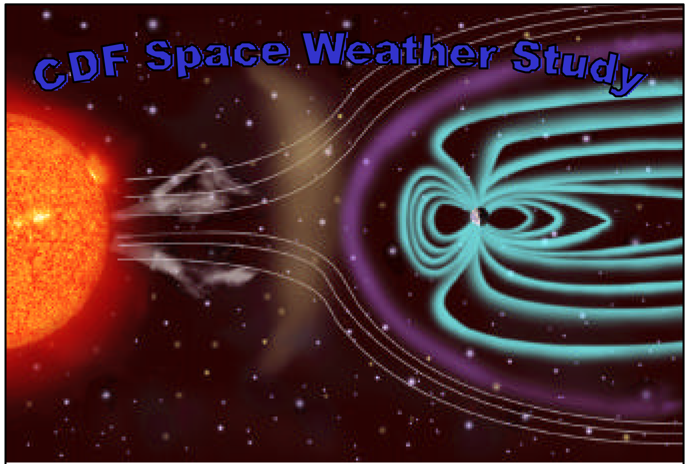


Table of Contents

Study Overview

This study was carried out:

- By the ESTEC CDF team
- on request by ESA TOS-EMA (Responsible of the Space Weather Study)
- in the period 2 October (Study Kick-off) to 27 November 2001 (Final Presentation), in 15 working sessions (half day each)
- by an interdisciplinary team of ESA technical specialists
- Using concurrent engineering methods and tools
- with as input draft reports from Alcatel & Ral consortia in ESA Space Weather studies

SW - CDF Study Objectives

- Assessment study of up to 3 missions (~in series) implementing the Space Weather Space Segment
  - System and S/S conceptual design
  - Mission and Ground System and Operations Assessment
  - Payload accommodation
  - Industrial Costing
  - Instruments Costing (as far as info is available)
  - Technical risk assessment
  - Programmatics/AIV
  - Simulation

System Architecture

SW Space Segment High Level Requirements

- To design a minimum set of S/C, missions and associated Ground Stations *performing continuous monitoring of Space Weather phenomena and performing near real time downlink to Earth and immediate processing on ground of the data*
- Design the set of S/C with a *lifetime of minimum 5 years*
- European independent system
- No connection with present or future Science Missions

SW Space Segment Priority missions

Three dedicated missions have been identified as high priority for the Space Segment:

Name	Mission	Main Objective
IMM	Inner Magnetospheric Monitor	To provide near-real time monitoring of Earth Magnetic field and particles
SWM	Solar Wind Monitor	To provide near-real time monitoring of Solar Wind
SAM	Solar Activity Monitor	To provide near-real time imaging of the Solar disk (for solar flare detection) and corona

System Architecture IMM & SWM orbits

Given the requirements the choice of the orbit for IMM and SWM is quite straightforward:

IMM constellation (4 S/C): GTO-like orbit

SWM: orbit around L1 (Halo or Lissajous)

All the architecture options have therefore been based on SAM

System Architecture Options-1

System Architecture Options			
Option	1	2	3
IMM	4 S/C in 650x39717 equat	4 S/C in 650x39717 equat	4 S/C in 650x39717 equat
SWM	1 S/C in L1 Halo	1 S/C in L1 Halo	1 S/C in L1 Halo
SAM	1 S/C in L1 Halo	Combined with SWM in L1 Halo	2 S/C in GEO (separation in long > 17 deg)
Number of launches	2 (4IMM on GSLV, SWM+SAM on Soyuz)	2 (4IMM on GSLV, Combined SWM&SAM on Soyuz)	3 (4IMM on GSLV, 1 SWM on Rockot + 2 SAM on GSLV or Soyuz or A5)
Total number of S/C	6	5	7
Groundstations			
No. of Ground antennas	7 (4 IMM, 3 SWM&SAM)	7	2
No. of Ground locations	4	4	1
Costs			
launch	Minimum number of launches Cheaplaunchers	As Option 1	Highest number of launches Launch to GEO expensive Launch of SWM to L1 with Rockot requires a STAR 37 motor
S/C	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)	Only 2 types of S/C (IMM spin stab, SWM&SAM 3-axis stab)	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)
Ground Station	High number of antennas and lines	As Option 1	Simplest Ground architecture
Complexity			
S/C	3 different designs but optimised for the payload accommodation	The combined SWM&SAM is more complex	Design of SAM more complex than Opt1 because it works both as data relay and service Design of SWM more complex because a STAR 37 motor must be accommodated
Requirements			
User req. Fulfilment	Satisfied with 2 exceptions: 1. gap of max 30 min for data from IMM, 2. CME seen from the front	Can be satisfied but in addition to the exceptions as in Opt 1 the SWM instruments must be adapted to a 3-axis platform	Satisfied with 1 exception: 1. CME seen from the front

System Architecture Options-2

System Architecture Options			
Option	4	5	6
IMM	4 S/C in 650x39717 equat	4 S/C in 650x39717 equat	4 S/C in 650x39717 equat
SWM	1 S/C in L1 Halo	1 S/C in L1 Halo	1 S/C in L1 Halo
SAM	1 S/C in 10-deg trailing orbit	Several high altitude polar balloons	1-2 S/C in SSO
Number of launches	2 (4IMM on GSLV, SWM+SAM on Soyuz and later separated)	2 (4IMM on GSLV, 1 SWM on Rockot) + balloon launches	3 (4IMM on GSLV, 1 SWM on Rockot, 1-2 SAM on Soyuz or PSLV)
Total number of S/C	6	5 S/C + at least 6 ballons	6 or 7
Groundstations			
No. of Ground antennas	8	7 + 2 polar for the balloons	very high
No. of Ground locations	4	4+2	very high
Costs			
launch	As option 1	As option 1 but launches and recoveries of balloons to be added	As option 3 but launch of SAM cheaper
S/C	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)	Only 2 types of S/C (IMM spin stab, SWM spin stab) + 1 balloon	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)
Ground Station	Highest number of antennas	High number of antennas and lines + need for 2 additional stations at the poles	Very High number of antennas and lines
Complexity			
S/C	SAM more complex than in opt. 1.: TT&C More complex, Propulsion must be carried to perform the transfer to the 10-deg TO A penumbra phase during transfer must be dealt with	Designs of IMM and SWM as in option 1. Long duration balloons in principle simple but a reliable technology is still not available	Comparable to Option1
Requirements			
User req. Fulfilment	Satisfied with 1 exception: 1. Gap of max 30 min for data from IMM	Satisfied with 1 exception: 1. Gap of max 30 min for data from IMM	Full coverage cannot be guarantee within a reasonable cost

Trade-Off Results - Conclusion

Option 1 has been selected as baseline architecture and as CDF reference for the design of the S/C because it represents the best compromise among user requirement satisfaction, technical complexity and cost

Data Relay Option is a possible alternative but, before it can be considered a valid competitor of Option 1, the design of SAM must be investigated in more detail

Combined SAM&SWM option should be considered in case cost reduction is required

Trailing Orbit Option should be considered in case emphasis is to be put on CME monitoring

Balloons and SSO Options are not recommended

System

IMM - Requirements

- Constellation of 4 S/C in highly eccentric,12-hour period, 10-deg orbit
- Lifetime: 5 yrs
- Launch date for pre-op system: 2006
- High Electromagnetic Cleanliness (Cluster-type)
- Spin stabilisation
- Maximum downlink gap acceptable ~30 min but data not immediately sent to Earth shall be stored and sent at the earliest opportunity

Inner Magnetosphere Monitor payload summary

Instrument name	Mass (kg)	Mass inc 8% mar. (kg)	Power (W)	Telemetry rate (Kbps)	Dim 1 (cm)	Dim 2 (cm)	Dim 3 (cm)
Thermal Plasma Monitor	5	5.4	8	2	20	20	20
Mid-Energy particle Monitor	2	2.16	4	2	15	15	15
High Energy particle Monitor	6.1	6.59	6.25	1.5	20	20	10
Magnetometer	1.2	1.3	2	0.2	20	10	15
Waves instrument	5.8	6.26	4	2	20	10	5
GPS Receiver - Ionosphere Sounder	5	5.4	12	1	6	6	6
	25	27	36.3	8.7			

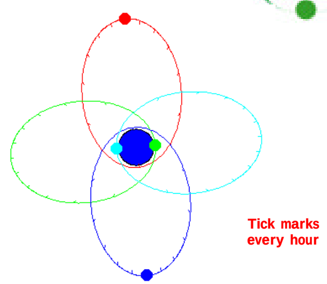
- S/C requirements summary:
  - AOCS: Spinning s/c, spin rate 15 rpm (4s per spin). Spin axis orientation perpendicular to ecliptic acceptable, (though ideally it should be in equatorial plane). Pointing accuracy about 1°
  - Demanding EMC requirements for in-situ plasma analysis

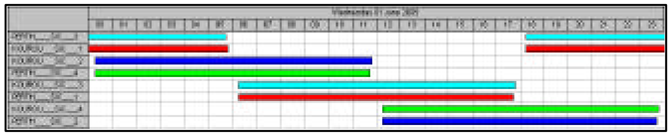
IMM Launcher Selection

- Single launch of the complete constellation much more efficient than launching one by one
- Launch to GTO very costly (only piggyback launches can be considered)
- “Cheap” launchers (e.g. Russian launchers) launch to too high inclination (45 to 63 deg) requiring a very large manoeuver to get to GTO
- Launch to low inclination LEO (18 deg) possible with PSLV and GSLV
- Only two cost effective solutions:
  - Launch with GSLV (>4000 Kg available)
  - Launch as A5 ASAP (1200 Kg available)

The IMM 12-h Orbit Design

Coverage:
+ Stations: Kourou and Perth (2x2 dishes)
+ Complete coverage of the orbit above 3000 km altitude
+ Only 30 mn coverage gap around perigee





Constellation Launch & Deployment

- Launch of stack of 4 satellites on LEO 200 km inclination 18° by GSLV
- Apogee satellite 1 raised to 39717 km by multi-burn of on-board propulsion system
- Apogee of other satellites raised when differential apsidal line rotation reaches 90°, 180° and 270° on day 12, 24 and 35 respectively
- Perigee raised to 650 km and inclination decreased to 10° by a last apogee manoeuvre
- Total ΔV for each satellite: ~2.7 km/s

IMM Options

	1	2
Mission		
Number of Satellites	4.0	4.0
Orbit-type	Elliptic 12-hour (sync)	Elliptic 12-hour (sync)
Perigee (Km)	650.0	650.0
Apogee (km)	39717.0	39717.0
Inclination (deg)	10.0	7.0
Launch Date	2006	2006
System		
Satellite Type	STORMS type	STIN-adapted
Existing Platforms Identified		
Dry Mass-class (kg)	<1000	<200
Stabilisation	Spin-stabilised	Spin-stabilised
Launcher		
Launcher	GSLV	A5 ASAP Minisat
Launch strategy	LEO+own prop	GTO as piggy-back + natural apsides drift (600 days max)+own prop
Payload		
Instrument set	nominal set (High energy Ion Spectrom, Thermal Plasma Monitor, Mid Energy particle Monitor, Magnetometer, GPS receiver, Waves instrument)	nominal set (High energy Ion Spectrom, Thermal Plasma Monitor, Mid Energy particle Monitor, Magnetometer, GPS receiver, Waves instrument)


IMM Baseline S/C Configuration

- Configuration largely driven by the accommodation of the propulsion system and by the power demand that size the external surface
- All equipment off-the-shelf
- Local shielding (6 mm Al) implemented for sensitive components

IMM : mass budget

Target Spacecraft Mass at Launch [illegible] kg
Below Mass Target by: 0 kg

	Without Margin	Margins %	Margins kg	Totals kg	% of Total
1. Structure	82.4 kg	[illegible]	17.4	100.0	10.83
2. Thermal Control	13.9 kg	10.0	1.4	15.3	1.52
3. Mechanisms	24.0 kg	10.0	2.4	26.4	2.63
4. Pyrotechnics	1.5 kg	5.0	0.1	1.6	0.16
5. Communications	11.5 kg	5.0	0.6	12.1	1.20
6. Data Handling	16.0 kg	10.0	1.6	18.8	1.83
7. AOCS	9.1 kg	10.0	0.9	9.9	0.99
8. Propulsion	72.3 kg	5.0	3.6	75.9	7.55
9. Power	40.9 kg	10.0	4.1	44.9	4.47
10. Harness	12.6 kg	20.0	2.5	15.1	1.50
11. Payload Allocation	25.1 kg	8.0	2.0	27.1	2.70
Total Dry (excl.adapter) - per sat.	317.2 kg			353.7	35.17
System Margin (excl.adapter)		17.0 %		60.1	
Total Dry with Margin (excl.adapter) - per sat.				413.9	41.15
Propellant			Total propellant	591.9	58.85
				0.0	
			Adapter Mass (incl Sep. Mech.)	50.0	4.97
Total Launch Mass (single satellite)				1005.7	
Total dry mass of last satellite of the stack (excludes separation mech)				345.6	
Total dry mass of last satellite with margin				404.2	
Propellant of last satellite				577.7	
TOTAL MASS OF LAST SATELLITE				981.9	

Mass margin with GSLV single launch of 4 S/C a bit tight, however little saving in the dry mass would improve dramatically the margin; 3 S/C would be no problem

IMM Conclusions and Open Points

•An IMM S/C based on a custom spin stabilised design is proposed

•The design fulfils the user requirements apart from a gap in continuous coverage of max 30 min for altitude < 3000 Km

Points requiring future investigation

•Increase of mass margin at launch and GSLV performance

•More detailed radiation analysis needed at component level

•Definition of a spare and replacement policy. Two replacement S/C could be launched by PSLV

SWM - Mission Requirements

- **Orbital location with continuous and unobstructed flow of the Solar Wind**
- **Near-real time data flow**
- **Lifetime: 5 yrs**
- **Launch date for pre-op system: 2006**
- **High Electromagnetic Cleanliness**
- **Spin stabilisation preferred**

Solar Wind Monitor payload summary

Instrument name	Mass (kg)	Mass inc 15% mar. (kg)	Power (W)	Telemetry rate (Kbps)	Dim 1 (cm)	Dim 2 (cm)	Dim 3 (cm)	Heritage
Thermal Plasma Monitor	5.0	5.8	8.0	2.0	20	20	20	CLUSTER/PEACE, EQUATOR-S/3DA
Mid-energy particle Monitor	2.0	2.3	4.0	2.0	15	15	15	
Magnetometer (2 sensors)	1.5	1.7	2.0	0.2	20	10	15	OTS
Coil Radio-Spectrograph	3.7	4.2	5.7	2.5	20	10	5	Breadboard. POLAR
	12.2	14.0	19.7	6.7				

- S/C main requirements summary:
  - AOCS: Spinning s/c, spin rate 15 rpm (4s per spin). Pointing accuracy about 1°
  - Demanding EMC requirements for in-situ plasma analysis

SWM Launcher Selection

•If Soyuz-Fregat or PSLV is chosen:

•Launch into 200 km parking orbit with upper-stage still attached, Upper-stage ignites and injects S/C into L1 transfer orbit

•Performance to L1: PSLV = 400 Kg, Soyuz-Fregat= 1600 Kg

•If Rockot (+ additional STAR 37 motor) is chosen:

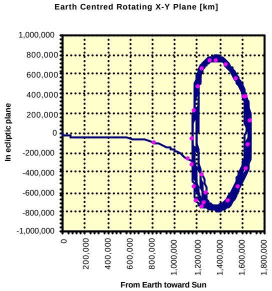
•Launcher puts S/C + STAR37FM solid engine attached into 200 km orbit, STAR37FM ignites and S/C+STAR37FM enter L1 transfer orbit

•Performance to L1: 306 Kg

S W M : Requirements and Mission Design

Requirements: uninterrupted
- view of the Sun (no eclipses)
- ground contact

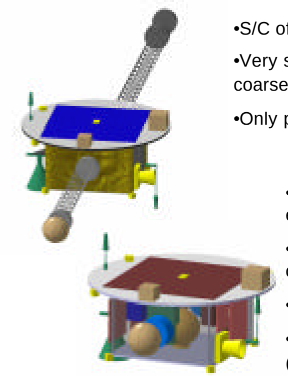
- Requirements met by Halo orbit around libration point L_1 (SOHO orbit)
- Continuous ground contact assured by three stations about 120° apart in longitude
- Direct launch with Soyuz + Fregat of composite SWM + SAM on transfer orbit to L1
- Separation between SWM and SAM a few hours after injection



S W M Options

		Current Baseline	Study Option 1
Mission			
Number of Satellites		1.00	1.00
Orbit		L1 Halo	L1 Halo
Launch Date		Jan.06	Jan.06
System			
Satellite Type/Platform		Custom design	Custom design
Dry-mass class		400.00	300.00
Stabilisation		spinner	spinner
Payload			
Instrument Set		magnetometer, thermal plasma mon., mid-energy particle monitor, low-frequency radio-spectrometer	magnetometer, thermal plasma mon., mid-energy particle monitor, low-frequency radio-spectrometer
Launcher			
Launcher		Shared Soyuz (or PSLV)	Rockot+STAR37
Launch Strategy		direct injection	direct injection
Propulsion			
Type of Propusion		no propulsion	no propulsion

S W M baseline Configuration



- •S/C of the Minisat class (~200 Kg)
- •Very simple attitude (spinning with solar array coarsely Sun pointing)
- •Only propulsion for AOCS required
- •Very simple power and thermal design (no eclipse)
- •Structural configuration inspired to commercial platforms
- •Avionics architecture: PROBA heritage
- •3 instruments out of 4 identical to IMM (cost saving)

S W M : mass budget

	Without Margin	Margins %	Margins kg	Totals kg
1. Structure	58.7 kg	20.0	11.7	70.4
2. Thermal Control	7.5 kg	10.0	0.7	8.2
3. Mechanisms	9.9 kg	10.0	1.0	10.9
4. Pyrotechnics	0.0 kg	0.0	0.0	0.0
5. Communications	23.9 kg	10.0	2.4	26.3
6. Data Handling	9.5 kg	5.0	0.5	10.0
7. ADCS	9.0 kg	10.0	0.9	9.9
8. Propulsion	4.6 kg	5.0	0.2	4.8
9. Power	16.3 kg	10.0	1.6	18.0
10. Harness	5.0 kg	0.0	0.0	5.0
11. Payload Allocation	12.2 kg	15.0	1.8	14.0
Total Dry (excl.adapter)	156.59 kg			177.5
System Margin (excl.adapter)		20.0 %		35.5
Total Dry with Margin (excl.adapter)				213.0
	Propellant:		Total propellant	5.7
				0.0
			Adapter Mass (incl. Sep. Mech.)	0.0
Total Launch Mass				218.8

Very large mass margin either in a double launch on Soyuz-Fregat (together with SAM) or with PSLV

SWM Conclusions and Open Points

- Very simple and reliable design
- Low mass leads to inefficient launch in terms of cost (dual launch with SAM by Soyuz Fregat still leaves some 800 Kg margin)
- Baseline design is compatible with a single launch using PSLV or dual-launch with SAM using Soyuz-Fregat
- Rockot Option feasible with some design changes but SAM launcher selection problematic
- Present SWM design could probably be made also compatible with the option of SAM in GEO as a relay satellite (needs further investigation)

SAM - Requirements

- S/C Sun pointing with accuracy of 7 arcsec (3-axis stabilisation)
- Location with unobstructed view to Sun
- Possibly pointing direction at an angle with the Sun-Earth direction
- Near real-time data downlink
- Lifetime: 5 yrs
- Launch date for pre-op system: 2006

SAM Design options

SAM options are discussed and traded at system architecture level (see above). Hereafter only consideration at S/C design level are reported and discussed

The design baseline selected is:

Mission	
Number of Satellites	1
Orbit	L1
Launch Date	2006
System	
Satellite Type/Platform	Custom
Dry-mass class	1000
Stabilisation	3-axis
Payload	
Instrument Set	nominal
Launcher	
Launcher	Soyuz-Fregat dual
Launch Strategy	Direct
Propulsion	
Type of Propusion	No main prop.

Solar Activity Monitor payload summary

Instrument name	Mass (kg)	Power (W)	Telemetry rate (Kbps)	Dim 1 (cm)	Dim 2 (cm)	Dim 3 (cm)	Heritage
White Light Coronagraph	23	20	21	130	30	15	Mod from SOHO - LASCO, STEREO -SECCHI
EUV Imager	15	18	10.5	100	20	20	Mod from SOHO - EIT, Trace, Solar Orbiter EXI
X-Ray Photometer	16	16	0.1	26	14	11	XRS-GOES
Cosmic Ray Monitor	6	4	2	20	20	20	Proposed Stereo, Solar Orbiter
	60	58	33.6				

- S/C main requirements summary:
  - **AOCS: 7 arc seconds pointing accuracy, 5 arc seconds during 15 min pointing stability.**
  - **Baseline T operating 0/+20°C, Non-operating -30/+60 °C; CCD detectors need passive cooling at -80 °C during operation**

SAM Launcher Selection

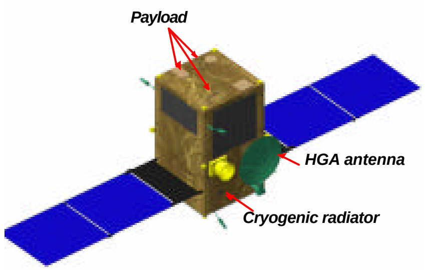
- Soyuz Fregat Dual launch with SWM selected as the most efficient launch strategy
- Dnepr Varyag possible back-up (if launch is earlier than 2008) but availability and performance of this launcher need confirmation
- Single launch with PSLV or Rockot impossible due to the low mass performance to L1 (400 or 300 Kg)
- No medium-size launcher available compatible with the mass of SAM+SWM

SAM Requirements and Mission Design

- Requirements similar to SWM
- Same orbit as SWM
- Launch together with SWM
- Performance of launcher (1600 kg) more than sufficient for dual launch
- Dish for SAM ground coverage in same location as for SWM

SAM Baseline Configuration

- Box-like SOHO-type design
- Configuration driven by the size of the PL and the need of interfacing with SWM during launch
- All equipment off-the-shelf



- Simple sun pointing operational mode
- Only propulsion for AOCS required (monopropellant system)

SAM baseline: Mass budget

	Without Margin	Margins %	Margins kg	Totals kg
Target Spacecraft Mass at Launch				1382
Below Mass Target by:				847
1. Structure	90.5 kg	20.0	18.1	108.6
2. Thermal Control	12.1 kg	10.0	1.2	13.3
3. Mechanisms	20.6 kg	10.0	2.1	22.6
4. Pyrotechnics	2.0 kg	5.0	0.1	2.1
5. Communications	35.0 kg	10.0	3.5	38.5
6. Data Handling	10.0 kg	10.0	1.0	11.0
7. AOCS	28.8 kg	10.0	2.9	31.7
8. Propulsion	16.2 kg	10.0	1.6	17.8
9. Power	36.1 kg	10.0	3.6	39.8
10. Harness	8.9 kg	10.0	0.9	9.8
11. Payload Allocation	60.0 kg	0.0	0.0	60.0
Total Dry (excl.adapter)	320.13 kg			355.1
System Margin (excl.adapter)		20.0 %		71.0
Total Dry with Margin (excl.adapter)				426.1
Propellant:		Total propellant		69.2
				0.0
Adapter Mass (incl. Sep. Mech.)				40.0
Total Launch Mass				535.3

Very large mass margin using Soyuz-Fregat dual launch with SWM. Additional payload could be carried

SAM Conclusions and Open Points

- A large number of options are possible for the SAM design. The L1 option has been estimated as the most straightforward to implement
- The user requirements have been fulfilled although the choice is not optimal as far as CME is concerned
- The design is compatible with dual launch together with SWM which allows for a very large mass margin (additional payload may be carried)
- Two options (Data Relay and 10-deg Trailing Orbit) require further investigation before considering them as potential alternatives

Conclusions

A reference Space Segment architecture has been selected and analysed into detail

Several options which could either increase the cost effectiveness or the user requirement satisfaction have been proposed and partially analysed

The proposed set of missions is simple and technically feasible with ample margins. No specific new technology development is needed (apart from some instruments)

The total cost (including instruments and operations) exceeds the target of 300 ME. However, several countermeasures are proposed to reduce the cost subject to further investigation

From the programmatic point of view the first feasible date for the deployment of the pre-operational system appears to be 2007