required by the Statement of Work [SOW] - namely, dedicated space weather missions, use of hitch-hiker payloads and use of existing and planned missions. We first identify the ground segment elements that are required for each option. We then consolidate these to produce a list of all potential ground segment elements that may be required in a Space Weather programme. This is effectively a list of "building blocks" which we can then analyse in further detail.

In section 4 we describe each of these ground segment "building blocks" in detail. We describe the general capability of each element and identify the equipment, software and staff required to build, verify and operate that element. In some cases, we identify options for the level of service to be provided. Finally, we provide an estimate of the costs of each factor.

In section 5, we use these building blocks to specify the ground segment needed for each of the space segment options identified in the space segment report [WP420] - and thus derive estimated costs for these ground segments. To maintain traceability from earlier requirements work (WP120 and 410), the ground segment options are cross-referenced to the numbered CSMRs in Appendix C of [WP410].

This methodology is illustrated in Figure 2 below: (a) the top (blue) layer represents the space segment options, (b) the middle (pink) layer represents the building blocks that are identified in Section 3 and described in Section 4, and (c) the bottom (red) layer represents the solutions constructed from those building blocks in Section 5.

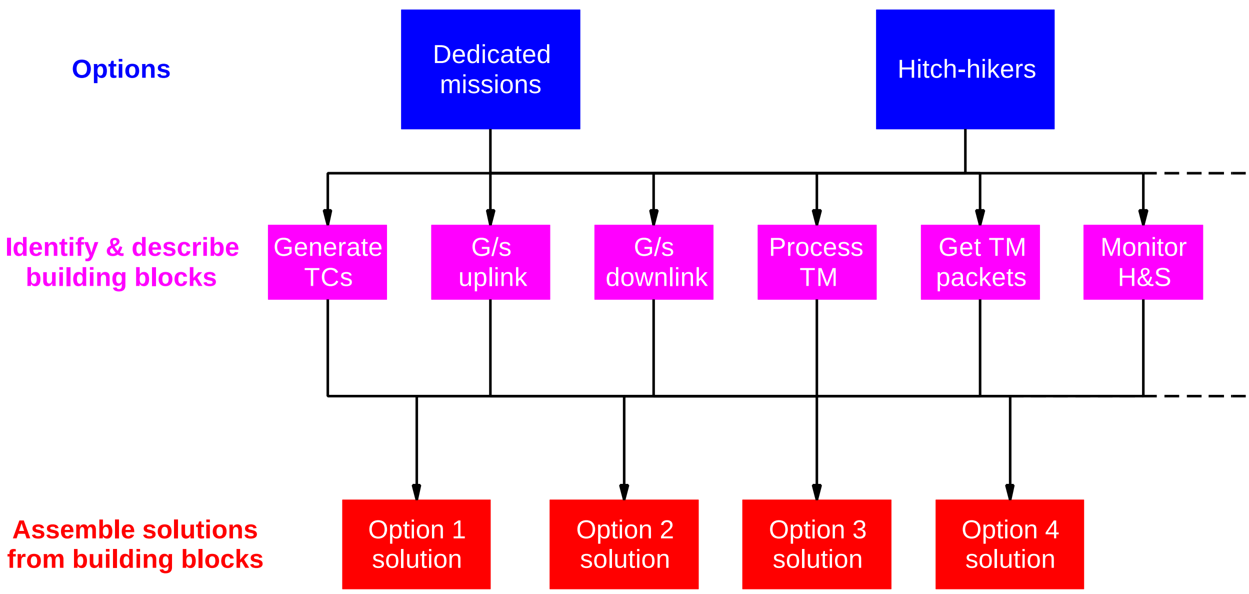

Figure 2. WP431 methodology

3 Space segment options

The space segment architecture [WP420] discussed three major options as required by the Statement of Work [SOW]. These are discussed in the following sub-sections.

3.1 Option 1. Development of dedicated Space Weather spacecraft missions.

In this case, the space weather programme would have full responsibility for spacecraft operations. Thus this option requires a full-scale ground segment with the classical range of functionalities including:

- Generation of commands and delivery to ground station
- Ground station for uplink of commands
- Ground station for reception of telemetry data
- Telemetry processing (extract packets, timestamping)
- Monitoring of the performance of the spacecraft and its sub-systems, including the payload
- Spacecraft operations team
- Deriving s/c orbit and attitude from tracking data etc.
- Generating orbit and event data
- Attitude planning
- Conversion of instrument data into calibrated physical data,
- Making all relevant mission data available to the Space Weather Service

3.2 Option 2. Development of hitchhiker payloads integrated onto existing and planned spacecraft

Here we need to consider how the uplink and downlink are provided:

- For uplink we consider two cases: (a) provision via the host spacecraft ground segment and (b) that there is no uplink, i.e. the hitchhiker instruments runs continuously in a single mode. The latter is likely to be an attractive option for hitchhikers because of its simplicity. We consider that dedicated uplink to a hitch-hiker is not a realistic option - it is extremely unlikely that a spacecraft operator would allow independent commanding of systems attached to that spacecraft.
- For downlink, we consider two cases: (a) provision via the host spacecraft ground segment and (b) provision by a dedicated ground segment. (Downlink must, of course, always be provided.)

This leads to a set of scenarios that are summarised in the following table.

Table 1. Uplink and downlink options for hitch-hiker payloads

		Downlink provided by	
		Host	Dedicated
Uplink provided by	Host	Submit commands to host GS, Collect all data from host GS	Submit commands to host GS, Receive telemetry from SC, collect orbit data from host GS
	None	Collect all data from host GS	Receive telemetry from SC, collect orbit data from host GS

However, it is important to note that any single space weather mission can follow different scenarios at different times. A prime example of this is the Real-Time Solar Wind (RTSW) experiment on the NASA ACE spacecraft - see page 633 of [ACE]. This is a hitch-hiker system that acquires data from science instruments on ACE and extracts selected parameters relevant to space weather conditions at the L1 Lagrangian point (where ACE is located) - namely solar wind density and velocity, the components of the interplanetary magnetic field and the fluxes of energetic particles. For most of the time the RTSW experiment uses a dedicated downlink system while the host spacecraft data are stored on an internal solid-state recorder. But for three hours each day the data are downlinked in the host spacecraft data stream that dumps the solid-state recorder.

The analysis allows us to identify optional and mandatory ground segment services for hitchhiker operations. The optional services are:

- Generation of commands and their delivery to the host satellite ground segment - in cases where commanding is required
- Ground station for reception of telemetry data, plus processing of that telemetry (e.g. to extract and timestamp packets) – in cases where dedicated downlink is used
- Retrieval of telemetry data from host satellite ground segment – where host system downlink is used
- Generation of orbit and event data as needed to support ground station operations (dedicated downlink) or instrument commanding (where required).
- Spacecraft operations team. This is required whenever any of the optional services are used.

The mandatory services are:

- Collection of orbit and attitude from host ground segment,
- Conversion of instrument telemetry data into calibrated physical data,
- Making all relevant mission data available to the Space Weather Service.

3.3 Option 3. Utilisation of the existing and planned space-based infrastructure

In this case the space weather programme would have no responsibility whatsoever for spacecraft operations. The Space Weather Service would retrieve relevant data directly from the ground segment of the relevant missions. Thus no spacecraft interface is required and hence this option is not discussed further in this report.

3.4 Summary of requirements for the different options

We now summarise the various ground segment services that have been identified in the previous section. These services are listed in the table below together with the mapping of these services to the space segment options 1, 2 and 3.

Table 2. Summary of ground segment requirements

Ground segment function	Option 1	Option 2	Option 3
Generation of commands and delivery to uplink service (dedicated ground station or host satellite ground segment)	Yes.	If commands needed	No
Ground station for uplink of commands	Yes	No	No
Ground station for reception of telemetry data	Yes	Dedicated downlink	No
Retrieve data from host satellite ground segment	No	Yes	No
Telemetry processing (extract packets, timestamping)	Yes	Dedicated downlink	No
Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Yes	No	No
Spacecraft operations team	Yes	Dedicated downlink, and if commands needed	No
Deriving s/c orbit and attitude from tracking data etc.	Yes	No	No
Generating orbit and event data	Yes	No	No
Collection of orbit and attitude data	No	Dedicated downlink, and if commands needed	No
Attitude planning	Yes	No	No
Conversion of instrument data into calibrated physical data,	Yes	Yes	No
Making all relevant mission data available to the Space Weather Service	Yes	Yes	No

These services, and the relationships between them, may also be summarised graphically. This is shown in the figure below. The various items are colour-coded to distinguish mandatory items (red), additional items needed to support dedicated downlink (purple) and additional items needed to support instrument commanding (green). Note that some items are coded with both purple and green to show that they would be needed in either the case of dedicated downlink or instrument commanding. For full dedicated operations, the items in blue should be added to those in the other three colours.

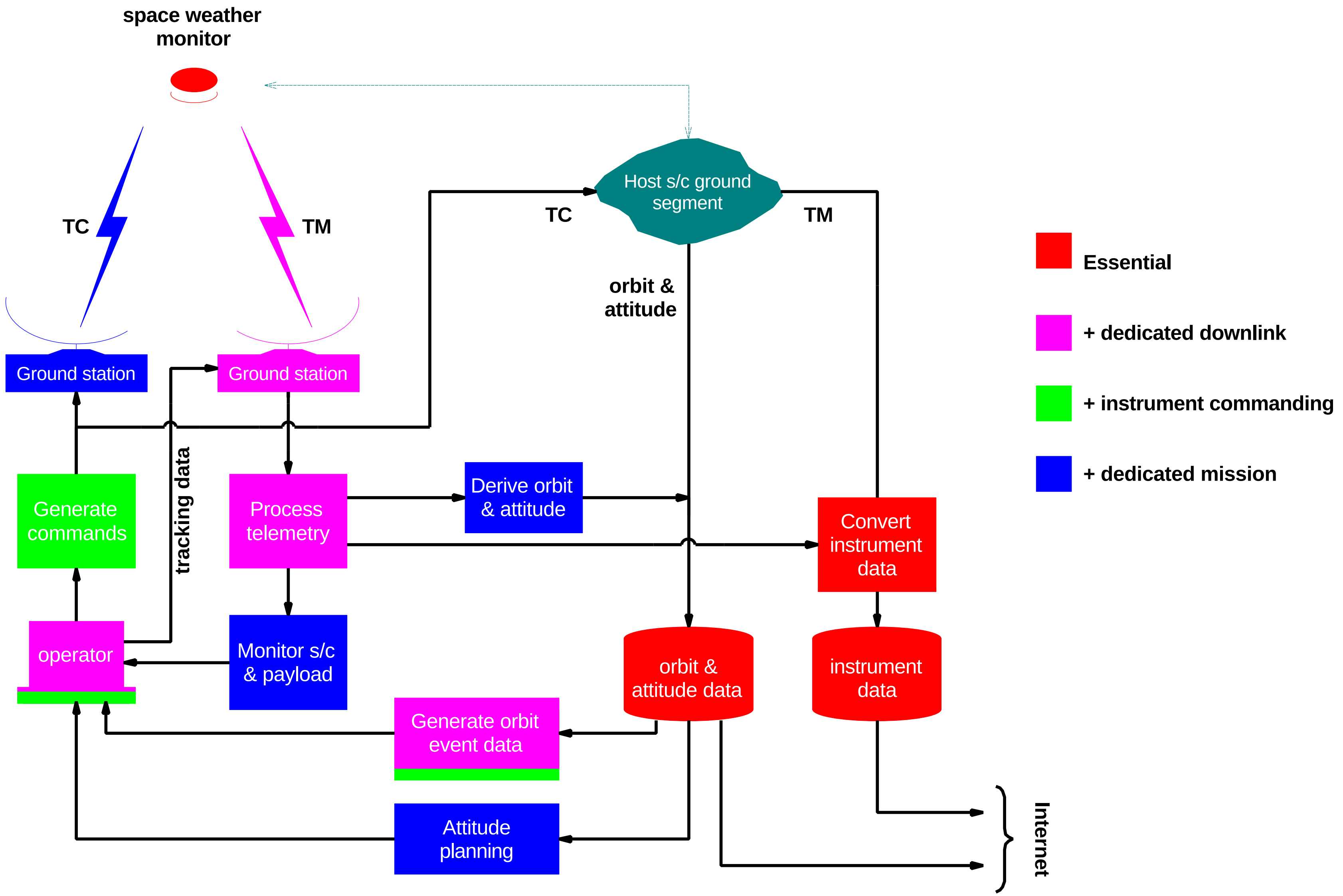

Figure 3. Conceptual design of spacecraft interface

4 Ground segment services

In the previous section we identified the various ground segment services required to support a dedicated space weather mission or a hitchhiker payload. We discuss those services below to identify:

- General capabilities of the service
- Key constraints on the service
- Equipment requirements
- Software requirements
- Staff requirements

The discussion of the last three bullets will specify the costs associated with each service. But note that these costs will be consolidated in section 5 when we apply them to specific space segment options. The aim in this section is only to identify the elements that can be used in that consolidation.

But before we discuss each services we list a few general assumptions that apply throughout. This avoids needless replication.

- Staff costs. We convert from staff years (SY) to money as follows: (a) for development (set-up and verification) costs we assume a staff rate of 130 kEuro per SY, but (b) for operations costs we assume a lower rate of 100 kEuro per SY.
- Software development environment. Several services require the development of bespoke software. In these cases the staff effort for software development is included in the staff requirements. But there is also the cost of providing a good environment for quality development of software, i.e. software tools for requirements management, design, coding and testing.
- Redundancy. The ground segment will require redundancy in terms of ground stations, computer systems and operations staff. We discuss provision of redundancy for ground stations and operations staff in the appropriate sub-sections below. Redundancy of computer systems (hardware, software and data) is covered by the provision of multiple units as discussed in section 5.

4.1 Generation of commands

General capabilities: This service must be able to generate a timeline of instrument telecommands and deliver them to the uplink service. For most space weather missions, we expect that the instruments will operate continuously in a fixed mode and hence we expect a relatively low command density with time. Indeed, in some cases, there may be zero commanding, i.e. the instrument remains in a fixed configuration throughout its mission. In such cases this service will not be required. These low command densities are in marked contrast to science missions for which high command densities are common (reflecting the setting of different modes to address different science targets).
Key constraints: Command triggers. What are the events that can require commanding of space weather instruments? Some possibilities include: • Predictable changes in the space environment, e.g. for instruments in polar low Earth orbit it may be necessary to vary instrument settings with latitude, for instruments in geo-or sun-synchronous orbits it be necessary to change settings during eclipse seasons. • Instrument monitoring, e.g. the monitoring of data from the instrument may lead to a decision to change a setting such as an instrument gain. • Contingencies, e.g. problems require action to restore nominal operation of the instrument. Command response. We assume that instrument commanding is prepared in normal working hours (i.e. no weekend or night-time working) Time-tagging. Some of the above triggers require that commands are time-tagged (e.g. changes in the space environment) while others are more suited to real-time operation (e.g. contingency operations). For simplicity it may be better to time-tag all commands and for operators to perform real-time operations by time-tagging to the top of the next minute.
Equipment: PC or workstation.
Software: The following software is essential: database of instrument commands and parameters (including database editors), tool to build command timeline in response to operator requests, mechanism to deliver timeline to ground station. These are available as COTS products at a cost of 20 kEuro (tbc). In addition the service may need a tool to build command timeline in response to predictions of change in the space environment. This will be required only if changes are frequent such that it is not practicable, safe or economic to perform this task using the manual command tool. This may require a bespoke software product.
Staff: For a simple instrument that does not require frequent commanding in response to the space environment we estimate a set-up and verification cost of 0.5 SY and an operating cost of 0.2 SY per year. For a more complex instrument that requires frequent commanding we estimate a set-up and verification cost of 2.0 SY and an operating cost of 0.3 SY per year.

4.2 Ground station for uplink of commands

General capabilities: This service has a number of attributes: 1. It must have an antenna that can transmit on the appropriate frequency. 2. It must be able to receive data on the predicted spacecraft position and use these to control the antenna to acquire and track the spacecraft. 3. It must be able to receive a series of spacecraft commands from the service above, encode it into the required telemetry format and uplink it to the spacecraft.
Key constraints: Spacecraft visibility. This is always the prime constraint on ground station operations. The spacecraft must be above the local horizon (including masking by nearby hills and buildings) in order to be in contact with the ground station. Safety. Active operation of a ground station may require consideration of margins over the local horizon in order to avoid excessive human exposure in side lobes. Also local safety rules may require that ground stations are staffed during active operations. Coverage: Uplink will be only an occasional activity - requiring perhaps 10% of a ground station's available time. Redundancy: We assume that, where practicable, backups will be provided for critical components of a ground station. But we also recognise that this is not feasible for some components, e.g. the antenna and its drive motors.
Equipment: Antenna and supporting equipment including control computer(s) such as PCs. We assume that, in general, a space weather service would make use of existing ground segment infrastructure and not develop new ground stations for its own use. Thus there would be no large capital outlay for construction of a ground station. However, the ground station operator may have to recover a part of their capital costs by a charge to users. We assume an operational charge of 50 kEuro/year in this respect. Note this capital element may not arise if using a ground station operated by a public sector organisation that is required only to recover running costs.
Software: This is included in the ground station equipment above.
Staff: The principal direct cost for using a ground station will be staff effort. We assume a set-up and verification cost of 0.5 SY and an operational cost of 0.2 SY for uplink.

4.3 Ground station for reception of telemetry data

General capabilities: This service has a number of attributes: 1. It must have an antenna that can receive on the appropriate frequency. 2. It must be able to receive data on the predicted spacecraft position and use these to control the antenna to acquire and track the spacecraft. 3. It must be located away from sources of interference
Key constraints: Spacecraft visibility. This is always the prime constraint on ground station operations. The spacecraft must be above the local horizon (including masking by nearby hills and buildings) in order to be in contact with the ground station. Safety. Passive operation of a ground station does not raise the safety issues discussed for active operations. Unstaffed operation is therefore a realistic option. This then requires an automated monitoring function that can alert on-call support staff, e.g. via a pager. It is also desirable to provide those staff with secure remote access to monitoring equipment and control systems outside working hours– so they can assess the problem and determine if a site visit is required or if remote fix is possible under software control. Coverage: Downlink will be a near-continuous activity - requiring all of a ground station's available time within visibility.
Equipment: Antenna and supporting equipment, control computer(s) such as PCs. As above we assume use of existing ground segment infrastructure. Given the much greater coverage required for downlink , we estimate an operational charge of 150 kEuro/year for 30% coverage and 500 kEuro/year for 100% coverage.
Software: This is included in the ground station equipment above.
Staff: The principal direct cost for using a ground station will be staff effort. We assume a set-up and verification cost of 0.5 SY. For the operational cost we estimate 1 SY for 30% coverage and 2 SY for 100% coverage.

4.4 Retrieve data from host satellite ground segment

General capabilities: This is a capability to establish a network link with the host satellite ground segment and retrieve processed telemetry packets via that link. The data flow over the link may be a data stream or a series of files; the choice depends on whether a continuous stream of data is required or if the data can be broken up into file
Key constraints: Security of the connection. Thus: • this should use secure protocols wherever appropriate, • packet level checking may be applied to ensure packets are exchanged only between authorised computers • operations staff should abide by local security policies – especially any requirements to monitor and implement regular security notices, e.g. CERT Advisories
Equipment: PC or workstation with internet connection
Software: Software to establish the required protocols is readily available as low-cost COTS products. We assume a set up cost of just 1 kEuro.
Staff: Set up and verification cost 0.1 SY, the operational cost is likely to be dominated by trouble-shooting occasional problems rather than routine operation and thus difficult to estimate. If we assume two problems per year, each of which takes a day of staff effort, the staff cost is still only 0.01 SY.

4.5 Telemetry processing

General capabilities: This is the function to decode the downlink telemetry into packets, to timestamp them and forward them to the data processing centre.
Key constraints: Use of modern telemetry standards greatly facilitates this function, e.g. through the use of COTS products.
Equipment: PC with dedicated computer card for telemetry decoding. Say 5 kEuro for board.
Software: COTS software say 5 kEuro.
Staff: Set up and verification cost 0.1 SY, the operational cost is likely to be dominated by trouble-shooting occasional problems rather than routine operation and thus difficult to estimate. If we assume two problems per year, each of which takes a day of staff effort, the staff cost is still only 0.01 SY. This can probably be neglected.

4.6 Performance Monitoring

General capabilities: This is the function to process housekeeping data from the payload (and the spacecraft where appropriate) and to assess that data through a combination of automatic and manual processes.
Key constraints: None
Equipment: PC or workstation. For small-scale projects this may be shared with other ground segment activities.
Software: Software to extract housekeeping parameters, to convert them to physical units (e.g. voltages, temperatures, …), check for out-of-limit values and place in short-term archive. To support manual assessment there must also be a capability to display particular values or sets of values as a function of time. This software may be a bespoke development but more generic solutions are possible using tables to specify: (a) rules for extraction of housekeeping parameters, (b) calibration curves for their conversion to physical units, and (c) out-of-limit values. For a simple system using generic COTS software we assume a software price of 20 kEuro. For a bespoke development we assume only minor software purchases (5 kEuro) and that the major cost is extra staff for software development.
Staff: Set up and verification cost 1 SY if an existing generic tool is adapted, 3SY if a bespoke tool is required; operational cost 1 SY/year

4.7 Spacecraft operations team

General capabilities: This is the team responsible for operation of the dedicated spacecraft or hitchhiker payload. It will have a responsibility for spacecraft/payload operation and management that goes beyond the functions described elsewhere in this section. In particular, it will be responsible for the following functions: • Project management - including reporting to appropriate authorities, support for project reviews, management of all staff involved in the ground segment and leadership role (especially in case of operational problems) • Mission Engineers - the acquisition and maintenance of adequate knowledge of the spacecraft systems/payload, maintenance of flight control procedures, planning of special operations, expertise for trouble-shooting problems. • Spacecraft controllers - the day-to-day operation of the spacecraft. This is anticipated to be a 24 hour operation, so 5 staff are required to ensure continuous availability of one person.
Key constraints: For the purpose of this exercise we assume that the spacecraft operations will not have to pay to meet any safety requirements with respect to two-person working outside normal working hours - and that such requirements will be satisfied by synergy with other activities. The team size for a dedicated mission should ensure backup of staff effort to cover unplanned staff absences (e.g. illness or other family emergency). For a hitch-hiker payload we assume that manual operations are not time critical and thus that prompt availability of backup staff is not required.
Equipment: None
Software: None
Staff: *Hitchhiker*: Set-up: project management 2 SY, mission engineers 2 SY, spacecon 0 SY; Operations: project management 0.3 SY/year, mission engineers 0.7 SY/ year, spacecon 0 SY/ year *Dedicated mission.* Set-up: project management 5 SY, mission engineers 4 SY, spacecon 5 SY; Operations: project management 1 SY/year, mission engineers 2 SY/ year, spacecon 5 SY/ year.

4.8 Deriving s/c orbit and attitude from tracking data etc.

General capabilities: This is the function of using tracking data from ground stations to build and update a mathematical model of the spacecraft orbit.
Key constraints:
Equipment: PC or Workstation
Software: Orbit processing software. This is a complex piece of software but COTS solutions are available - costed at 25kEuro.
Staff: An analyst is required to operate the software. Set up and verification cost 0.3 SY, operational cost 0.6 SY.

4.9 Generating orbit and event data

General capabilities: This is the function of taking a mathematical model of the spacecraft orbit (e.g. as derived above or taken from NORAD data) and propagating it into the future to provide planning data.
Key constraints:
Equipment: PC or Workstation
Software: COTS orbit software. If predictions of location within the magnetosphere are required, this may require some bespoke extension. Thus it is necessary to use a COTS solution that supports user-extensions. We estimate 10 kEuro for the COTS product.
Staff: Simple approach. Set up and verification cost 0.3 SY, operational cost 0.4 SY. Magnetospheric planning needed. Set up and verification cost 0.6 SY, operational cost 0.4 SY.

4.10 Collection of orbit and attitude data from host satellite ground segment

General capabilities: As with retrieval of instrument data above, this requires a capability to establish a network link with the host satellite ground segment. But in this case that link will be used to retrieve orbit and attitude data. In this case we anticipate that the data flow over the link will be a series of files as orbit and attitude data will be updated periodically rather than continuously.
Key constraints: Security of the connection – as for retrieval of instrument data
Equipment: PC or workstation with internet connection – as for retrieval of instrument data
Software: Software – as for retrieval of instrument data
Staff: As for retrieval of instrument data

4.11 Attitude planning

General capabilities: This is a capability to predict satellite attitude into the future and to assess its implications, e.g. with respect to power and thermal control.
Key constraints:
Equipment: PC or workstation
Software: Software for predicting attitude and assessing its implications. Use COTS s/w where appropriate. 10 kEuro.
Staff: An analyst is required to operate the software. Set up and verification cost 0.5 SY, operational cost 1 SY

4.12 Conversion of instrument data into calibrated physical data

General capabilities: This is a capability to process instrument telemetry packets, to extract the measured values and convert them into calibrated physical units. The output files should be written in the agreed format for dissemination via the space weather service and follow the agreed file naming convention. It may be appropriate to write the master copy of each file to a secure archive and then make an operational copy which is made available for remote access, e.g. by placing the files in the correct directory on the appropriate server. It may also be necessary to update various catalogue entries.

Key constraints:
Continuous operation. This service must run continuously in order to provide up-to-date space weather data. Thus:

- Software must be capable of reliable autonomous operation overnight and over weekends
- There should be some automated ability to detect problems and notify support staff that attention is required
- It is very desirable to have a backup system in case of the failure of the main system

Equipment: PC or workstation.

Software: This is likely to require bespoke software as the conversion to calibrated physical data is usually very specific to the instrument design and especially any special features or problems associated with that design. The latter may only emerge with flight experience. It may be possible to use standard software for telemetry decoding. Thus the major software cost is staff effort and is included in the figures below. There will be a direct cost in terms of providing a good environment for quality software development, i.e. software tools for requirements management, design, coding and testing. Say 15 kEuros.

Staff: Set-up and verification 2.5 SY/instrument (2 SY pre-launch and 0.5 SY post-launch). Operation 0.1 SY/year/instrument.

4.13 Making all relevant data available to the Space Weather Service

General capabilities: This is a capability to provide on-line access to a regularly updated database of calibrated physical data. For the purposes of this report we model this service as an anonymous FTP server with data files being updated
Key constraints: Security of the connection. Thus: • Open access to the data may be preferred as this eliminates the need to exchange authentication data across the internet. If authentication is required, the server should use secure protocols to encrypt the authentication data. • If open access is granted, the server must be configured in a secure manner – following appropriate guidance for whatever software is run on the server, e.g. anonymous FTP, HTTP, etc. • Operations staff should abide by local security policies – especially any requirements to monitor and implement regular security notices, e.g. CERT Advisories Continuous operation. This service must run continuously in order to provide up-to-date space weather data. Thus: • Software must be capable of reliable autonomous operation overnight and over weekends • There should be some automated ability to detect problems and notify support staff that attention is required • It is very desirable to have a backup system in case of the failure of the main system
Equipment: PC or workstation with internet connection.
Software: FTP or HTTP server. Cost 5 kEuro.
Staff: Set up and verification costs 0.2 SY. The operational cost is likely to be dominated by trouble-shooting occasional problems rather than routine operation and thus difficult to estimate. If we assume two problems per year, each of which takes a day of staff effort, the staff cost is 0.01 SY.

4.14 Summary of ground segment elements and their costs

			Equipment & software (kEuro)		Staff (SY)			
Sec.	*Ground segment function*	Option	Set-up	Ops	Set-up	Ops	Set-up cost (kEuro)	Ops cost (kEuro / year)
1	Generation of commands and delivery to uplink service (dedicated ground station or host satellite ground segment)	Simple	20	4	0.5	0.2	85	24
		Complex	20	4	2	0.3	280	34
2	Ground station for uplink of commands		0	50	0.5	0.2	65	70
3	Ground station for reception of telemetry data	30%	0	150	0.5	1	65	250
		100%	0	500	0.5	2	65	700
4	Retrieve data from host satellite ground segment		1	0	0.1	0.01	14	1
5	Telemetry processing (extract packets, timestamping)		10	1	0.1	0.01	23	2
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	20	4	1	1	150	104
		Complex	5	1	3	1	395	101
7	Spacecraft operations team	Hitchhiker	0	0	4	1	520	100
		Dedicated	0	0	14	8	1820	800
8	Deriving s/c orbit and attitude from tracking data etc.		25	5	0.3	0.6	64	65
9	Generating orbit and event data	Simple	10	2	0.3	0.4	49	42
		Mag'sphere	10	2	0.6	0.4	88	42
10	Collection of orbit and attitude data		1	0	0.1	0.01	14	1
11	Attitude planning		10	2	0.5	0.4	75	42
12	Conversion of instrument data into calibrated physical data,		15	3	2.5	0.1	340	13
13	Making all relevant mission data available to the Space Weather Service		5	1	0.2	0.01	31	2

Table 3. Summary of ground segment building blocks.

5 Solutions

We can now use the building blocks from the previous section to specify the ground segment services required by the various space segment options developed in the ESWS study. These options are listed in tables 55 and 56 of the space segment report [WP420].

5.1 Hitch-hiker options

5.1.1 Summary of options

The hitch-hiker options are taken from table 55 of [WP420] and are summarised in the following table (note that we include only items identified as hitch-hikers in that table; we exclude items identified as requiring dedicated or ground-based solutions). For each option we also assign a reference number (leftmost column) and specify how downlink of hitch-hiker data has been modelled.

Option	CSMR	Description	Orbit	Downlink options
1	1	Whole disk imager	GEO	Via host
2	2	Coronagraph	GEO	Via host
3	4,6	Auroral imager	SS	2 ground stations
4	8 to 11	X-ray photometer / spectrometer	GEO	Via host
5	12	UV photometer	GEO	Via host
6	13	EUV photometer	GEO	Via host
7	36 to 38	Magnetograph	GEO	Via host
8	53 to 55	Medium energy electron spectrometer	GEO	Via host
9	56 to 58, 62	Thermal energy ion spectrometer	GEO	Via host
10	59 to 61	Thermal energy ion spectrometer	GEO	Via host
11	63 to 65	High energy ion detector	GEO	Via host
12	66 to 67	High energy electron spectrometer	GEO	Via host
13	69 to 71	Debris monitor	SS	Via host
14	72	Dose monitor	Onboard s/c	Return of mission

Table 4. Summary of hitch-hiker options

5.1.2 Detailed costings

The detailed costings are shown in the three tables on the three following pages (one table per page). Each table shows the different ground segment building blocks as rows and the hitch-hiker options as columns labelled 1 to 14. The three tables show:

- The number of instances of each ground segment building block that are required for each hitch-hiker option. For hitch-hikers this number is normally either 0 (i.e. building block not required) or 1 (building block required); values greater than 1 appear only in the case that more than more ground-station is required.
- The set-up costs of the instances shown in the first table. These costs include purchase of equipment and software, costs of implementing the required functionality and costs of verifying its correct operation. The set-up costs for each hitch-hiker option also include a block cost for purchase of general purpose computer equipment (e.g. CPU, screens and discs) for dedicated support of each option. It is better to cost computer equipment on a per option basis since it will then be shared by all the different building blocks that require computer power. This set of computing equipment must include purchase of sufficient multiple units (of CPUs, discs, etc) to ensure redundancy of all ground segment functions supported by the computers. The sub-totals at the bottom of this table show the set-up costs of each hitch-hiker option.
- The annual costs of operating the instances shown in the first table. These include a block cost for computer maintenance estimated at 20% of purchase cost. The sub-totals at the bottom of this table show the operational costs of each hitch-hiker option.

There are a number of assumptions built into these tables as follows:

- It is assumed that all hitch-hikers are commanded via the host spacecraft ground segment and its uplink service - so that the operator of the host can monitor that command stream to assure spacecraft safety.
- It is assumed that all hitch-hikers return data via the host spacecraft telemetry except for option 3, auroral imager in sun-synchronous orbit, and option 14, the on-board dose meter. Most hitch-hikers are in GEO orbit and thus we assume that they have continuous telemetry contact. In contrast, the two hitch-hikers in sun-synchronous orbit (option 3 and 13) will have only intermittent telemetry contact. This is a major issue for option 3 as this requires rapid data downlink and so a dedicated downlink is assumed here. In contrast, option 13 places no urgent demands on downlink and so downlink at the convenience of the host is assumed. Option 14 is considered to be an instrument on a manned mission and that the instrument and its data will return with the mission.
- It is assumed that telemetry processing (time-stamping, etc) of packets returned via host spacecraft downlink is performed by the host spacecraft ground segment.

Matrix to match GS blocks to SS options			Hitch-hiker space segment options													
Block	Description	Sub type	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Generation of commands and delivery to uplink service	Simple	1	1	1	1	1	1	1	1	1	1	1	1	1	0
		Complex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ground station for uplink of commands		0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ground station for reception of telemetry data	30%	0	0	2	0	0	0	0	0	0	0	0	0	0	0
		100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Retrieve data from host satellite ground segment		1	1	0	1	1	1	1	1	1	1	1	1	1	1
5	Telemetry processing (extract packets, timestamping)		0	0	2	0	0	0	0	0	0	0	0	0	0	0
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		Complex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Spacecraft operations team	Hitchhiker	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8	Deriving s/c orbit and attitude from tracking data etc.		0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Generating orbit and event data	Simple	1	1	0	1	1	1	1	0	0	0	0	0	0	0
		Mag'sphere	0	0	1	0	0	0	0	1	1	1	0	0	0	1
10	Collection of orbit and attitude data		1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	Attitude planning		0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Conversion of instrument data into calibrated physical data,		1	1	1	1	1	1	1	1	1	1	1	1	1	1
13	Making mission data available to the Space Weather Service		1	1	1	1	1	1	1	1	1	1	1	1	1	1

Set-up costs (KEuro total)			Hitch-hiker space segment options													
Block	Description	Sub type	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Generation of commands and delivery to uplink service	Simple	85	85	85	85	85	85	85	85	85	85	85	85	85	0
		Complex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ground station for uplink of commands		0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ground station for reception of telemetry data	30%	0	0	130	0	0	0	0	0	0	0	0	0	0	0
		100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Retrieve data from host satellite ground segment		14	14	0	14	14	14	14	14	14	14	14	14	14	14
5	Telemetry processing (extract packets, timestamping)		0	0	46	0	0	0	0	0	0	0	0	0	0	0
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	150	150	150	150	150	150	150	150	150	150	150	150	150	150
		Complex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Spacecraft operations team	Hitchhiker	520	520	520	520	520	520	520	520	520	520	520	520	520	520
8	Deriving s/c orbit and attitude from tracking data etc.		0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Generating orbit and event data	Simple	49	49	0	49	49	49	49	0	0	0	0	0	0	0
		Mag'sphere	0	0	88	0	0	0	0	88	88	88	0	0	0	88
10	Collection of orbit and attitude data		14	14	14	14	14	14	14	14	14	14	14	14	14	14
11	Attitude planning		0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Conversion of instrument data into calibrated physical data,		340	340	340	340	340	340	340	340	340	340	340	340	340	340
13	Making mission data available to the Space Weather Service		31	31	31	31	31	31	31	31	31	31	31	31	31	31
	Computers		30	30	30	30	30	30	30	30	30	30	30	30	30	30
		sub-totals	*1233*	*1233*	*1434*	*1233*	*1233*	*1233*	*1233*	*1272*	*1272*	*1272*	*1184*	*1184*	*1184*	*1187*

Operational costs (kEuro per year)			Hitch-hiker space segment options													
Block	Description	Sub type	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Generation of commands and delivery to uplink service	Simple	24	24	24	24	24	24	24	24	24	24	24	24	24	0
		Complex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Ground station for uplink of commands		0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Ground station for reception of telemetry data	30%	0	0	500	0	0	0	0	0	0	0	0	0	0	0
		100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Retrieve data from host satellite ground segment		1	1	0	1	1	1	1	1	1	1	1	1	1	1
5	Telemetry processing (extract packets, timestamping)		0	0	4	0	0	0	0	0	0	0	0	0	0	0
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	104	104	104	104	104	104	104	104	104	104	104	104	104	104
		Complex	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Spacecraft operations team	Hitchhiker	100	100	100	100	100	100	100	100	100	100	100	100	100	100
8	Deriving s/c orbit and attitude from tracking data etc.		0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Generating orbit and event data	Simple	42	42	0	42	42	42	42	0	0	0	0	0	0	0
		Mag'sphere	0	0	42	0	0	0	0	42	42	42	0	0	0	42
10	Collection of orbit and attitude data		1	1	1	1	1	1	1	1	1	1	1	1	1	1
11	Attitude planning		0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Conversion of instrument data into calibrated physical data,		13	13	13	13	13	13	13	13	13	13	13	13	13	13
13	Making all relevant mission data available to the Space Weather Service		2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Computer maintenance		6	6	6	6	6	6	6	6	6	6	6	6	6	6
		Sub-totals	*293*	*293*	*796*	*293*	*293*	*293*	*293*	*293*	*293*	*293*	*251*	*251*	*251*	*269*

5.2 Dedicated space segment options

5.2.1 Summary of options

The dedicated space segment options are taken from table 56 of [WP420] and are shown in the table below. For each option we also assign a reference number (leftmost column) and specify the number of ground-stations needed for downlink of data.

Option	CSMR	Description	Orbit	No. of spacecraft	No of ground stations
1	3	Coronagraph	leading heliocentric (L4)	1	3
2	2, 3, 75	Coronagraph, Radio Wave Detector	trailing heliocentric (L5)	1	3
3	39 to 43	Magnetometer	M/sphere	30	4
4	52, 53 to 55, 59 to 61, 66 to 67	Thermal energy ion spectrometer;/Ionosonde,/UV Imager, Medium energy electron spectrometer, Thermal energy ion spectrometer, High energy electron spectrometer	GTO	4	4
5	1, 8 to 11, 12, 13	Whole disk imager, X-ray photometer / spectrometer, UV photometer, EUV photometer	L1	1	3
6	23 to 27, 36 to 38, 56 to 58, 62, 63 to 65	Thermal energy ion spectrometer, Magnetometer, Thermal energy ion spectrometer, High energy ion detector	L1	1	3
7	4,6, 69 to 71	Auroral imager, Debris monitor	SS	1	2
8	4,6	Auroral imager	SS	1	2

Table 5. Summary of dedicated mission options

5.2.2 Detailed costings

The detailed costings are shown in the three tables on the three following pages (one table per page). Each table shows the different ground segment building blocks as rows and the dedicated options as columns labelled 1 to 8. The three tables show:

- The number of instances of each ground segment building block that are required for each dedicated option. For dedicated options this number is normally either 0 (i.e. building block not required) or 1 (building block required); values greater than 1 appear in two cases: (a) where more than more ground-station is required, and (b) where more than one instrument is flown on the dedicated mission.
- The set-up costs of the instances shown in the first table. These costs include purchase of equipment and software, costs of implementing the required functionality and costs of verifying it correct operation. The set-up costs for each dedicated option also include a block cost for purchase of general purpose computer equipment (e.g. CPU, screens and discs) for support of that option. It is better to cost computer equipment on a per option basis since it will then be shared by all the different building blocks that require computer power. This set of computing equipment must include purchase of sufficient multiple units (of CPUs, discs, etc) to ensure redundancy of all ground segment functions supported by the computers. The sub-totals at the bottom of this table show the set-up costs of each dedicated option.
- The annual costs of operating the instances shown in the first table. These include a block cost for computer maintenance estimated at 20% of purchase cost. The sub-totals at the bottom of this table show the operational costs of each dedicated option.

There are a number of assumptions built into these tables as follows:

- That only a small amount of commanding is required - so this can be handled by a single ground station, i.e. command uplink can wait until the spacecraft is in view from that ground-station.
- That L1 missions require at least three ground stations spaced in longitude around the Earth for 24-hour coverage. This issue is the same as that for the present space weather monitoring by ACE and is discussed in the relevant section of [ACE].
- That the 4 GTO missions will require one ground station each, i.e. a total of 4 stations
- That 4 ground stations will suffice for the SWARM concept.
- That 2 ground stations are required for the auroral imager (i.e. one in each of the polar regions).
- That the cost of converting instrument data into calibrated physical data scales linearly as the number of instruments. This seems reasonable given that each instrument will have its own unique features.

Matrix to match GS blocks to SS options			Dedicated space segment options							
Block	Description	Sub type	1	2	3	4	5	6	7	8
1	Generation of commands and delivery to uplink service	Simple	0	0	1	1	0	1	1	1
		Complex	1	1	0	0	1	0	0	0
2	Ground station for uplink of commands		1	1	1	1	1	1	1	1
3	Ground station for reception of telemetry data	30%	3	3	0	0	3	3	2	2
		100%	0	0	4	4	0	0	0	0
4	Retrieve data from host satellite ground segment		0	0	0	0	0	0	0	0
5	Telemetry processing (extract packets, timestamping)		3	3	4	4	3	3	1	1
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	1	1	1	0	1	0	1	1
		Complex	0	0	0	1	0	1	0	0
7	Spacecraft operations team	Dedicated	1	1	1	1	1	1	1	1
8	Deriving s/c orbit and attitude from tracking data etc.		1	1	1	1	1	1	1	1
9	Generating orbit and event data	Simple	1	1	0	1	1	1	0	0
		Mag'sphere	0	0	1	0	0	0	1	1
10	Collection of orbit and attitude data		0	0	0	0	0	0	0	0
11	Attitude planning		1	1	1	1	1	1	1	1
12	Conversion of instrument data into calibrated physical data,		1	2	1	4	4	4	2	1
13	Making mission data available to the Space Weather Service		1	1	1	1	1	1	1	1

Set-up costs (KEuro total)			Space segment options							
Block	Description	Sub type	1	2	3	4	5	6	7	8
1	Generation of commands and delivery to uplink service	Simple	0	0	85	85	0	85	85	85
		Complex	280	280	0	0	280	0	0	0
2	Ground station for uplink of commands		65	65	65	65	65	65	65	65
3	Ground station for reception of telemetry data	30%	195	195	0	0	195	195	130	130
		100%	0	0	260	260	0	0	0	0
4	Retrieve data from host satellite ground segment		0	0	0	0	0	0	0	0
5	Telemetry processing (extract packets, timestamping)		69	69	92	92	69	69	23	23
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	150	150	150	0	150	0	150	150
		Complex	0	0	0	395	0	395	0	0
7	Spacecraft operations team	Dedicated	1820	1820	1820	1820	1820	1820	1820	1820
8	Deriving s/c orbit and attitude from tracking data etc.		64	64	64	64	64	64	64	64
9	Generating orbit and event data	Simple	49	49	0	49	49	49	0	0
		Mag'sphere	0	0	88	0	0	0	88	88
10	Collection of orbit and attitude data		0	0	0	0	0	0	0	0
11	Attitude planning		75	75	75	75	75	75	75	75
12	Conversion of instrument data into calibrated physical data,		340	680	340	1360	1360	1360	680	340
13	Making mission data available to the Space Weather Service		31	31	31	31	31	31	31	31
	Computers		30	30	30	30	30	30	30	30
		sub-totals	*3168*	*3508*	*3100*	*4326*	*4188*	*4238*	*3241*	*2901*

Operational costs (kEuro per year)			Space segment options							
Block	Description	Sub type	1	2	3	4	5	6	7	8
1	Generation of commands and delivery to uplink service	Simple	0	0	24	24	0	24	24	24
		Complex	34	34	0	0	34	0	0	0
2	Ground station for uplink of commands		70	70	70	70	70	70	70	70
3	Ground station for reception of telemetry data	30%	750	750	0	0	750	750	500	500
		100%	0	0	2800	2800	0	0	0	0
4	Retrieve data from host satellite ground segment		0	0	0	0	0	0	0	0
5	Telemetry processing (extract packets, timestamping)		6	6	8	8	6	6	2	2
6	Monitoring of the performance of the spacecraft and its sub-systems, including the payload	Simple	104	104	104	0	104	0	104	104
		Complex	0	0	0	101	0	101	0	0
7	Spacecraft operations team	Dedicated	800	800	800	800	800	800	800	800
8	Deriving s/c orbit and attitude from tracking data etc.		65	65	65	65	65	65	65	65
9	Generating orbit and event data	Simple	42	42	0	42	42	42	0	0
		Mag'sphere	0	0	42	0	0	0	42	42
10	Collection of orbit and attitude data		0	0	0	0	0	0	0	0
11	Attitude planning		42	42	42	42	42	42	42	42
12	Conversion of instrument data into calibrated physical data,		13	26	13	52	52	52	26	13
13	Making mission data available to the Space Weather Service		2	2	2	2	2	2	2	2
	Computer maintenance		6	6	6	6	6	6	6	6
		Sub-totals	*1934*	*1947*	*3976*	*4012*	*1973*	*1960*	*1683*	*1670*

5.3 Summary of ground segment costs

5.3.1 Dedicated missions

Option	*CSMR*	*Description*	*Set-up (MEuro)*	*Operations (Meuro / year)*
1	3	Coronagraph	3.2	1.9
2	2, 3, 75	Coronagraph, Radio Wave Detector	3.5	1.9
3	39 to 43	Magnetometer	3.1	4.0
4	52, 53 to 55, 59 to 61, 66 to 67	Thermal energy ion spectrometer;/Ionosonde,/UV Imager, Medium energy electron spectrometer, Thermal energy ion spectrometer, High energy electron spectrometer	4.3	4.0
5	1, 8 to 11, 12, 13	Whole disk imager, X-ray photometer / spectrometer, UV photometer, EUV photometer	4.2	2.0
6	23 to 27, 36 to 38, 56 to 58, 62, 63 to 65	Thermal energy ion spectrometer, Magnetometer, Thermal energy ion spectrometer, High energy ion detector	4.2	2.0
7	4,6, 69 to 71	Auroral imager, Debris monitor	3.2	1.7
8	4,6	Auroral imager	2.9	1.7

Table 6. Ground segment costs for dedicated mission options

5.3.2 Hitch-hiker options

Option	*CSMR*	*Description*	*Set-up (MEuro)*	*Operations (Meuro / year)*
1	1	Whole disk imager	1.2	0.3
2	2	Coronagraph	1.2	0.3
3	4,6	Auroral imager	1.4	0.8
4	8 to 11	X-ray photometer / spectrometer	1.2	0.3
5	12	UV photometer	1.2	0.3
6	13	EUV photometer	1.2	0.3
7	36 to 38	Magnetograph	1.2	0.3
8	53 to 55	Medium energy electron spectrometer	1.3	0.3
9	56 to 58, 62	Thermal energy ion spectrometer	1.3	0.3
10	59 to 61	Thermal energy ion spectrometer	1.3	0.3
11	63 to 65	High energy ion detector	1.2	0.3
12	66 to 67	High energy electron spectrometer	1.2	0.3
13	69 to 71	Debris monitor	1.2	0.3
14	72	Dose monitor	1.2	0.3

Table 7. Ground segment costs for hitch-hiker options