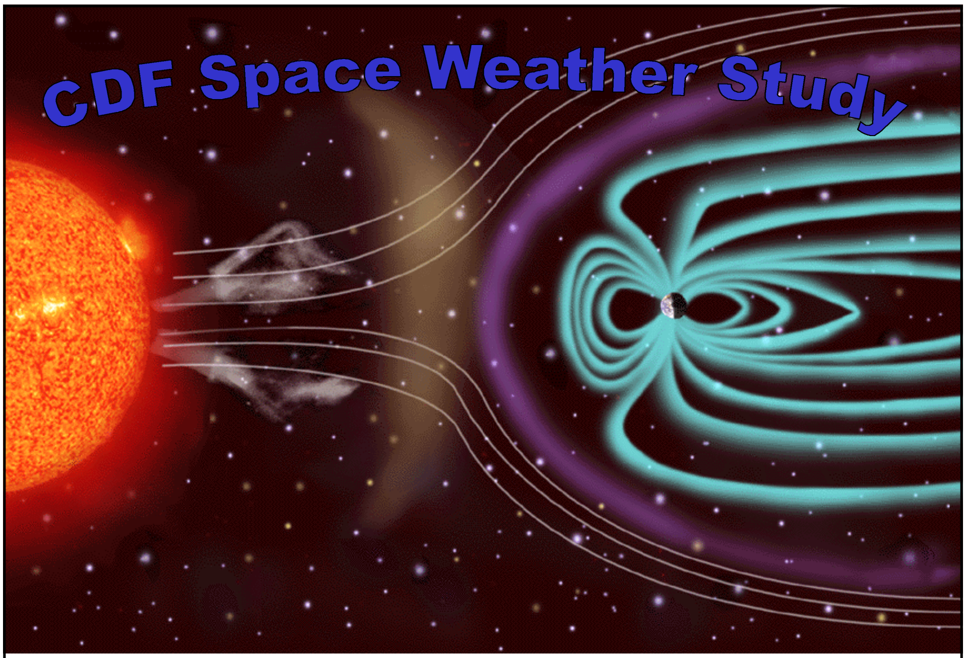


Table of Contents

- Study overview
- System Architecture
- Instruments
- Mission analysis & Ground System
- & Operations (global)
- System and Sub-Systems design
- Conclusions

Study Overview

This study was carried out:

- 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

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 Scince 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

SW Space Segment Orbital Requirements

According to the user objectives the following requirements on number of S/C and orbital locations can be defined

Name	Number of S/C	Orbital location
IMM	Constellation (min 3)	Around the Earth Orbital plane close to the equatorial plane Eccentric orbits in order to sweep several altitudes
SWM	1	Inside the Solar Wind streamlines Between Earth and Sun and sufficiently ahead of Earth Unobstructured view of Sun
SAM	1	Sun pointing Unobstructed view of Sun Possibly pointing direction at an agle with the Sun-Earth direction

System Architecture Baseline Trade-Off

The aim is to select baseline:

- Orbits
- Number of S/C
- Number and location of ground stations
- Launch strategies

optimising:

- User requirement fulfilment
- Cost
- Technical feasibility
- Reliability

to proceed with the S/C and mission design

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 Option 1

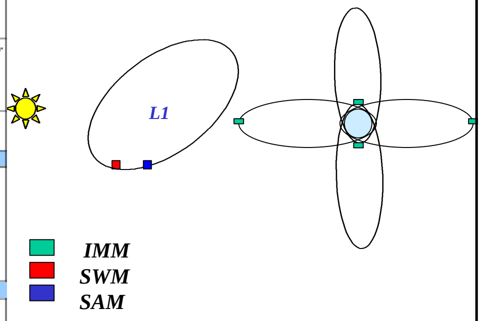
Option	1
IMM	4 S/C in 650x39717 equat
SWM	1 S/C in L1 Halo
SAM	1 S/C in L1 Halo
Number of launches	2 (4IMM on GSLV, SWM+SAM on Soyuz)
Total number of S/C	6
Groundstations	
No. of Ground antennas	7 (4 IMM, 3 SWM&SAM)
No. of Ground locations	4
Costs	
launch	Minimum number of launches Cheap launchers
S/C	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)
Ground Station	High number of antennas and lines
Complexity	
S/C	3 different designs but optimised for the payload accommodation
Requirements	
User req. Fulfilment	Satisfied with 2 exceptions: 1. gap of max 30 min for data from IMM, 2. CME seen from the front

Option 1

4 IMM in GTO-like orbits

1 SWM in L1 (Halo orbit)

1 SAM in L1 (Halo orbit)



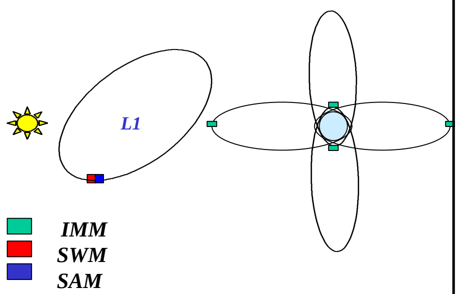
System Architecture Option 2

Option	2
IMM	4 S/C in 650x39717 equat
SWM	1 S/C in L1 Halo
SAM	Combined with SWM in L1 Halo
Number of launches	2 (4IMM on GSLV, Combined SWM&SAM on Soyuz)
Total number of S/C	5
Groundstations	
No. of Ground antennas	7
No. of Ground locations	4
Costs	
launch	As Option 1
S/C	Only 2 types of S/C (IMM spin stab, SWM&SAM 3-axis stab)
Ground Station	As Option 1
Complexity	
S/C	The combined SWM&SAM is more complex
Requirements	
User req. Fulfilment	Can be satisfied but in addition to the exceptions as in Opt 1 the SWM instruments must be adapted to a 3-axis platform

Option 2

4 IMM in GTO-like orbits

1 S/C combining SWM & SAM in L1 (Halo orbit))



System Architecture Option 3

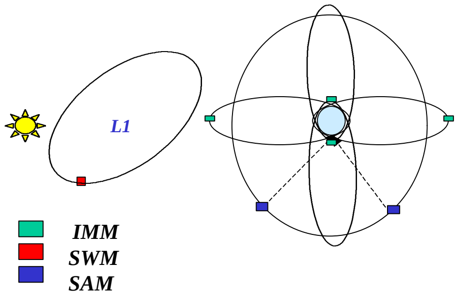
Option	3
IMM	4 S/C in 650x35717 equat
SWM	1 S/C in L1 Halo
SAM	2 S/C in GEO (separation in long > 17 deg)
Number of launches	3 (4IMM on GSLV, 1 SWM on Rocket + 2 SAM on GSLV or Soyuz or A5)
Total number of S/C	7
Groundstations	
No. of Ground antennas	2
No. of Ground locations	1
Costs	
launch	Highest number of launches Launch to GEO expensive Launch of SWM to L1 with Rocket requires a STAR 37 motor
S/C	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)
Ground Station	Simplest Ground architecture
Complexity	
S/C	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 1 exception: 1. CME seen from the front

Option 3

4 IMM in GTO-like orbits

1 SWM in L1 (Halo orbit)

2 SAM in GEO working also as Data Relay for the other satellites



System Architecture Option 4

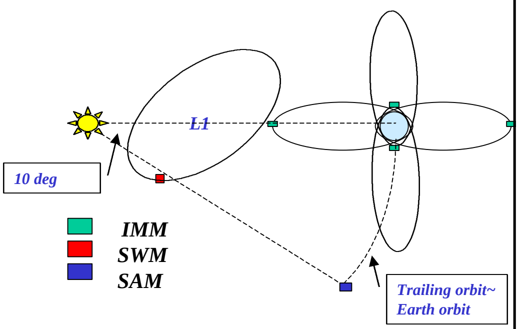
Option	4
IMM	4 S/C in 650x35717 equat
SWM	1 S/C in L1 Halo
SAM	1 S/C in 10-deg trailing orbit
Number of launches	2 (4IMM on GSLV, SWM+SAM on Soyuz and later separated)
Total number of S/C	6
Groundstations	
No. of Ground antennas	8
No. of Ground locations	4
Costs	
launch	As option 1
S/C	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)
Ground Station	Highest number of antennas
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
Requirements	
User req. Fulfilment	Satisfied with 1 exception: 1. Gap of max 30 min for data from IMM

Option 4

4 IMM in GTO-like orbits

1 SWM in L1 (Halo orbit)

1 SAM in a 10-deg trailing orbit



System Architecture Option 5

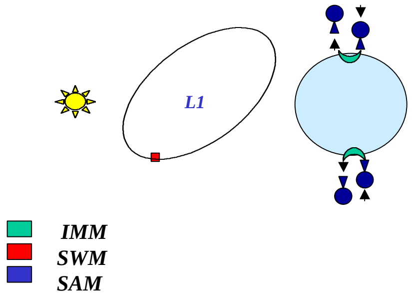
Option	5
IMM	4 S/C in 650x39717 equat
SWM	1 S/C in L1 Halo
SAM	Several high altitude polar balloons
Number of launches	2 (4IMM on GSLV, 1 SWM on Rockot) + balloon launches
Total number of S/C	5 S/C + at least 6 balloons
Groundstations	
No. of Ground antennas	7 + 2 polar for the balloons
No. of Ground locations	4+2
Costs	
launch	As option 1 but launches and recoveries of balloons to be added
S/C	Only 2 types of S/C (IMM spin stab, SWM spin stab) + 1 balloon
Ground Station	High number of antennas and lines + need for 2 additional stations at the poles
Complexity	
S/C	Designs of IMM and SWM as in option 1. Long duration balloons in principle simple but a reliable technology is still not available
Requirements	
User req. Fulfilment	Satisfied with 1 exception: 1. Gap of max 30 min for data from IMM

Option 5

4 IMM in GTO-like orbits

1 SWM in L1 (Halo orbit)

Several SAM as long duration polar balloons



System Architecture Option 6

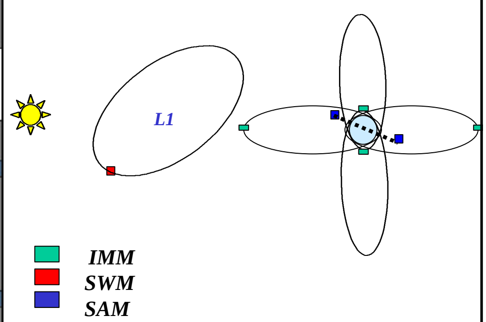
Option	6
IMM	4 S/C in 650x39717 equat
SWM	1 S/C in L1 Halo
SAM	1-2 S/C in SSO
Number of launches	3 (4IMM on GSLV, 1 SWM on Rockot, 1-2 SAM on Soyuz or PSLV)
Total number of S/C	6 or 7
Groundstations	
No. of Ground antennas	very high
No. of Ground locations	very high
Costs	
launch	As option 3 but launch of SAM cheaper
S/C	3 different types of S/C (IMM spin stab, SWM spin stab, SAM 3-axis stab)
Ground Station	Very High number of antennas and lines
Complexity	
S/C	Comparable to Option1
Requirements	
User req. Fulfilment	Full coverage cannot be guarantee within a reasonable cost

Option 6

4 IMM in GTO-like orbits

1 SWM in L1 (Halo orbit)

1 or 2 SAM in SSO



Trade-Off Results -1

Option 6 (SAM in SSO) has been rated low because it would imply a very high number of ground antennas to satisfy the coverage requirement

Option 5 (SAM as polar balloons) looks attractive from a cost point of view but the technology of long duration balloons is still not mature enough. In addition, launching and recovering balloons in polar regions is complex. Communication balloon-to-Earth is also an issue (presently Data relay satellites are used)

Option 2 (combined SAM and SWM) is the one corresponding to the lowest total cost but the least satisfactory from the user requirements point of view

Trade-Off Results - 2

Option 3 (SAM in GEO) is the one with minimum Ground Segment but with the highest number of (expensive) launches and with a rather complex SAM. The saving from reduction of the ground antennas has been found little as compared to the cost to be paid for the above points

Option 1 (SAM in L1) is the simplest concerning the S/C design, the one with the minimum launch cost and provides a satisfactory outcome from the user point of view

Option 4 (SAM in 10 deg TO) would allow the best monitoring of CME. However the design of SAM would be complex because of the long distance from Earth of the final location and the cruise (interplanetary-like mission)

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

Dta 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

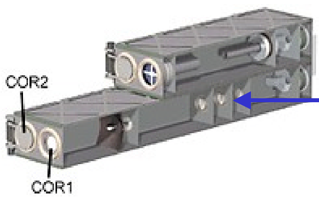
Balloons and SSO Options are not recommended

Instruments

Model Payload for the Priority Missions

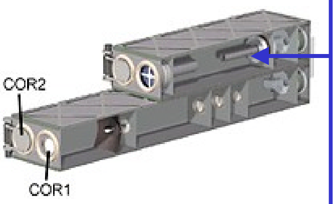
- As part of the CDF activity a set of instruments has been selected and defined
- This set represents the minimum model payload that fulfils the SW Space Segment user requirements
- Whenever possible an enlarged set of instruments has been considered but accommodation studies on this additional payload have not been performed

SAM payload: Coronagraph



- Performance Requirements:
  - **Cadence 1 image/20 min, FOV: 15 solar radii, Resolution: 28'' enough**
- Selected design
  - **2 coronagraphs, COR1 (FOV 1.25-4 solar radii, 1 pic/10 min, 7.5'' pixel) & COR2 (FOV 2-15 solar radii, 1 pic/ 20 min, 28'' pixel)**
  - **Sensors 2 front illuminated 1024 x 1024 CCD's**
  - **Design based on SECCHI coronagraph, proposed for STEREO**

SAM payload: EUV Imager



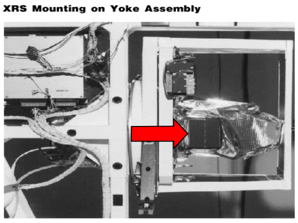
- Performance Requirements:
  - **Cadence 2.5 min, angular resolution 10''**
  - **4 bands: Fe XII 195 Å, He II 304 Å, Fe XV 284 Å, HI (Ly-a)1216 Å.**
- Selected design:
  - **TRACE-like single telescope with 4 mirror quadrants, with optimised coatings**
  - **Optics: Normal incidence multilayer Ritchey-Cretien telescope**
  - **Sensor back-illuminated 256 x 256 CCD**
  - **Heritage: SECCHI, TRACE, EIT**
  - **3 simultaneous bands, 2 modes of operation (quiet/active sun)**

SAM payload: XRP, CRM

X-ray photometer

- Heritage: GOES - XRS
- Uses ion chamber detectors
- Permits real-time determination of the solar x-ray emission in 2 spectral bands: 0.5-5 Å and 1-8 Å.
- 0.5 s time resolution, 1% accuracy
- FOV (less than 1 degree) should include Sun

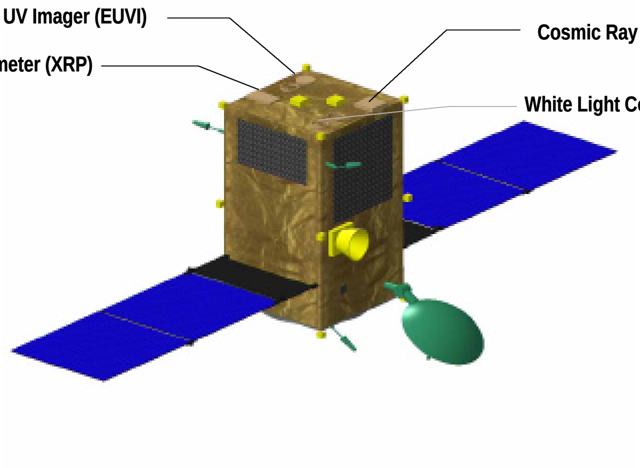
XRS Mounting on Yoke Assembly



Cosmic Ray Monitor

- Energy ranges 2-100 MeV ions, 2-20 MeV electrons (solar component of cosmic rays).
- Instrument is based on STEREO/ IMPACT-SEP (Solar Energetic Particles package), also baseline in SOLO
- FOV of the sensors include the nominal Parker spiral (IMF configuration)
- One more sensor needs to be added to the SEP package to look at higher energy, Galactic Cosmic Rays (500 MeV /nucleon and above) particles, FOV not as tightly constrained.

SAM payload: Instrument accommodation



Solar Activity Monitor payload summary

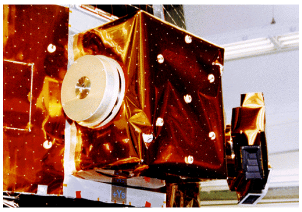
Instrument name	Mass (kg)	Power (W)	Telemetry rate (Kbps)	Dim 1 (cm)	Dim 2 (cm)	Dim 3 (cm)	Heritage
White Light Coronagraph	23	20	21	130	30	15	Mod from SOHO - LASCO, STEREO -SECCHI
EUV Imager	15	18	10.5	100	20	20	Mod from SOHO - EIT, Trace, Solar Orbiter EXI
X-Ray Photometer	16	16	0.1	26	14	11	XRS-GOES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

S W M payload: TPM, MEM & MAG

Thermal Plasma Monitor

- Top-Hat electrostatic analyser
- Measuring 0-40 keV ions and electrons. S/C charging
- FOV 180°x15°, pointing direction perpendicular to spin axis
- Heritage: Equator-S, WIND, Cluster



- **Equator-S - 3DA (10eV - 25 keV)**

Mid-Energy Particle Monitor

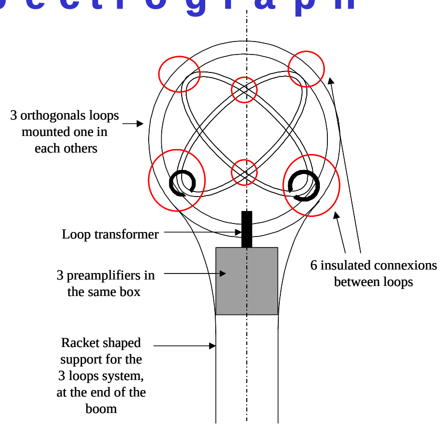
- Measuring 40keV-2MeV ions and electrons (Deep Dielectric charging)
- FOV 180°x20°, pointing direction perpendicular to spin axis

Magnetometer

- Determining the local IMF topology
- EM cleanliness: DC magnetic background <0.3 nT at boom tip
- 3-axes flux-gate magnetometers
- One sensor mounted at the end of a 4 m boom, the other 50 cm further inboard
- OTS design considered

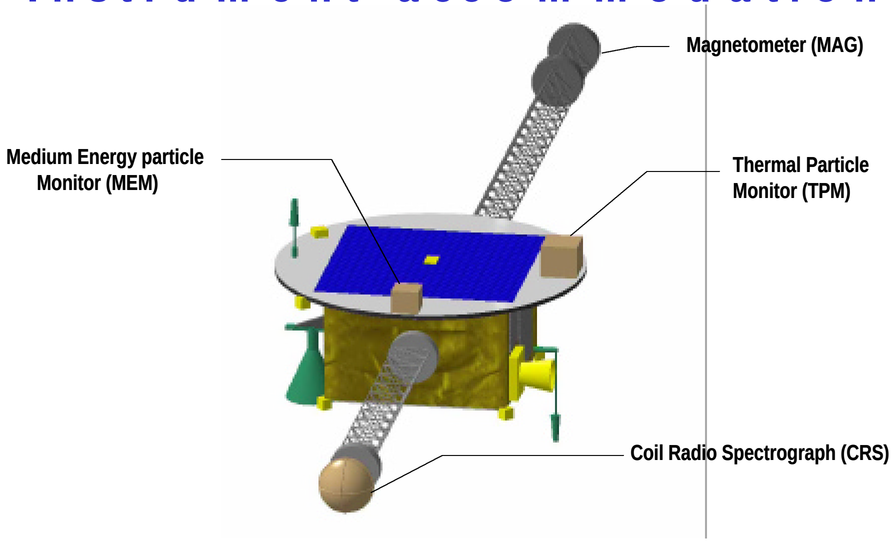
S W M payload: Coil Radio Spectrograph

- Detecting solar radio bursts associated with propagating disturbances e.g. CMEs
- Breadboard model developed by LPCE/CNRS, Orleans, France
- Bandwidth 50 kHz to 30 MHz, sensitivity threshold <1.0×10-6 nT.Hz-1/2 in the 700kHz - 20MHz range
- Sensor head 30 cm sphere mounted on a 1.8 m-long boom
- (Limited) heritage: Polar, Akebono



Antenna assembly - Detail
(courtesy of LPCE/CNRS)

S W M payload: Instrument accommodation



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

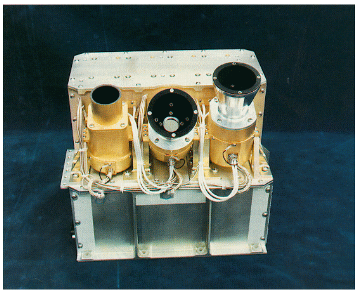
IMM payload: TPM, MEM & MAG

Thermal Plasma Monitor
Mid - Energy Particle Monitor
Magnetometer

- The design of these three instruments is the same as considered for SWM
- In the case of the MAG the boom is shorter (2 m)

IMM payload: Hi-Energy Particle Monitor

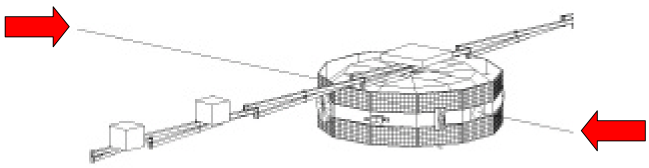
- Protons 500 keV- 160 MeV; can also be used to detect electrons 30 keV - 5 MeV.
- Suggested design: Modification of UARS-HEPS, substituting LEP telescope
- A single unit made up by 3 “telescopes”, silicon detectors arranged in stacks
- The 3 telescopes are mounted on the same box at angles of -15 degrees, +15 degrees and +45 degrees with respect to the zenith. FOV +/-15 degrees for each telescope, total FOV approx. 90° in the spin axis plane.



High-energy particle spectrometer (HEPS) 1 on UARS

IMM payload: Waves instrument

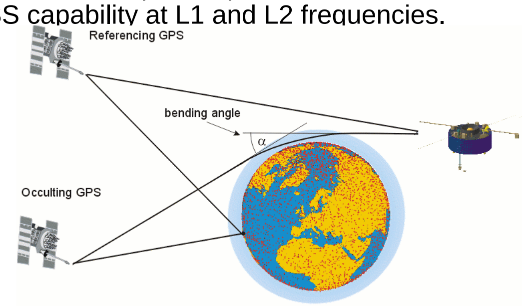
- Detecting plasma boundaries, providing information on particle acceleration processes
- Electric field measurements in the 0.1 Hz-16 MHz range. Magnetic measurements spectral renage 0.1 Hz- 1 MHz
- BepiColombo MMO as reference
- Unit breakdown: Electronics, 2 x wire booms + deployers + search coil magnetic antenna (on 1.3 m boom)
- Two 30-m booms on each side of the spacecraft



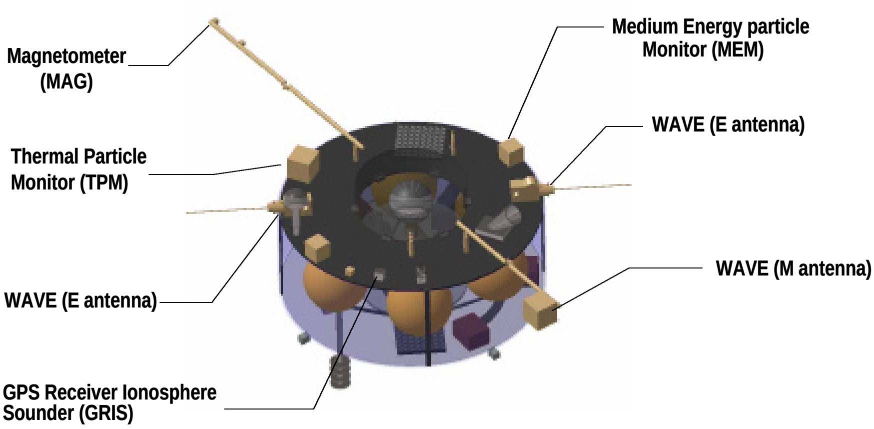
BepiColombo- MMO

IMM payload: GPS Receiver

- Provides some remote sounding capability -in the ionosphere and plasmasphere- by signal delay determination
- Baseline: STRV-1d / GAGE-like configuration, but more likely using MosaicGNSS instead, a commercial GPS receiver currently under development at Astrium GmbH.
- MosaicGNSS is based on an ESA-developed chip called AGGA that is able to provide GPS/GLONASS capability at L1 and L2 frequencies.
- Receiver mass about 5 Kg, power 12 W, including front end electronics, antennas and DC-DC converters



IMM payload: Instrument accommodation



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

Conclusions

- A set of instruments has been selected and defined for each of the elements of the Space Weather monitoring system
- These instruments will detect and follow up the evolution of the space environment perturbations from its origin on the Sun surface to their aftermath in the proximity of the Earth
- The **Solar Activity Monitor** payload will enable to identify active regions on the Sun surface (EUV) and will observe the white light scattered by CMEs as they propagate through the corona
- The **Solar Wind Monitor** will measure the in-situ plasma conditions upstream the magnetopause. It will also be able to detect the radio signature of perturbations propagating in the solar corona
- The **Inner Magnetosphere Monitor** payload uses the same particle (for the low and medium energy range) and magnetic field detectors as SWM for the in-situ measurements. It also includes a plasma wave experiment but also some ionosphere/plasmasphere remote sensing capability (GPS)
- Most instruments should be adapted from existing designs. New technology development is limited

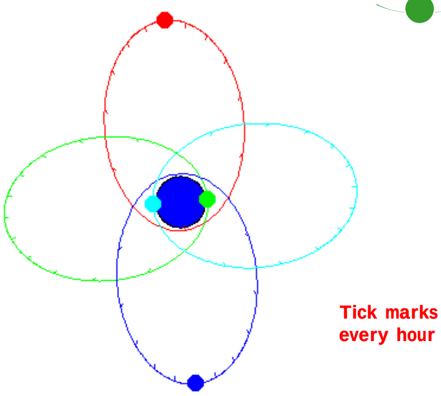
Mission Analysis

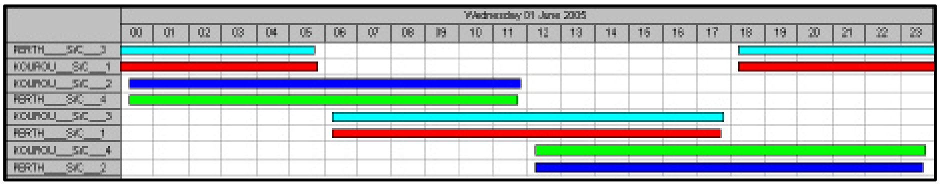
IMM: Mission Design Requirements

- Requirements:
  - Optimum coverage of the Earth magnetosphere
  - Optimum visibility from a minimum number of ground stations
- Requirements met by:
  - Constellation of 4 satellites
  - Near equatorial 12-h synchronous orbits

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

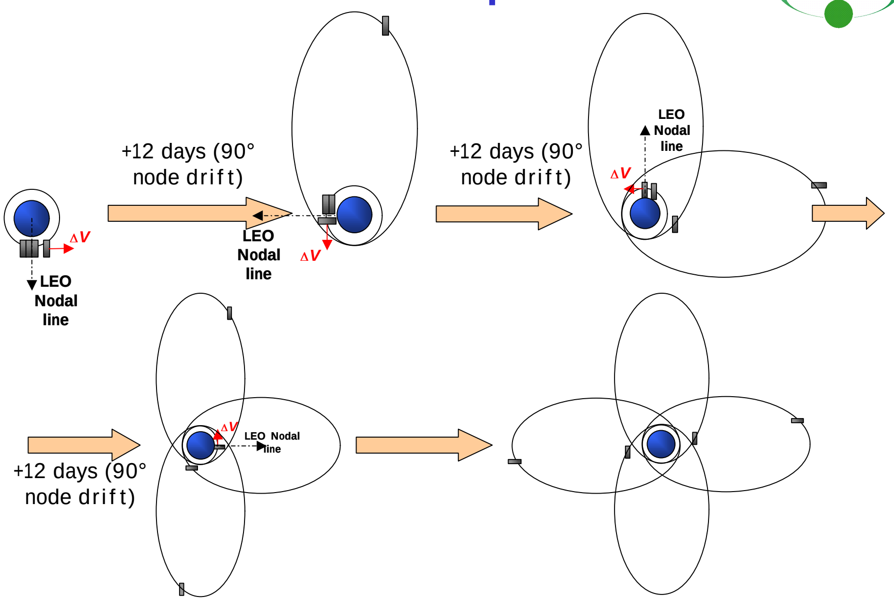




Constellation Launch & Deployment

- 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 Orbit Acquisition



IMM: ASAP 5 Option

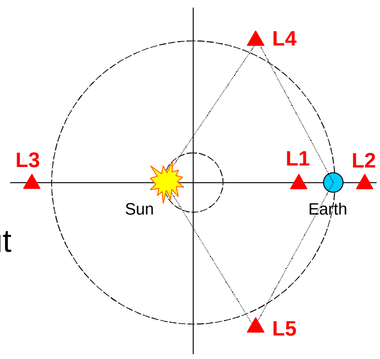
- IMM 4 satellites launched together on Ariane 5 GTO (560x35890 km, i = 7°) as ASAP Minisat passengers
- Satellite 1 raised to 12-h orbit apogee (39807 km)
- Apogee of other satellites decreased to 20000 km for initiating an apsidal line differential rotation rate
- After 200, 400 and 600 days, apogee of satellite 2, 3 and 4 respectively raised to 39807 km
- Inclination kept at 7°
- Total ΔV = 854 m/s

SWM: Requirements and Mission Design

Requirements: uninterrupted

- ❍ view of the Sun (no eclipses)
- ❍ ground contact

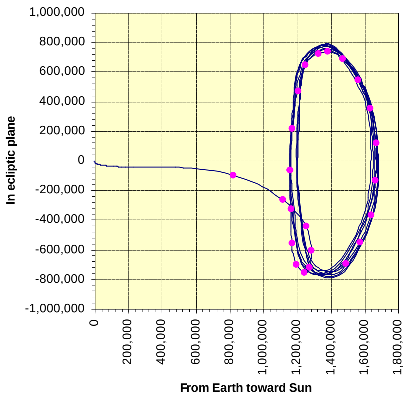
- Requirements met by Halo orbit around libration point L_1 (SOHO orbit)
- Continuous ground contact assured by three stations about 120° apart in longitude



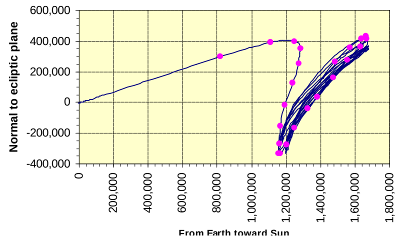
The Halo Orbit

- Five years propagation
- Tick marks every 10 days during transfer and first revolution in Halo orbit

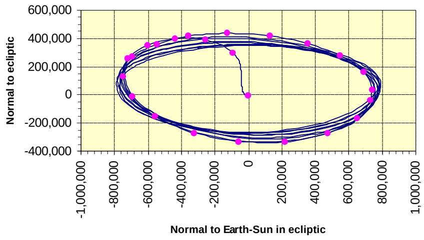
Earth Centred Rotating X-Y Plane [km]



Earth Centred Rotating X-Z Plane [km]



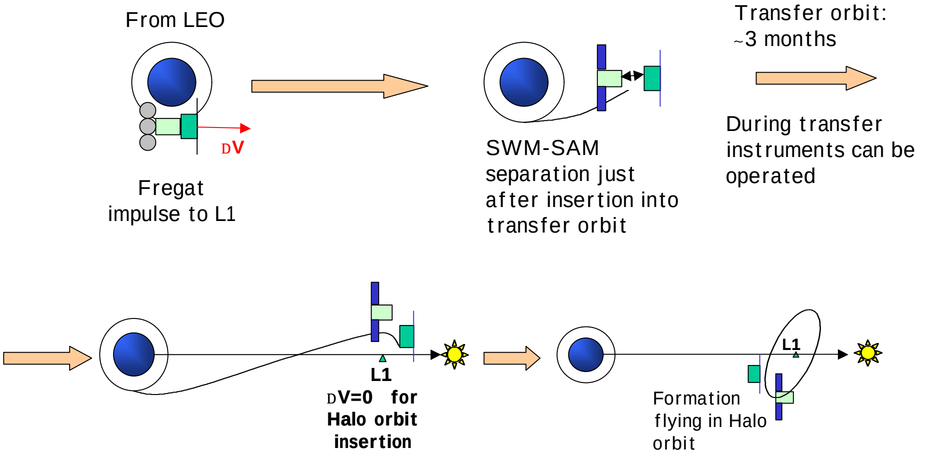
Earth Centred Rotating Y-Z Plane [km]



Launch and Transfer

- Direct launch with Soyuz + Fregat of composite SWM + SAM on transfer orbit to L1 (launcher performance: 1600 kg)
- Separation between SWM and SAM a few hours after injection
- Transfer orbit:
  - Duration: ~3 months,
  - Sun pointing attitude, instruments ON
- Injection into Halo orbit: $\Delta V = 0$

SAM & SWM Orbit Acquisition

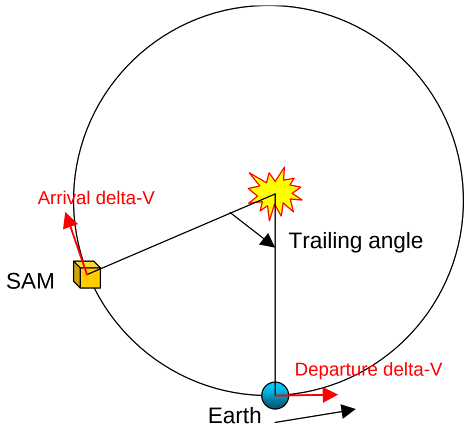


SAM Requirements and Mission Design

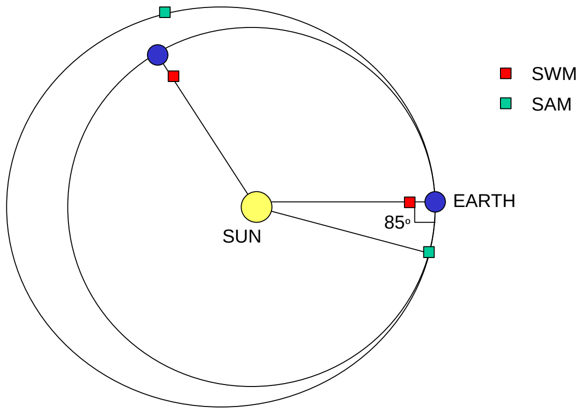
- Requirements similar to SWM
- Same orbit as SWM
- Launch together with SWM
- Performance of launcher (1600 kg) more than sufficient for dual launch
- Dish for SAM ground coverage in same location as for SWM

Option: SAM on Earth Trailing Orbit

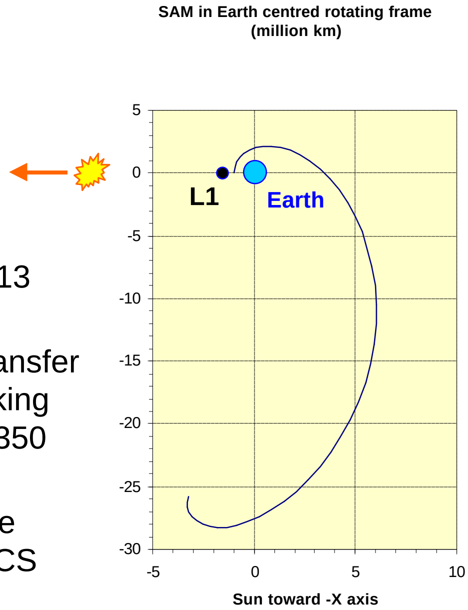
- Better than on L1: SAM on Earth orbit around Sun trailing behind Earth by 10°
- SAM + SWM still launched together
- Close to L1, SAM injected into transfer trajectory to trailing point



SAM on Earth Trailing Orbit: Transfer Configuration

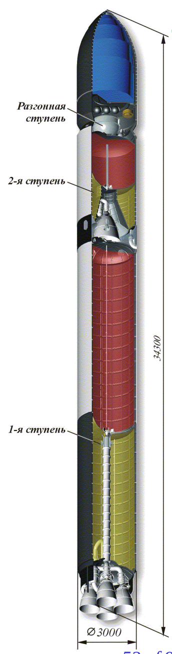


Transfer Orbit to Trailing Point



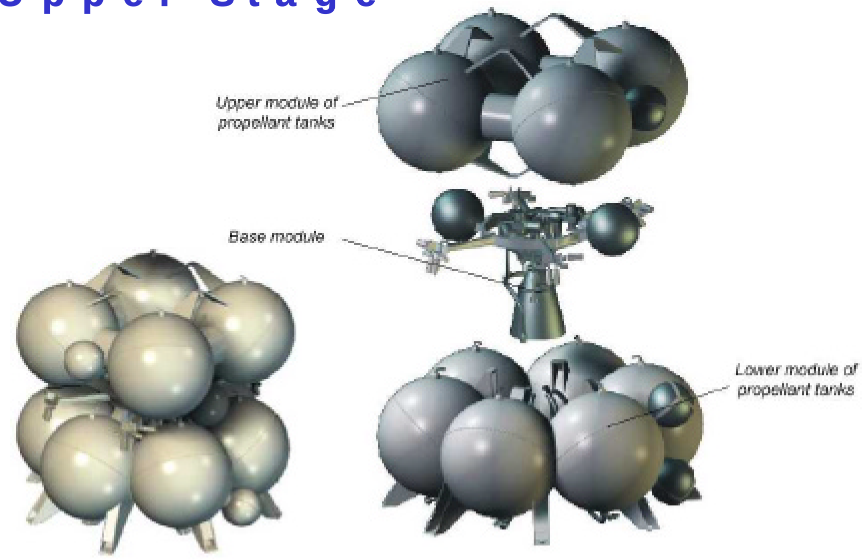
- Transfer duration: 13 months
- ΔV injection into transfer orbit and final breaking manoeuvre: 350 + 350 m/s
- Manoeuvres can be performed with AOCS

Alternative launcher: Dnepr-M + Varyag



- Dnepr: derived from the world most powerful ICBM (SS-18)
- Launch from a silo in Baikonur
- 159 successful launches
- New elongated fairing

Varyag Upper Stage



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The Varyag Upper Stage

- Varyag is based on Phobos/Mars96
- Highly efficient because of staging concept: two sets of tanks:
  - upper module fixed
  - lower module jettisonable
- Same engine as Fregat (S5.92)
- Same adapter as Fregat (TBC)
- Same performance as Soyuz + Fregat
- Half the cost of Soyuz + Fregat

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Ground Systems & Operations

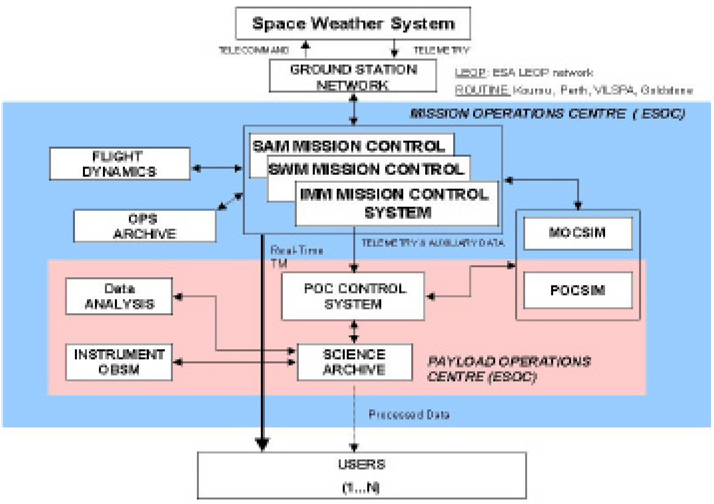
Ground Systems & Operations: Requirements & Assumptions

- General requirement: real time and continuous (when altitude > 3000 km for IMM) data retrieval and distribution
- Assumptions:
  - Relatively low data rate
  - X-band used for up and down link

Ground System & Ops.

- IMM
  - Kourou: 1 TM and 1 TM/TC 8 m antenna
  - Perth: 2 TM 8 m antennas
  - HK up and down link: 2 kB/s
  - Payload data: 11 kB/s
  - Perigee dump: 170 kB/s
- SWM
  - Perth: 1 TM/TC 15 m antenna
  - Villafranca & Goldstone: 1 TM 15 m antenna
  - HK up and down link: 2 kB/s
  - Payload data: 9 kB/s
- SAM
  - Same as SWM, same antenna (dual feed)
  - Payload data: 35 kB/s

Ground System & Ops.



Ground Systems & Ops. Option: Relay on GEO

- *Mission design:* two SAM S/C in GEO:
  - to cover for eclipses during equinoxes
  - acting also as relay satellites for IMM and SWM
- Separation between two SAM satellites in GEO > 17º
- IMM coverage for **full** orbit and no need for special phasing
- **Only one ground station with 2 TM/TC antennas ensures complete real time coverage**
- *Drawback:* additional cost and complexity to the space segment:
  - Complex inter-spacecraft communications
  - **Two** SAM S/C with science **and** telecommunications capabilities
  - Higher ΔV for transfer to GEO than to L_1
  - Higher launcher cost

Ground Systems & Ops. Option: Earth Trailing Orbit

- SAM S/C on trailing orbit 10° behind Earth
- Ground stations: 4 locations ~ 90° apart in longitude for ensuring real time data retrieval and complete coverage
- Each location with a dedicated TM receive antenna. Two possible options:
  - 35 m X-band antennas (10º min. elevation for AOS) or
  - 15 m Ka-band antennas for downlink (min. el. for AOS: 30°), X-band used for uplink; during contingency 35 m antenna needed for uplink
- Possible ground station selection: Papeete, Kourou, Malindi, and Darwin
- During transfer to operational orbit instruments are on, except when:
  - geometry prevents contact
  - spacecraft in Earth penumbra

System

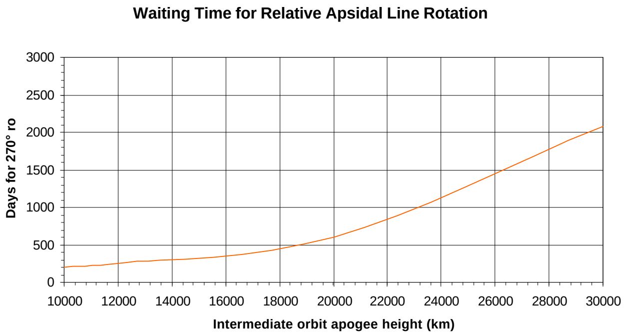
IMM - Requirements

- 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

I M M Design drivers - 1

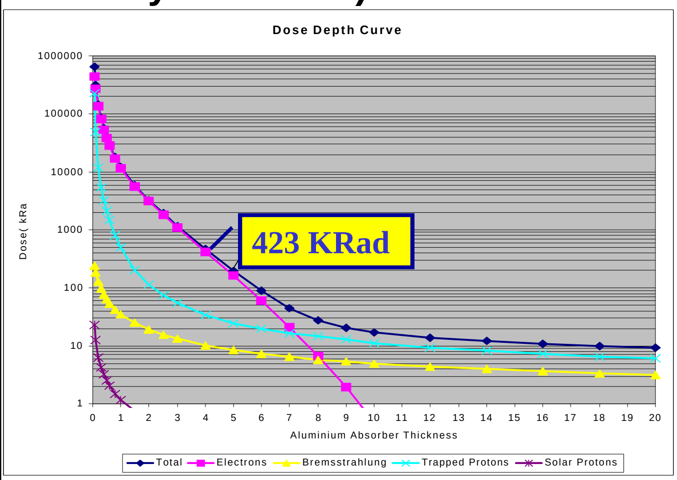
•The S/C need an onboard propulsion

•No possibility found to build up the final constellation from launching to GTO or LEO w/o propulsion (natural drift too slow, chances to get 4 GTO piggyback launches 90 deg apart very little)



I M M Design drivers - 2

•Harsh radiation environment (very high dose for 5 yrs mission)



•Additional shielding must be considered for sensitive equipment and rad hard components preferred

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)

GSLV

- Capability to 200 Km 18 deg LEO: 4050 Kg
- Capability of PSLV for the same orbit: ~2800 Kg
- First launch performed in April 2001
- Launch is from Sriharikota (India)

I M M   P l a t f o r m   r e - u s e

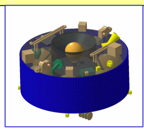
Platforms analysed

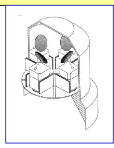
	S/C mass	P/L	Mission	Orbit	AC	Prop	Rad hard	Note
STRV C&D	112 Kg	25 Kg	Inner Magnetosphere	300X36000 Km	Spin (? rpm)	None	YES	Propulsion needs to be accommodated
Equator-S	230 Kg	45.7 Kg	Inner Magnetosphere	500X63700 Km	Spin (40 rpm)	Solid prop	YES	Propulsion adequacy to be assessed
SSTL Emicro	up to 140 Kg	up to 45 Kg	Various	LEO	3-axis (spin possible ?)	Resistojet (for AOCS)	not specific	Stabilisation and propulsion to be checked
Proba	100 Kg (TBC)	?	Technology	Polar	3-axis	None	?	The platform requiring the biggest adptation
Freja	235 Kg	73 Kg	Magnetosphere	Polar	Spin	Solid prop	?	
Astrid-2	30 Kg	9 Kg	Magnetic field	Polar	Spin	None	?	Too small

- From a mechanical point of view no standard platform can be entirely re-used (engine and tanks need to be accommodated, structures and thermal control adapted)
- Most of the platforms don't use rad hard components. Choice of the platform must be limited to the ones flown in a similar environment
- Best candidate STRV 1c-d

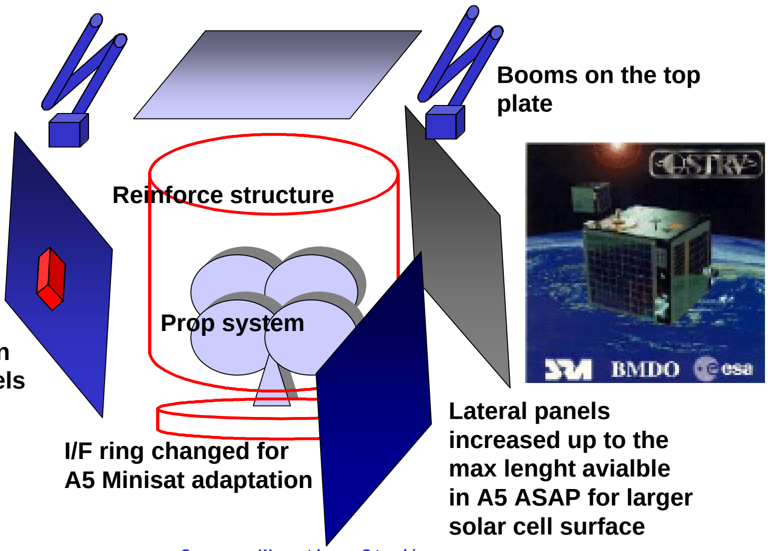
I M M   O p t i o n s

Mission		1	2
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	STRV-adapted
Existing Platforms Identified			
Dry Mass-class (kg)		<1000	<300
Stabilisation		Spin-stabilized	Spin-stabilized
Launcher			
Launcher		GSLV	AR5 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)





Option 2 - Modifications to STRV



IMM Trade-Off

<u>Although the same payload can be accommodated in both options, Option 2 has the following drawbacks:</u>

•The STRV power design cannot be re-used because of the different strategy (the payload must be operated continuously and downlink must be in real time)

•The STRV structure must be redesigned because of the additional propulsion system on board (~70 Kg propellant needed and a height of 0.8 m to accommodate the engine and the tanks)

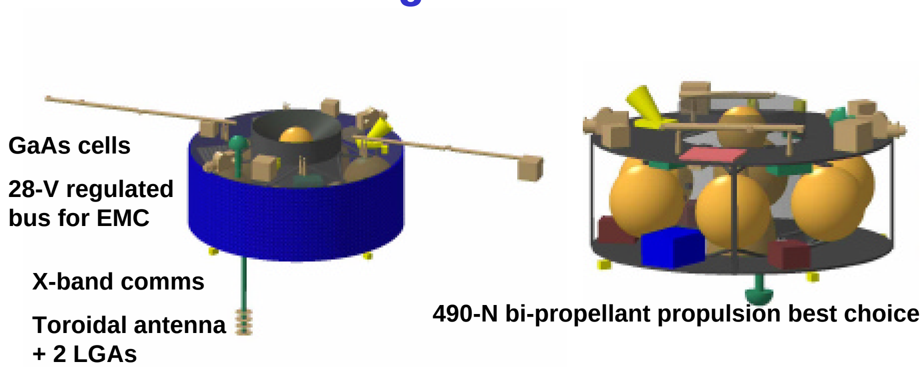
• The size of the S/C allowed by the A5 ASAP I/F is rather small (1.5 m side max) which limits the area of the solar cells and then the power onboard

•The very large time to achieve the constellation (up to ~600 days) has impact on reliability and cost

•The launch cost is still rather high (40 ME as compared to 50 ME from GSLV)

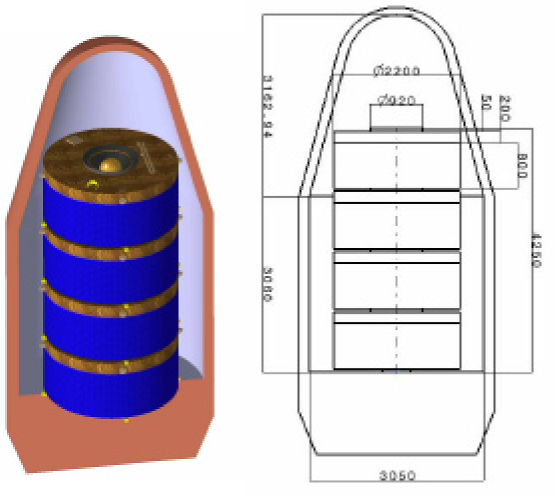
<u>Option 1 gives more flexibility and therefore has been preferred</u>

I M M 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

I M M GSLV Fairing accommodation



Central cylinder of the IMM structure dimensioned for 10 Hz first lateral frequency of the stack

I M M : m a s s b u d g e t

ESA SPACE WEATHER STUDY

	Without Margin	Margins %	Margins kg	Totals kg	% of Total
Target Spacecraft Mass at Launch				4050 kg	
Below Mass Target by:				1 kg	
1. Structure	92.4 kg	18.8	17.4	109.9	10.92
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	15.0 kg	10.0	1.5	16.5	1.64
7. AOCS	8.1 kg	10.0	0.8	9.0	0.89
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.	317.3 kg			353.7	35.17
System Margin (excl.adapter)		17.0 %		60.1	
Total Dry with Margin (excl.adapter) - per sat.				413.8	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)				345.5	
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

I M M : p o w e r b u d g e t

ESA SPACE WEATHER STUDY

Mode names are linked		Instr.	Thermal	AOCS	Comms	Propulsion	OBDH	Power Cons.	Pyro	Mech	Harness (excl. PSS)	TOTAL CONSUMPTION
		manual	manual	manual	manual	manual	linked	computed	manual	manual	computed	
Launch Mode	MAX	0	30	0	10	0	48	31	0	0	1.8	120
	NOM	0	30	0	10	0	32	26	0	0	1.4	99
	MIN	0	0	0	10	0	10	20	0	0	0.4	41
Separation and Transfer Mode	MAX	0	20	5	18	0	48	31	0	0	1.8	123
	NOM	0	25	5	18	0	32	26	0	0	1.6	107
	MIN	0	0	5	18	0	10	20	0	0	0.7	54
Initialisation Mode	MAX	36	20	5	18	0	48	31	0	0	2.5	160
	NOM	33	20	5	18	0	32	26	0	0	2.2	136
	MIN	33	0	5	0	0	10	20	0	0	1.0	70
Operational Mode	MAX	36	20	5	18	0	48	31	0	0	2.5	160
	NOM	33	20	5	18	0	32	26	0	0	2.2	136
	MIN	33	0	5	18	0	10	20	0	0	1.3	88
Eclipse Mode	MAX	36	25	5	18	0	48	31	0	0	2.6	165
	NOM	33	30	5	18	0	32	26	0	0	2.4	146
	MIN	33	0	5	18	0	10	20	0	0	1.3	88
Safe Mode	MAX	0	25	5	18	0	48	31	0	0	1.9	128
	NOM	0	30	5	18	0	32	26	0	0	1.7	112
	MIN	0	0	5	18	0	10	20	0	0	0.7	54

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

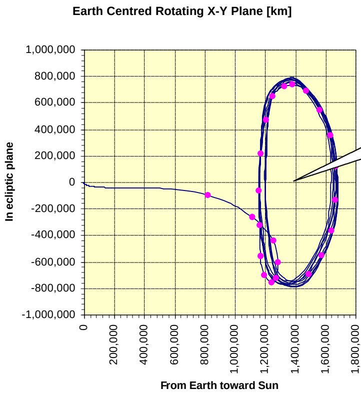
•More detailed radiation analysis needed at component level

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

SWM - Mission Requirements

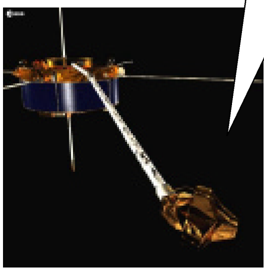
- **Orbital location with continuous and unobstructed flow of the Solar Wind**
- **Near-real time data flow**
- **Lifetime: 5 yrs**
- **Launch date for pre-op system: 2006**
- **High Electromagnetic Cleanliness**
- **Spin stabilisation preferred**

S W M - Design drivers



Halo Orbit around the L1 point between Earth& Sun drives communication, power and thermal design

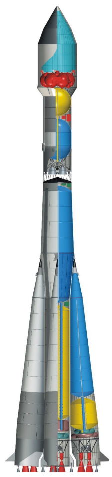
Cluster-type EMC cleanliness



- L1 Halo orbit has a large communication distance: between 1.2 & 1.7 million km

S W M Launcher Selection

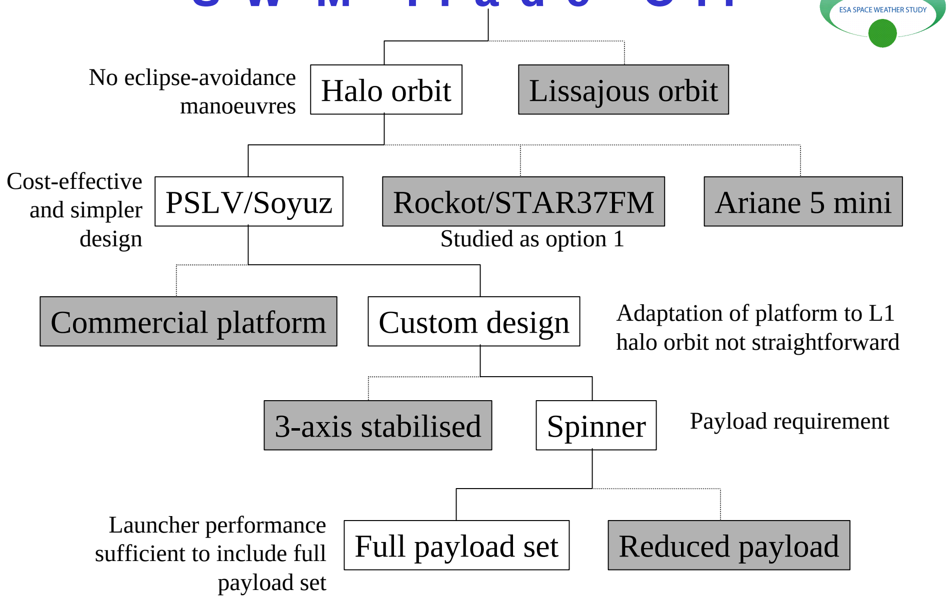
- If Soyuz-Fregat or PSLV is chosen:
  - Launch into 200 km parking orbit with upper-stag[e] still attached, Upper-stage ignites and injects S/C into L1 transfer orbit
  - Performance to L1: PSLV = 400 Kg, Soyuz-Fregat: 1600 Kg
- If Rockot (+ additional STAR 37 motor) is chosen:
  - Launcher puts S/C + STAR37FM solid engine attached into 200 km orbit, STAR37FM ignites and S/C+STAR37FM enter L1 transfer orbit
  - Performance to L1: 306 Kg



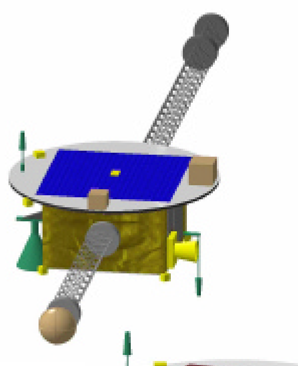
S W M Options

	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

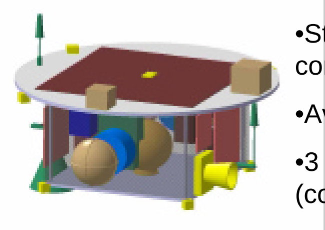
S W M Trade-Off



SWM baseline Configuration

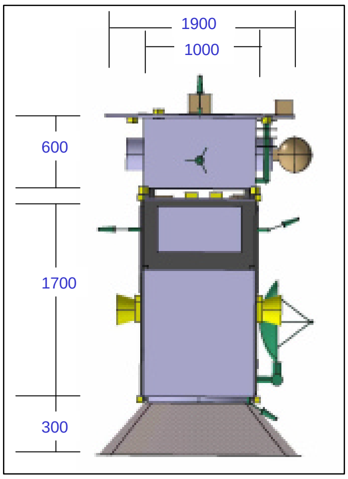


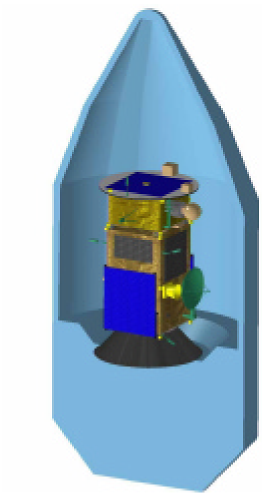
- S/C of the Minisat class (~200 Kg)
- Very simple attitude (spinning with solar array coarsely Sun pointing)
- Only propulsion for AOCS required



- 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)

SWM baseline Fairing accommodation (with SAM)





SWM : mass budget

ESA SPACE WEATHER STUDY

	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. AOCS	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	0.5	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 : power budget

ESA SPACE WEATHER STUDY

		PCU	PDU	TCU	BATTERY	PSS Harness	PSS TOTAL DISSIPATION	S/C TOTAL DISSIPATION
Launch Mode	MAX	26	12	5	3.4	1.8	48	93
	NOM	24	10	4	3.2	1.7	43	87
	MIN	21	9	4	3.0	1.6	38	82
Transfer mode	MAX	25	15	5	0.0	1.9	47	120
	NOM	23	13	5	0.0	1.8	43	113
	MIN	19	11	4	0.0	1.5	35	90
Initialisation Mode	MAX	28	16	6	0.0	2.2	52	144
	NOM	25	15	5	0.0	2.1	47	137
	MIN	19	11	4	0.0	1.5	35	90
Operational Mode	MAX	28	16	6	0.0	2.2	52	144
	NOM	25	15	5	0.0	2.1	47	137
	MIN	19	11	4	0.0	1.5	35	90
Safe Mode	MAX	41	17	6	6.4	3.5	73	146
	NOM	38	15	5	6.1	3.3	67	137
	MIN	31	13	4	5.1	2.8	56	111

SWM Option

•Option 1 is technically feasible however:

•The structure needs reinforcement due to the high thrust of the solid motor

•AOCS must be re-designed (fast spin-up, nutation dumpers, more prop. for ΔV dispersion)

•The antennas need to be reallocated because of interference from the solid rocket structure

•SAM must be launched in a single dedicated launch with cost increase

•A launcher for the mass class of SAM in L1 (600 Kg) could not be found

SWM Conclusions and Open Points

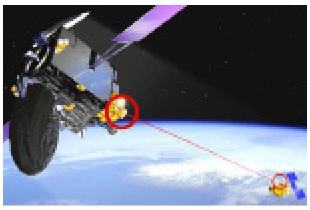
•Very simple and reliable design

•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 Drivers

•P/L dimensions (height of Coronograph ~1.4 m)

•P/L data rate: 35 Kbps

• If L1 halo or 10 deg trailing orbit selected, high distance from Earth determines TT&C architecture and power consumption. In both cases very stable thermal environment

• If L1 halo orbit selected low propellant for station-keeping maneouvres and direct injection (no need of main propulsion system).

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.

SAM Launcher Selection

• Soyuz Fregat Dual launch with SWM selected as the most efficient launch strategy

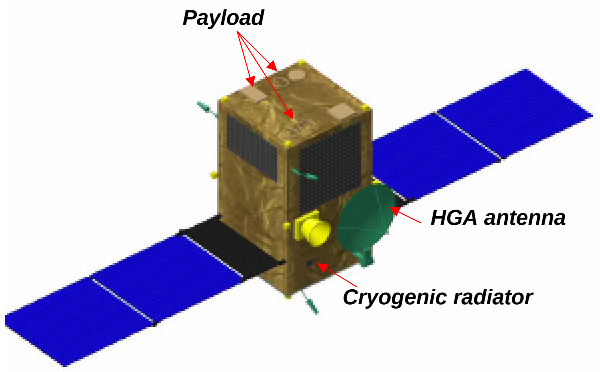
•Dnepr Varyag possible back-up (if launch is earlier than 2008) but availability and performance of this launcher need confirmation

•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

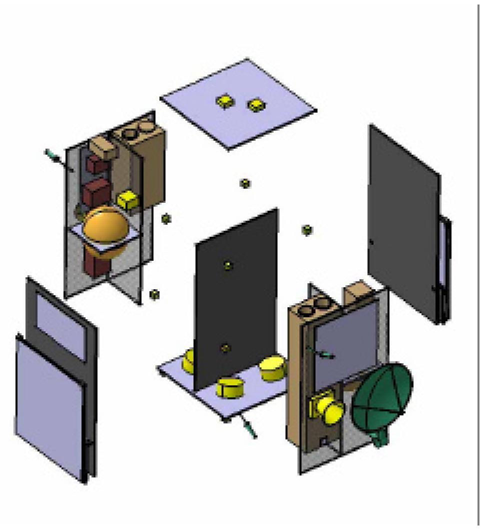
SAM Baseline Configuration

- 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 Configuration - 2



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		59.2
				0.0
Adapter Mass (incl. Sep. Mech.)				50.0
Total Launch Mass				535.3

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

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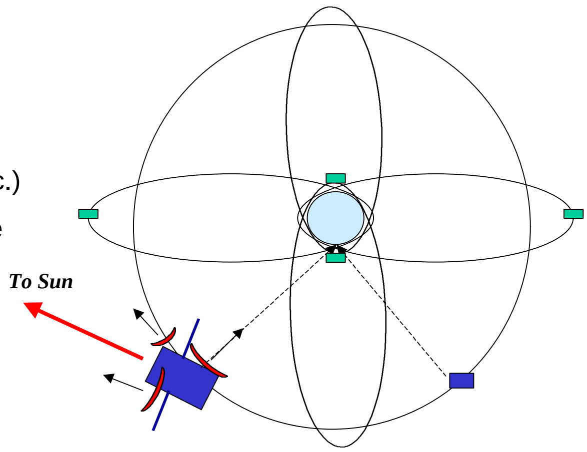
SAM GEO & Data Relay Option

- The SAM S/C works as Solar Monitor and as Data Relay for the SWM and the IMM's

The S/C should include both the features of a Telecom sat and accommodate the solar monitor payload (cryogenic radiators, etc.)

Link to L1 would require non-off-the-shekf equipment

Cost saving due to simplification of the Ground Segment would only be 10-20 ME



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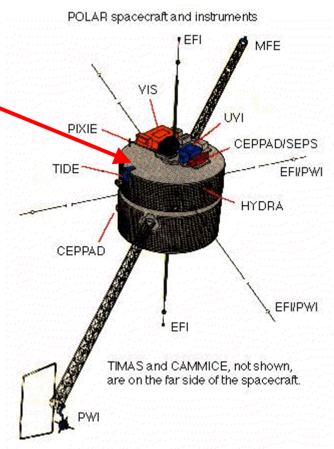
Combined SAM & SWM

•If the combined S/C is a spinner additional complexity and technology development for the despun platform necessary for the remote sensing payload

•If the combined S/C is 3-axis stabilised the SWM payload needs to be re-designed.

•This option has not been studied further into detail. It is technically feasible and may be considered if cost reduction of the whole system is required (to be confirmed)



SAM in Trailing Orbit

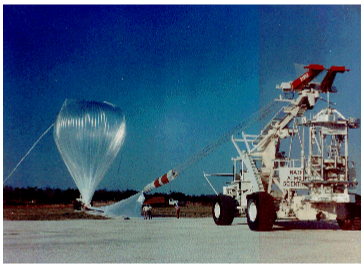
As far as the S/C design is concerned the following critical issues have been identified:

•During cruise to 10 deg trailing orbit the S/C experiences a penumbra phase. This has not been studied into detail but the impact on the power and thermal design may be large

•The Telecom system onboard must be designed to cope with the very large distance from Earth (25 million Km) and with the high variability of the angle to Earth during cruise (up to 180 deg steering)

• The ground segment necessary is the one needed for 100% availability in a deep space mission using either X or Ka band.

SAM Balloon Option

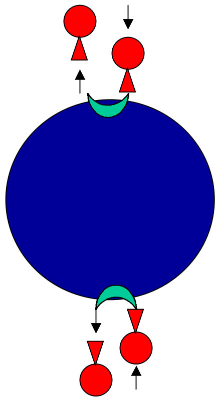


The option would require a large number of balloons (depending on the lifetime of the balloons) (presently ~10 days) on both poles alternatively at an altitude of ~35 Km

Lifetime of the balloon limited by the thermal excursion during mission.

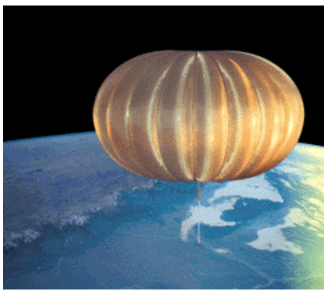
To keep the altitude between a predefined range ballast must be ejected.

•The ballons should be recovered in order to reuse the payload, refurbished and re-launched



SAM Balloon Option - Pro's and Con's

Pro's	Con's
Low cost of a single balloon	Comms require data relay satellites (Ground Stations in polar regions difficult)
Low cost of launch	Need of very high number of balloons (with the present lifetime)
High payload mass	Need of difficult recovery operations (otherwise cost benefit is greatly reduced)



Conclusion: Technology not sufficiently mature

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