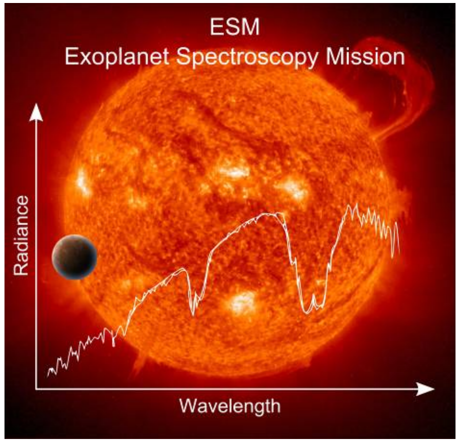
ESM
Exoplanet Spectroscopy Mission

Internal Final Presentation

ESTEC, 26th March 2010



Prepared by the ESM/ CDF* Team

(*) ESTEC Concurrent Design Facility

ESM - Assessment Study

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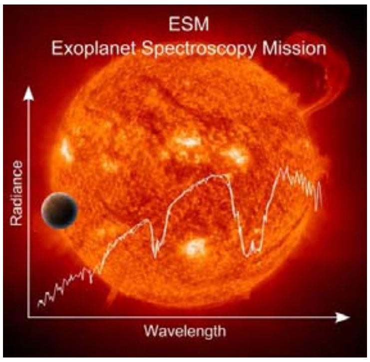
Exoplanet Spectroscopy Mission

Agenda



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Study sessions overview

16/02 Session 1 - Kick-Off

18/02 Session 2

03/03 Session 3

05/03 Session 4

12/03 Session 5

17/03 Session 6

19/03 Session 7

26/03 Session 8 - Internal Final Presentation

IFP Agenda

- Overview / Agenda
- System Presentation
- Payload Instruments
  - Telescope
  - Instruments
  - Detectors
- Discipline presentations
  - AOCS
    - Overall S/C
    - FGS
  - Configuration
  - Structures
  - Thermal
    - SVM
    - PLM/Cryogenics
  - Propulsion
  - Power
  - DHS
  - GS/OPS
  - Communications
  - Programmatics
  - Risk
- Conclusions

Study sessions overview

- Start of session at 9:30
- Lunch at about 12:00
- Re-Start max ! 13:00
- IFP end at max !16:00

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ESM context and CDF results

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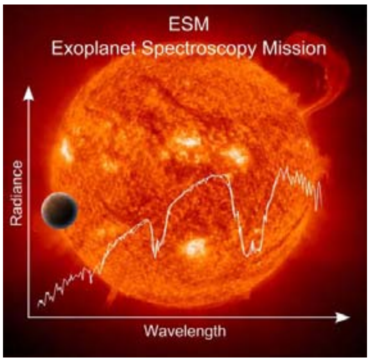

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ESM context

- Phase 0 study on mission concept
- ESA M-class mission:
  - Launch by 2020 on Soyuz from Kourou: 2165 kg
  - TRL 5 by end of Definition Phase (~2015)
  - PLM mass: ~700 kg max *
  - M1 size: ~1.2 m *
- Derived from THESIS science case:
  - Required wave range: 0.7 to 5 microns
  - Goal wave range: 0.7 to 15 microns
  - Spectral resolution: 200
  - Instrument dynamic range: 10^5

* Based on CV15-25 experience and to be assumed for the purpose of the study

ESM CDF baseline design

- Optical design from 0.7 to 15 microns split in 3 channels with 2 orders of dispersion each: optimised integration times and enhanced throughput
- HgCdTe detectors require technology development activities:
  - DR seems achievable up to 10 microns
  - Between 10 and 15 microns, dark current dramatically reduces DR
- Instrument Optical Bench at 30 K (10 µm), telescope under 50 K
- Enhanced stability: no moving parts on the S/C apart from magnetic bearing reaction wheels
- Large usage of heritage: Herschel (communications), Herschel, SPICA and Euclid (telescope and shields), Gaia (magnetic bearing reaction wheels), LPF (FEEP) etc.

ESM CDF baseline design

ESM CDF demonstrated a robust design within the Soyuz specifications, with margin available for mitigation of typical increases in complexity and budgets during future study phases.

Definition level commensurate to Phase 0 study, thus results require further validation and analysis to confirm the resource budgets.

Impact of alternative designs

- Extension between 10 and 15 microns with a Si:As detector:
  - Additional cryocooler stage at 7 K, increased mass and power
  - Micro vibrations and thermal gradients on instrument platform will reduce the stability performance
  - Technology development activities also required to achieve DR requirement
- Optical design alternatives:
  - A single optical design performed: no comparison of performance possible
  - ESA design only: provision of instruments by industry or institutes would modify the design and its mass
- Alternative AOCS actuators:
  - FEEPs and reaction wheels
  - Increased mass and complexity

Future analysis required

- Detailed optical design (telescope and spectrometer)
- Structural analysis of telescope assembly and overall PLM
- Refocusing mechanism on M2:
  - Extra mass, and stiffer support structure on M2
  - Increased risk, single point failure
- Internal metrology system for calibration of PLM
- Shielding of detectors:
  - Thick metal protection rather than MLI tent
- Consolidation of resource budgets (mass, power, data, ΔV)
- If increase in power requirement:
  - Deployable solar array to be investigated

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Systems

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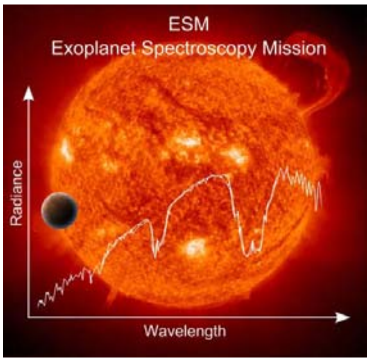

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Summary of main mission requirements (1)

	Mission Requirements		
	System Requirements		
SR-1	The spacecraft shall be launched from Kourou.	Yes	
SR-2	The spacecraft shall be launched by a Soyuz ST.	Yes	
SR-3	The spacecraft incl. launch adapter and system margins mass shall not exceed 2165 kg.	Yes	Currently well below the launcher performance
SR-4	The lifetime of the spacecraft shall be at least 3 years.	Yes	
SR-5	Safe mode shall last at least 2 days.	Yes	4 days
	Configuration/Structure		
SR-6	The ESM space segment shall consist of a single spacecraft that includes a Payload Module and a Service Module.	Yes	
SR-7	Volume & launch loads shall be compatible with Soyuz ST 2-1b	Yes	

Summary of main mission requirements (2)

##		Mission Requirements			
		Payload			
SR-8		The distance between M1 and M2 shall not be greater 1,6 m.	Yes	1.4 m	
SR-9		The ESM telescope primary mirror diameter shall be no smaller than 1.2 m, and as large as possible considering requirement R-PM-CLA-10. (TBC)	Yes		
SR-10		The ESM telescope effective aperture shall be no smaller than 1.06 m and as large as possible considering requirement R-PM-CLA-10, including the primary mirror central hole and obscuration by the secondary mirror. (TBC)	Yes		
SR-11		The ESM telescope effective aperture shall be no smaller than 1.2 m and as large as possible considering requirement R-PM-CLA-10, including the primary mirror central hole and obscuration by the secondary mirror. (TBC)	No		1.1937 m
SR-12		The ESM telescope FoV shall be no smaller than the FGS required FoV defined in R-SC-ACS-60.	Unknown	True if no beamsplitter for second FGS. Unknown at this stage in case of beam splitter	
SR-13		The ESM telescope back focal length (distance from primary mirror to focal plane) shall be no greater than 1.1 m. (TBC)	No		1.1397 m
SR-14		The telescope shall be near diffraction limited in an area large enough to contain a single star in the considered wave range in the centre of its FoV. (TBC)	Yes		
SR-15		The scientific instrument shall cover the 0.7 to 15 micron wave range with at least 2 channels. (TBC)	Unknown	0.7-10 can be achieved 10-15 need USA Si-As detector	
SR-16		The scientific instrument shall cover the 1 to 17 micron wave range with at least 2 channels. (TBC)			
SR-17		The scientific instrument shall have a spectral resolution R≥ 200 throughout the considered wave range. (TBC)	Yes		
SR-18		The total throughput (telescope reflections and instrument optics down to the detectors) of the science channels shall be no lower than 0.25 throughout the considered wave range, and as high as possible. (TBC)	Unknown		

Summary of main mission requirements (3)

SR-18		The total throughput (telescope reflections and instrument optics down to the detectors) of the science channels shall be no lower than 0.25 throughout the considered wave range, and as high as possible. (TBC)	Unknown	
SR-19		The QE of the science detectors shall be no lower than 0.8 throughout the considered wave range, and as high as possible. (TBC)	Yes	Yes for MCT, Si-As currently 0.7
SR-20		The slit diameter shall be greater than the PSF at the telescope focus of a point source at infinity at the maximum considered wavelength, plus the Absolute Pointing Error (APE). (TBC)	Yes	
SR-21		The slit diameter at telescope focus shall be small enough to limit the impact of the telescope thermal emission on the science detectors as a noise contributor following R-SP-INS-110.	Unknown	
SR-22		The size of the image of the slit, in the spatial direction in each individual detector, shall be constant, and equal or greater than 2 pixels. (TBC)	Yes	
SR-23		The HEW of a target star shall be no more than 2 pixels wide, in the spectral direction of the dedicated detector, at any wavelength λ within the considered wave range. (TBC)	Unknown	Yes if the HEW is the monochromatic imge of the slit
SR-24		Any two consecutive wavelengths in the considered wave range (separated by Δλ defined by the spectral resolution R) shall be separated in the spectral direction of the dedicated detector by at least 3 pixels. (TBC)	Yes	
SR-25		The telescope and any hardware in view of the science detectors shall be sufficiently cooled to ensure thermal noise is negligible compared to other noise sources (photon noise and instrumental noises). (TBC)	Yes	
SR-26		The science detectors shall be sufficiently cooled to ensure instrumental noise is negligible compared to photon shot noise. (TBC)	Unknown	Dark noise: yes (by detector selection) but readout: to be developed
SR-27		The scientific instrument shall have the capability to bin several pixels line together, to perform spectro-photometry for fainter targets. A spectral resolution as low a R=5 shall be considered. (TBC)		
SR-28		The science detector's dynamic range shall be greater than 5x10[illegible] and as high as possible. (TBC	Yes	

Summary of main mission requirements (4)

		Mission Requirements				
		Comms				
SR-29		For up- and downlink communications X-band shall be used.	Yes			
		Data storage				
SR-30		Data storage shall have the minimum size of 1 day nominal operations without ground contact	Yes			
		Thermal				
SR-31		The overall down cooling of the payload module shall be 50 K.	Yes	20 (short wave)	7 (long wave)	30 (used in this design)
SR-32		For the detector a temperature of tbd K is required.				
		Programmatics				
SR-33		The S/C shall be launched before 2020.				
SR-34		Payload flight units shall be delivered until 2014.	No	Schedule to be refined Critical item: TRP start & definition	2022	
SR-35		TLR 5 shall apply to the most critical technologies at time of PDR.	Yes	But dectors follow critical line		

Summary of main mission requirements (5)

		Mission Analysis		
SR-36		For ESM a L2 orbit in the Earth-Sun system shall be used.	Yes	
		AOCS		
SR-37		A overall stability of the s/c of tbd shall be ensured.		
SR-38		The Absolute Pointing Error shall be better than 4,5”.	Yes	2.25"
SR-39		The Absolute Measurement Error shall be better than 3”.	Yes	1.5"
SR-40		A pointing stability better than 1/10 pixel shall be achieved in the pitch and yaw axes at the science instrument detector level, over a period defined by the longest exposure time per frame. (TBC)	Yes	0.1"/10s but a change in requirement definition is proposed (see AOCS)
SR-41		The S/C shall be able to observe for a period of 9 hours while meeting the APE requirement.	Yes	
SR-42		The S/C shall be able to make a full 360 rotation in the plane perpendicular to the Sun vector.	Yes	
SR-43		The S/C shall be able to make a rotation of ± 45 deg in any plane containing the Sun vector.	Yes	

Summary of main mission requirements (6)

		Mission Requirements		
		Ground System		
SR-44		The ESM Mission operation Centre shall be ESOC.	Yes	
SR-45		Science Operations Centre shall be ESAC.	Yes	
SR-46		The MOC shall provide all the telemetry to the SOC.	Yes	
SR-47		ESA ground network shall be used.	Yes	New Norcia
SR-48		LEOP phase from launch to end of the 1st correction manoeuvre.	Yes	
SR-49		Commissioning shall be completed within two months after the transfer phase.	Yes	
SR-50		Nominal science operations shall be 3 years.	Yes	
SR-51		Possible extended operations of 3 years.	Yes	
		Costing		
SR-52		The ESM shall be a M-class mission.	Yes	

Updates on CDF requirements have led to an updated Mission Requirements Document

Design options

- Orbit
- S/C configuration

Orbit options

- L2 orbit was chosen for:
  - Science ops can start already 1 month after launch
  - Low orbit maintenance budget, science interruption once a month
  - Very stable thermal environment
  - Low level of perturbations
  - Acceptable launcher performance with Soyuz-ST
- However for this orbit, several options exist:
  - Small versus large amplitude orbit
  - High-elliptic parking orbit versus direct insertion

Orbit trade-off

	Large amplitude	Small amplitude
Parking orbit	**No insertion ΔV** **May need antenna re-pointing** **Engine calibration possible** **Relaxes launcher dispersion manoeuvre**	**High insertion ΔV** **No antenna re-pointing** **Engine calibration possible** **Relaxes launcher dispersion manoeuvre**
Direct insertion	**No insertion ΔV** **May need antenna re-pointing** **Tight schedule for launcher dispersion manoeuvre**	**High insertion ΔV** **No antenna re-pointing** **Tight schedule for launcher dispersion manoeuvre**

Orbit conclusions

- A large amplitude L2 orbit with launcher injection into parking orbit was chosen, for:
  - – The mass in L2 when using the parking orbit is the same as using direction injection into L2
  - – The use of a parking orbit lowers the risk of missing the time slot of the launcher dispersion manoeuvre
  - – A large amplitude drastically lowers the total ΔV
  - – The low data rate allows for data downlink twice a week
    - Use spacecraft pointing instead of risky/costly antenna pointing mechanism
    - The required observation duty-cycle can still be achieved
- Heritage from Herschel, LPF

Delta-V budget summary

- AOCS: 30195 pulses @ 1 N → 1.82 m/s
- Mission:

		Δv			
		30 d station-keeping			
		spher.		hemisph.	
man.	day	unbal.	bal.	unbal.	bal.
TCM#1	2	34.8	34.8	69.6	69.6
TCM#2	5	1.1	1.1	2.2	2.2
TCM#3	20	0.5	0.5	1.0	1.0
station-keeping	30 to 2222	18.0	7.9	36.0	15.8
margin (10%)		5.4	4.4	10.9	8.9
total		59.8	48.8	119.7	97.5

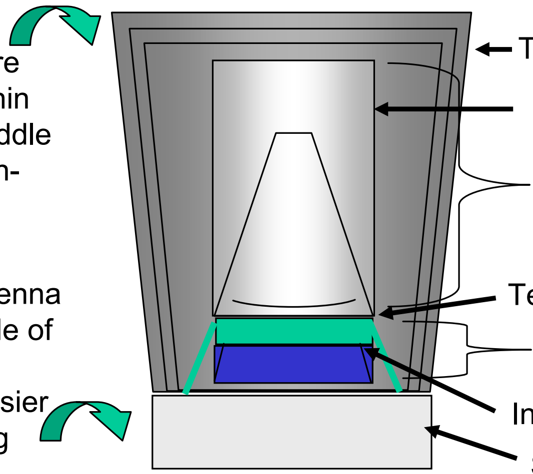
  - – For this study a spherical capability (unconstrained thrust direction) is chosen, with un-balanced thruster configuration (i.e. no free torque)

S/C configuration options

- S/C design can be based on Herschel, Planck & SPICA heritage
- A SPICA-similar design was chosen due to the thermal design of the spacecraft

Solar panels are mounted as a thin tall strip in the middle of the outer sun-shield

Medium-gain antenna on Sun/Earth side of the SVM.
No S/A gives easier access during integration



Product tree

	SVM	PLM				
		Telescope	Instruments			
			SWS spectrometer	MWS spectrometer	LWS spectrometer	
Structures	SVM structure SA structure	Baffle Mirror Supporters PLM-SVM I/F	SWS optical bench SWS equipment bay	MWS optical bench MWS equipment bay	LWS optical bench LWS equipment bay	
AOCS	AOCS					
FGS	FGS Module		Detector FGS			
Comms	Communications					
Power	Power					
Propulsion	Propulsion					
Thermal	SVM Thermal control	Cryogenics				
DHS	S/C DHS, mass memory					
Optics		All optic before beam split				
Instruments			SWS optics SWS mechanisms SWS detectors	MWS optics MWS mechanisms MWS detectors	LWS optics LWS mechanisms LWS detectors	

Mass Budget Summary - PLM

Payload Module					
	Target Spacecraft Mass at Launch			1400.00	kg
	Below Mass Target by:			827.88	kg
	Without Margin	Margin		Total	% of Total
Dry mass contributions		%	kg	kg	
Structure	222.78 kg	10.00	22.28	245.06	55.68
Instruments	32.43 kg	20.00	6.49	38.91	8.84
Cryogenics	131.00 kg	19.16	25.10	156.10	35.47
FGS	0.02 kg	10.00	0.00	0.02	0.00
Total Dry(excl.adapter)	386.23			440.09	kg
System margin (excl.adapter)		30.00 %		132.03	kg
Total Dry with margin (excl.adapter)				572.12	kg
Other contributions					
Wet mass contributions					
Adapter mass (including sep. mech.), kg	0.00 kg	0.00	0.00	0.00	0.00
Total wet mass (excl.adapter)				572.12	kg
Launch mass (including adapter)				572.12	kg

Mass Budget Summary - SVM

Service Module					
	Target Spacecraft Mass at Launch			600.00	kg
	ABOVE MASS TARGET BY:			-120.89	kg
	Without Margin	Margin		Total	% of Total
Dry mass contributions		%	kg	kg	
Structure	107.58 kg	12.17	13.09	120.67	28.20
Thermal Control	10.15 kg	16.61	1.69	11.83	2.76
Communications	23.50 kg	5.00	1.18	24.68	5.77
Data Handling	31.60 kg	20.00	6.32	37.92	8.86
AOCS	80.30 kg	8.81	7.08	87.38	20.42
Propulsion	26.76 kg	10.29	2.75	29.51	6.90
Power	32.00 kg	5.00	1.60	33.60	7.85
Harness	80.00 kg	0.00	0.00	80.00	18.69
FGS	2.00 kg	20.00	0.40	2.40	0.56
Total Dry(excl.adapter)	393.89			427.99	kg
System margin (excl.adapter)		30.00 %		128.40	kg
Total Dry with margin (excl.adapter)				556.39	kg
Other contributions					
Wet mass contributions					
Propellant	74.50 kg	N.A.	N.A.	74.50	11.81
Adapter mass (including sep. mech.), kg	90.00 kg	0.00	0.00	90.00	0.12
Total wet mass (excl.adapter)				630.89	kg
Launch mass (including adapter)				720.89	kg

Mass Budget Summary

Target Dry Spacecraft Mass incl. Margin at Launch	2075.00	kg
Below Mass Target by:	781.99	kg
Dry Mass PLM incl. 30% Margin	572.12	kg
Dry Mass SVM incl. 30% Margin	556.39	kg
Mass Adapter	90.00	kg
Mass Propellant	74.50	kg
Total s/c mass	1293.01	kg

Duty Cycle

	Action	Duration [min/ day]
Communication with G/S	• High data rate and Doppler navigation • Medium rate communication, ranging, and Doppler • Orbit Maintenance + larger checks	12.90 4.30 16.00
Manoeuvres	• Slewing • Pointing for communication	150.00 4.30
Maintenance of S/C	• Safe mode • Calibration	2.30 8.60

Time used for communication, manoeuvres, maintenance [min/ day]	**198.40**
Time available for observations [min/ day]	**1241.60**

→ For 10 observations à 2 hours per day a **duty cycle of 83,3 %** can be achieved.

Open points

- Focus on telescope design
- Detector technology versus number of detectors
- Confirm thruster configuration (spherical, pure-torque) as a non-spherical configuration may double the ΔV budget
- Confirm use of magnetic bearing reaction wheels
- Confirm thermal design w.r.t. mounting Solar Arrays on sun-shield
- Optimize Service Module configuration
- Optimize schedule

Conclusion

- Current design is based on:
  - Preliminary telescope design
  - Avoidance of mechanisms
  - SPICA configuration & Herschel equipment heritage
  - PLATO-type mission analysis
  - Different temperature ‘blocks’ in the system
- A 30% system margin was applied due to the low maturity of the telescope design
- With this margin, a comfortable mass budget is achieved

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Instruments Overview

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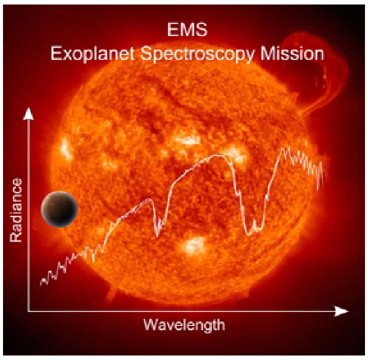

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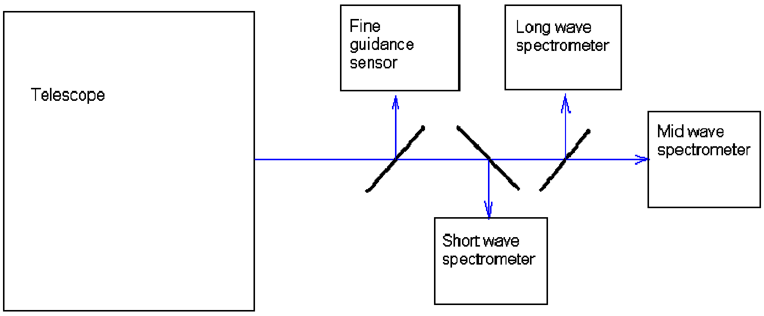
Payload requirements

- Aperture: 1.2 m Ø primary mirror
- Wavelength range: 0.7 to 5 microns
  – goal additionally 5 to 15 microns
  – *achieved 5 to 10 microns*
- Instrument spectral resolution: 200

Baseline payload

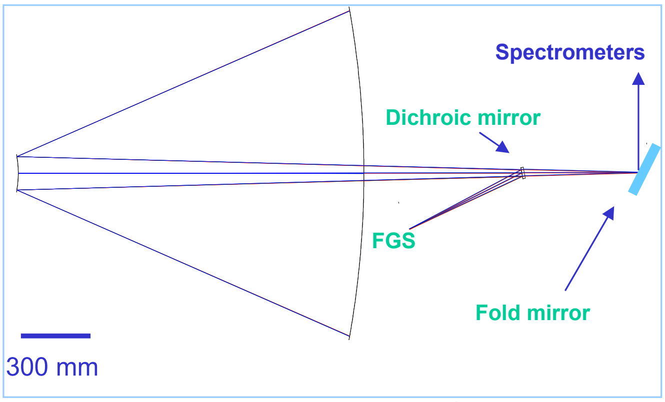
- Telescope: 1.2 m diameter (primary)
- Detectors:
  - SWS (0.7-1.8 μm)
  - MWS (1.8-5.0 μm)
  - LWS (5.0-10.0 μm)
- FGS with small FoV
  - part of AOCS



Note that the detector names changed: VNIR → Short wave spectrometer (SWS)
SWIR → Mid wave spectrometer (MWS)
MWIR → Long wave spectrometer (LWS)

Baseline telescope

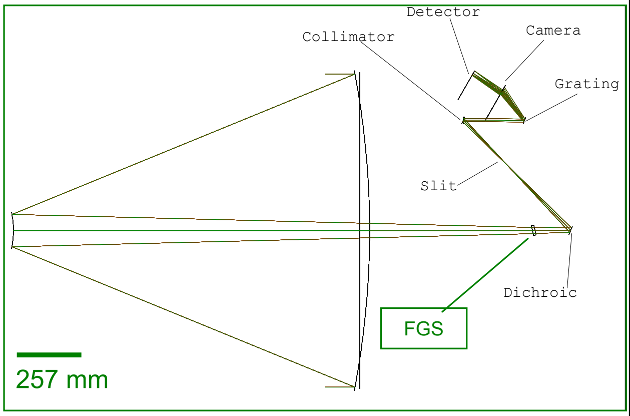
- No change to baseline design
- Cassegrain configuration with parabolic primary
- Paraxial properties:
  - EFL: 24761 mm
    plate scale: 0.1 arc sec/12 μm
  - Entrance pupil Ø: 1200 mm
  - Primary mirror Ø: 1212 mm
  - Secondary mirror Ø: 122 mm
  - Distance primary-secondary: 1400 mm
  - small FOV: ±10 arc sec



Baseline optical for all detectors

λ = 0.7-1.8 µm / 1.8-5 µm / 5-10 µm

- First instrument behind telescope focal plane
- Separated from the other instruments by a Germanium dichroic reflecting λ ≤ 1.8 µm



Detectors - overview

- See presentation by B. Leone

Budgets

Mass budget:

Item	Mass [kg]
Primary mirror	30.000
Secondary mirror	0.500
Fold mirror 1	0.022
SWS spectrometer	0.706
MWS spectrometer	0.447
LWS spectrometer	0.791
Detectors ASIC	0.070
Total	**32.536**
Total incl. 20% margin	**39.044**

Power budget:

Item	Power [W]
SWS spectrometer	0.070
MWS spectrometer	0.040
LWS spectrometer	0.070
Detectors ASIC	0.020
Total	**0.200**
Total incl. 20% margin	**0.240**

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FGS

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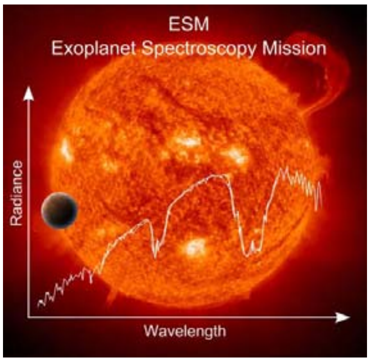

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Requirements and Design Drivers

- **Derived from ESM MRD**
  - Star to be tracked on the FGS is identical to the one observed by the science
  - Visible Magnitude of stars to be observed : 8 to 12
  - No performance requirement on Roll axis (order of magnitude of the degree)
  - FGS system shall be redundant (loss of FGS induces loss of mission)
  - FGS to be placed inside the focal plane to avoid thermo elastic distortion between FGS FoV and Payload FoV.
  - FoV : 20 x 20 arcsec
- **After iteration with the other subsystems**
  - FGS shall provide 2-axis information every 10 Hz (AOCS)
  - Stability of the S/C better than 0.1 arcsec /s (AOCS)
  - Slews with FGS in the loop (star centring) : 0.1 arcsec/s (AOCS)
  - Power dissipation of the detector lower than 50 mW (Cryo)

Assumptions and Trade-Offs : Number of stars to be tracked

- **There will always be at least one star in the FGS field of view (the Science target)**
- **Consecutive question is: will there be other stars? To answer, two methods:**
  - Hipparcos, targeting the densest direction in the galaxy (center).
  - For low magnitude stars, model of the Milky Way has been used.
    - In 1 degree², Besancon Model computed 539 targets with a limit magnitude of 18, targeting the same direction.
    - If this computation is rescaled to 20 arcsec x 20 arcsec (32400 times smaller),
  - Statistically less than one star in the FoV.
- **Based on these two computations, ESM FGS will :**
  - Track one star at a time
  - perform a filtering on the magnitude of star, in case two targets are present at the same time in the FoV.

Assumptions and Trade-Offs : SNR & predicted integration time

- Inputs :
  - Optics transmission in VIS for <u>ONE</u> FGS : 36 % (1 dichroic mirror, 3 reflective, mirrors, 1 beam splitter)
  - Target FF x QE = 45 % (no glass lid foreseen)
  - Telescope aperture = 1.2 m
- Outputs : Mag 12 123272 e-/sec ; Mag 8 : 4908415 e-/sec.
- Noise figures coming from HAS2 tests. (pessimistic due to temperature)
  - DC : 3.3 e-/s ; DCNU : 6.6 e-/s ; PRNU : 1% ; Readout Noise = 50 e-.
  - The simulations presented all error factors into account. ADC quantization and noise is also simulated.
- Radiation figure (TID on the detector) is not yet available. (impact is limited at low T)
  - DC and DCNU have been computed using RD[4] with temperature and TID variation.
  - At L2, order of magnitude is around 10 to 20 Krad beside 3 mm of Al.
  - Both DC and DCNU should not exceed 1 e-/s, but this assumption has to be supported by one test (since no measurement point exists below -40°C).
- The FGS has to provide information to the AOCS every 10 Hz.
  - Integration time has be lower than 100 ms. The maximal value for the faintest star is set at **95 ms**, to allow readout and computation in the cycle.
- Lowest SNR for edge pixels = 7. (28 DN while background ≈ 4).

Assumptions and Trade-Offs : Detector

- *Technology: CCD or APS ?*
  - 2 main arguments are favourable to APS technology:
    - FPA@30K. CMOS technology has better experience at low temperature.
    - Power dissipation of the unit shall be minimized. APS allows pixel direct access and windowing.
    - Preferable to CCD (more power), since the area of interest (the star) on the detector is very small.

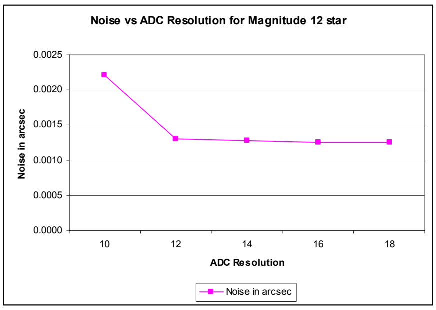
- *Off-the-shelf or custom?*
  - VIS detectors available in Europe have not been proven at low temperature. The study is based on the performance achievable with HAS2 detector (existing and qualified).
  - TRP activity : de-risk this development by testing the HAS2 device at low temperature and assess its characteristics
    - Glass lid removal, ceramic compatibility, main performances after irradiation.
  - *Power consumption of HAS2 is too high (target HAS3 also is).*
    - *At -40°C, stand by mode consumption is 60 mW and operating mode is 120 mW.*
    - Development of one detector is needed, based on existing technology, but rescaled to our need :
      - Number of pixels to be scaled down (HAS2 is 1024 x 1024)
      - Operating frequency and ADC complexity (resolution) to be possibly reduced

Assumptions and Trade-Offs : Detector

- *Number of pixels and pixels size*
  - Resolution of the focal plane is 0.1 arcsec / 12 µm.
  - PSF is 3x3 pixels, for proper centroiding, pixels below 12 µm are needed.
    - Based on 3-T pixels (HAS2, 0.35 µm technology), min pixel size is 18 µm.
    - Based on 4-T pixels (HAS3, 0.18 µm technology), min pixel size is 10 µm.
  - The best compromise is to propose 4-T pixels (HAS3 baseline) resized to **12 µm**
  - The size of the array will then be **200x200 pixels** (0.1 resolution for 20 arcsec FoV)

- *ADC Requirements : Operating frequency*
  - To be kept at 5 MHz in a first approach

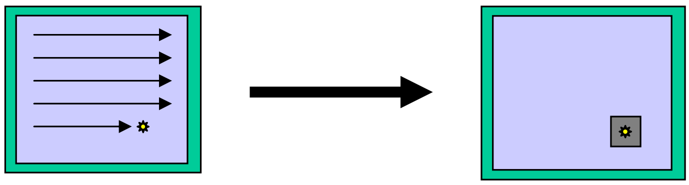
- *ADC Requirements : Resolution*
  - ADC resolution vs noise for high magnitude star (12)
  - From 10 to 12 bits, the increase of complexity is worth
  - Above 12 bits, improvement is negligible. Power and complexity increase.
  - **12-bits ADC** is the best choice for this application.



Assumptions and Trade-Offs : Software

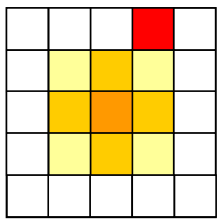
- The proposition is to develop two operating modes:
  - **Acquisition Mode** of the star on the FGS, using Full Frame.
  - **Tracking Mode** of the star with propagation of an area of interest.
- The main driver is to avoid the full frame readout at each image to save time and power.

- **A**cquisition **S**tar **M**ode (ASM) requirements
  - Perform full-frame acquisition to detect the target star.
  - When the star is detected SW orders FGS to enter the tracking mode.
  - After launch, misalignment between STR and FGS could be bigger than FoV. In case sky-scanning has to be performed during the first calibration, 30 mn is needed to scan 60x60 arcsec.
- **T**racking **S**tar **M**ode (TSM) requirements
  - Every cycle, a “window” is opened at the former position of the star. The window size contains the star spot plus a margin to allow slow star motion and background measurement. No propagation is foreseen due to the flight domain requested to the FGS (0.1 arcsec/s maximal velocity).

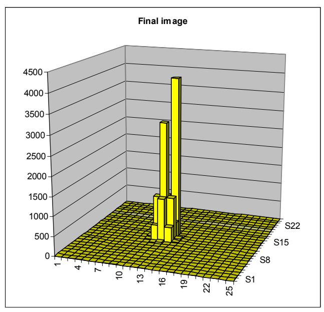


Assumptions and Trade-Offs : SEU effect on the detector

- Several missions like CoRoT have been affected by SEU on their FGS.
  - ESM FGS will use one star. If corrupted, impact on attitude restitution is direct.
  - FGS is different from traditional Star Trackers : State-of-the-art Star Trackers are tracking 15 stars every cycle, allowing filtering at star-level (rejection) : **On the FGS it is different.**



- The worst case is driven by an SEU impacting the cluster’s edge.
- The impact is bigger on faint stars :
  - **Mag 12** On x axis : 0.176 arcsec ; On y axis : 0.088 arcsec
  - **Mag 9** On x axis : 0.06 arcsec ; On y axis : 0.03 arcsec

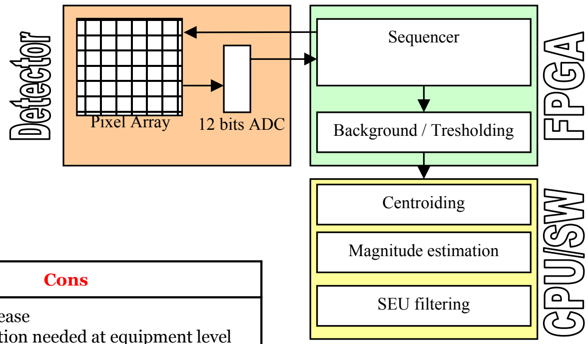


- SEU occurrence on the FGS detector is difficult to assess.
  - But one output of this CDF is the need of smart filtering.

- Ways to filter :
  - Compare two successive images,
  - Use of Non Destructive Readout (NDR) to perform several readouts during integration to detect an impulsional increase in pixel brightness.

Assumptions and Trade-Offs : FGS Electronics

- Readout electronics have to be placed close to the pixel array.
  - ADC has to be on-chip.
- For the centroiding/filtering blocks, there are two electrical configurations to trade-off.
  - The development of one dedicated unit, embedding Processor, Drivers/Receivers for communication with the ACC and memory for the software.
  - The integration of this additional processing inside the AOCS computer.



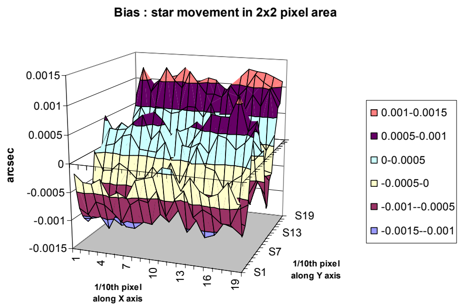
	Pros	Cons
Dedicated Unit	- Development independent of AOCS SW - Easy industrial set-up - Stand-Alone verification & test - Additional function to be easily added (noise compensation)	- Cost increase - Qualification needed at equipment level
Use of AOCS SW	- The amount of processing to be done by the CPU is low (around 1 ms / cycle in tracking)	- Data exchange between FPGA and ACC complicated: long and high speed. - Patch of FGS SW needs AOCS SW revalidation and switch to redundant ACC.

Baseline Design

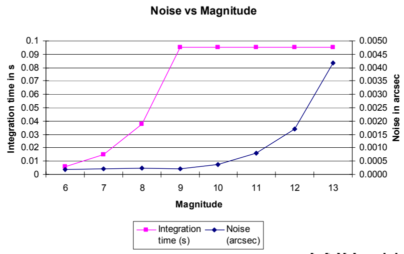
- **Detector**
  - Detector matrix : 200 x 200 pixels
  - Pixel size : 12 µm
  - Pixel type : 4-T (HAS3 baseline)
  - Star airy disk : 3x3 pixels
  - Maximal dissipation : 50 mW
  - Operating frequency : at least 1 MHz
  - ADC on-chip
  - ADC resolution : 12 bits
  - Target FF x QE = 45 % (no glass lid foreseen)
  - PRNU : less than 1%
  - DC@30 K : less than 3.3 e-/s (at 233K)
  - DCNU@30 K : less than 6.6 e-/s (at 233K)
  - Readout noise : 50 e-

- **FGS Electronics & Software design**
  - Working frequency : 10 Hz
  - Integration time magnitude dependant (95 ms for magnitude 9 and up)
  - FPGA for the readout (risk and cost reduction vs ASIC)
  - Size : max 100x100x100
  - 1 kg
  - Less than 4W
  - To be placed as close as possible of the detector
  - SEU filtering capabilities at SW level
  - Processing inside the AOCS computer

Performance



- **Bias**
  - Driven by stability of the focal plane (FGS1 vs FGS2 and FGS vs the three payloads).
  - To be assessed by thermal/structure.
  - Constant bias will be calibrated.
  - Calibration data will be different for each FGS due to the beam splitter.

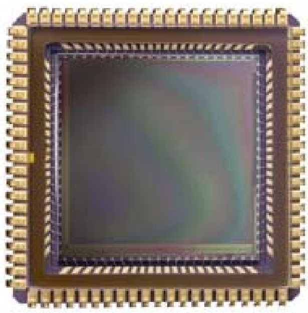


- **Drift** :
  - Driven by pixel array non uniformity and temporal noise :
  - Less than **0.0015** arcsec (See chart) for magnitude 12.

- **Noise** :
  - Less than **0.002** for magnitude 12.

List of equipments

- **Detector**
  - Custom detector to be developed on basis of HAS3 pixels (4-T), scaled down to 200x200 pixels. ADC 12-bits on the chip.
  - Lead time for qualified detector: 2.5 years.



- **Fine Guidance Sensor Electronics**
  - FPGA from ACTEL RTAX series (with on-board RAM)
  - High speed link (Spacewire) between FPGA and AOCS computer
  - Fine processing performed inside AOCS computer

Options & Technology requirements

- **Options :**
  - FGS Electronics : Processing performed in the FGS box containing the FPGA.
  - Detector in InSb : *Raytheon AE194 InSb Focal Plane Array* - 256 × 256 pixels, 20 mW@30K. But the pixel pitch is too high (30µm). Needs custom redesign.
- **Technology Requirements**
  - TRP activity : test of current HAS2 device at low temperature to be planned.

Equipment and Text Reference	Technology	Suppliers and TRL Level	Technology from Non-Space Sectors	Additional Information
FGS Detector	Low temperature, low power CMOS - Active Pixel Sensor	Cypress, CMOSIS TRL-5 (due to low temperature)	Yes	Confidence test to be performed at low temperature on existing detector

Conclusion

- Intrinsic performance of the FGS is not the issue of this development.
- **Custom detector** to be developed to cope with power dissipation requirement
- **Single star tracking** is enough for the requested performance.
- **SEU impact** has been **studied** and **filtering** has to be implemented.
- **Radiation TID at detector level** to be computed for this mission.
- **Technology development activity** to be performed on existing device at low temperature.
- Fine processing can be either done inside AOCS computer or in a dedicated box (pros & cons for each).
- **Thermoelastic behaviour** of the instrument and the telescope will drive FGS bias budget.

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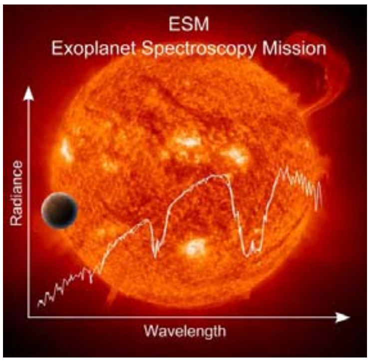
Detection Chain



Internal Final Presentation

ESTEC, 26th March 2010

Prepared by Bruno Leone

Detector Requirements

- Wavelength range: 0.7 - 10 µm (15 µm) divided in 3 channels:
  - SWS: 0.7 - 1.8 µm
  - MWS: 1.8 - 5 µm
  - LWS: 5 - 10 µm (15 µm)
- Detector matrix size: 614×10, 276×10, 653×10, 384×10, 682×10, 438×10,
- Pixel size: 25 µm, 35 µm
- QE > 80%
- Detector noise < photon shot noise
- Charge handling capacity (well depth): 1.5×10^{6}
- Read noise: 10 e^{-}
- Dynamic range: 1×10^{5}
- Integration/exposure time: 10^{-2} to minutes
  - And such that pixels do not exceed 70% of well depth (charge handling capacity)

Detector Technologies

- Detector technologies
  - A.H. Hoffman *et al.*, Proc. of SPIE Vol. 6276 62760Y-1
- Three-channels:
  - 0.7 - 1.8 µm: InSb, HgCdTe
  - 1.8 - 5 µm: InSb, HgCdTe
  - 5 - 10 µm: HgCdTe
- Beyond 10 µm: Si:As BIB

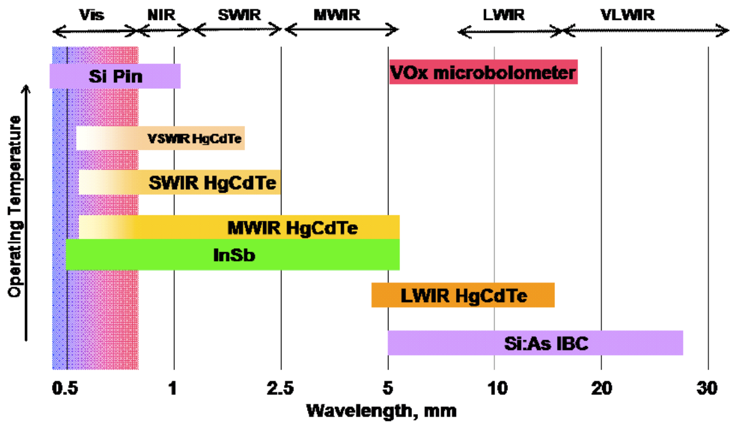


Figure 1. High-performance detector materials available at Raytheon. *Operating temperatures for low-background systems is shown qualitatively for each material along with the spectral band of greatest sensitivity. Spectral response of HgCdTe into the visible band has been demonstrated by removing the detector substrate.*

Detector Technologies (2)

Material / Property	InSb	HgCdTe	Si:As BIB
Spectral Range	0.6 - 5.4 µm	0.8 - 5 µm 9 µm	5 - 28 µm
Operating Temperature	30 K	70 - 80 K 45 - 50 K	7 K
Dark Current	< 0.5 e^-/s	< 1 e^-/s = 160 zA	< 0.1 e^-/s - 16 zA
Well Capacity	≥ 3×10^5 e^- (1V)	≥ 3×10^5 e^- (0.5V)	> 1×10^5 e^-
Read Noise	< 25 e^- (CDS)	< 20 e^- (CDS)	< 19 e^- (Fowler-8)
QE	> 80%	> 80%	> 40% (5 - 6 µm) > 60% (6 - 12 µm) > 70% (12 - 26 µm)

Noise Considerations

- Noise sources:
  - Photon shot noise: depends on signal SNR = $\sqrt{N}$
  - Dark current: thermal noise in detector material, need to cool down detectors
  - Readout noise:
    - Low-frequency, 1/f, flicker noise: readout rate, electronics design
    - Johnson noise, Nyquist noise, white noise, electronics thermal noise: rms voltage $\sqrt{(4kTR\Delta f)}$: Fowler sampling, up-the-ramp sampling
    - Capacitive shunting of thermal noise, kTC noise: rms voltage equals $\sqrt{(kT/C)}$, can be eliminated using CDS, Fowler sampling etc…

Readout

- CMOS 0.8 - 0.25 µm processes
- Indium bump flip chipped
- Integrating amplifier schemes:
  - SFD: source follower / detector (buffer amplifier): low noise, no detector bias control/stability
  - FEDI: feedback enhanced direct injection: detector bias stability, high background, higher complexity
  - CTIA: Capacitive feedback trans-impedance amplifier: excellent bias control, good well capacity/read noise compromise, drift and offset robustness (hysteretic effects at low temperatures)
  - Dual gain readout
- Sampling schemes for KTC and white noise reduction:
  - CDS: correlated double sampling
  - Fowler sampling
  - Up-the-ramp sampling

Detector Baseline

- SWS HgCdTe: 0.7 - 1.8 µm, 70 - 80 K, QE > 80%
- MWS HgCdTe: 1.8 - 5 µm (several butted optimised spectral ranges), < 40 K, QE > 80%
- LWS HgCdTe: 5 - 10 µm, butted optimised spectral ranges 70 - 80 K, QE > 80%
- Optional: Si:As BIB: 10 - 15 µm, single array, 7 K, QE > 70%
  - BUT increased system complexity

Heritage

- US
  - Raytheon: HgCdTe, InSb, Si:As BIB
  - Teledyne: HgCdTe
- Europe
  - Sofradir: HgCdTe
  - Xenics: HgCdTe, InSb
  - AIM: HgCdTe

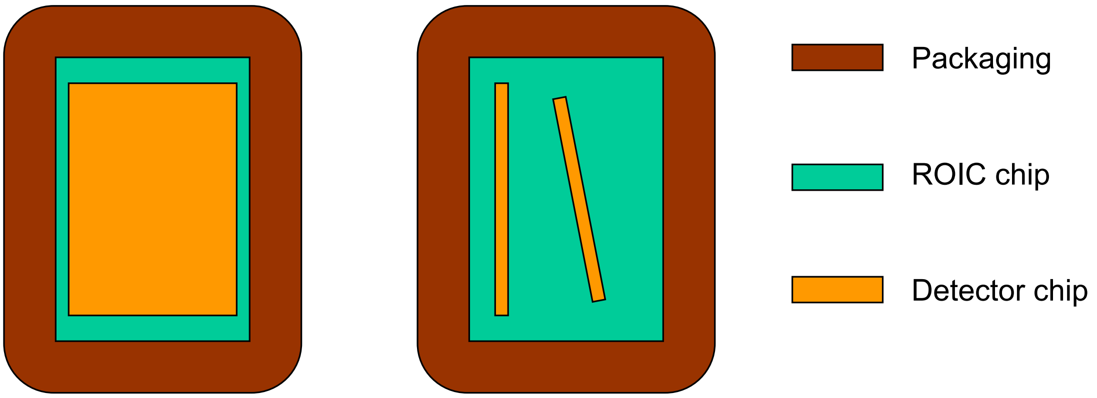
Detector Matrix Size

Order / Band	1st	2nd	No. of Pixels
SWS	614 × 10	276 × 10	8900
MWS	653 × 10	384 × 10	10340
LWS	682 × 10	438 × 10	11200
Total	19490	10980	30440

Detector Size

Order / Band	Matrix Size [mm]	Chip Size [mm]	No. of Pixels
SWS	2.7 × 15.4	5 × 20	8900
MWS	1.6 × 16.4	5 × 20	10340
LWS	7.3 × 24	10 × 30	11200
Total	19490	10980	30440

Detector Geometry



Power

- Assumptions
  - Raytheon Aquarius Si:As at 7 K: 100 nW/pixel
  - SIDECAR ASIC: 11 - 100mW
- Power for sensor chip: 30440 pixels = 3 mW
- Total power < 100 mW
- Digitization ASIC operates > 37 K

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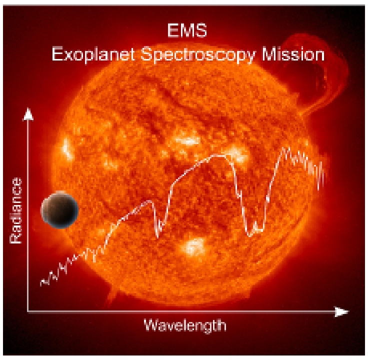
AOCS



Internal Final Presentation
ESTEC, 26th March 2010

Prepared by the ESM/ CDF* Team

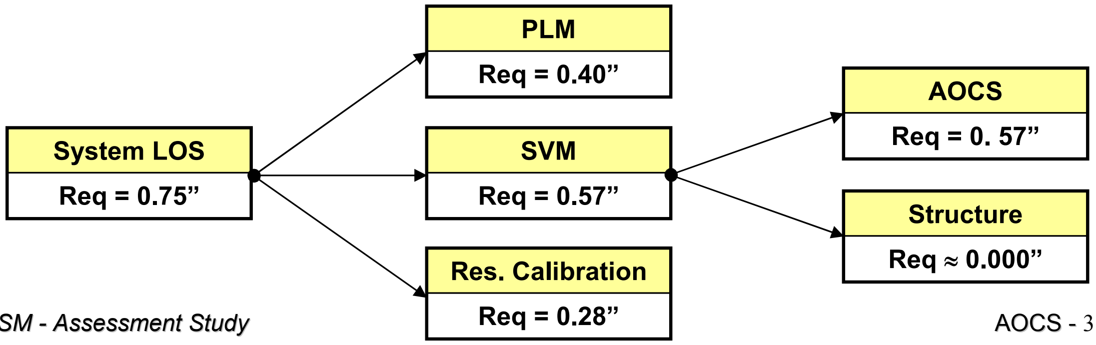
(*) ESTEC Concurrent Design Facility

Functional Requirements

- **Sun pointing after separation or major failure, including:**
  - Separation angular rates damping
  - Adequate solar array illumination
  - Prevention of direct Sun illumination on delicate parts, e.g. PLM or STRs
  - Autonomy for extended periods of time
- **Attitude determination and control**
  - 3-axes stabilised
  - autonomous operations for extended periods of time, without ground contact
  - large slew capability (±30deg) in any plane containing the Sun vector
- **Orbit correction and maintenance**
  - Launcher and cruise trajectory correction
  - L2 orbit maintenance

Performance Requirements

- **Absolute Pointing Error (APE)**
  – Angular separation between the desired direction and the instantaneous actual direction.
  – At focal plane level instruments APE better than 0.75'' at 3σ shall be achieved in the pitch and yaw axes.

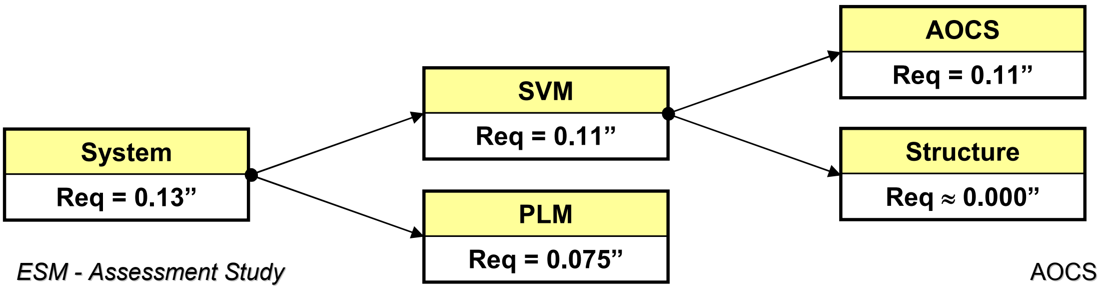


Performance Requirements

- **Relative Pointing Error (RPE)**
  – Angular separation between the instantaneous pointing direction and the short time average pointing direction during the reference time interval.
  – According to the current instrument base line have

Pixels size = 25μm
Focal length = 4m
Exp. time = 10min

$$RPE = \arcsin\left(\frac{p/10}{L}\right) = 0.13''$$



Major prerequisites to reach the pointing performances

- **Microvibrations**
  - The AOCS actuators have shall induce a disturbance not higher than 250μNm ➔Magnetic Bearing RW or μThrusters
  - The same limit applies to any moving part in the PLM
- **The instrument performances**
  - Bias, stability and drift (if any) have to be of the same order of magnitude than those of the FGS
- **Thermoelastic stability**
  - Instrument//FGS stability
    - *ST better than 0.01arcsec*
    - *LT better than 0.05arcsec*
  - Not relevant at SVM level
    - *This only applies for the Science mode*

Other Performance Requirements

- **Large Slew capability**
  - The S/C shall be able to perform a 180deg slew in less than 30min
  - The slew time includes the complete settling of the attitude
  - Assuming as largest moment of inertia 3500Kgm^2, the minimum torque required is 15mNm
    - *It doubles for a 90deg slew in 15 minutes*
- **FGS: target acquisition and locking (see FGS presentation)**
  - APE = 3.0” 1σ
  - RPE = 0.01” over 100ms 1σ
  - To be achieved with STR and GYRO
    - *This could push for a high accuracy gyro*

Performance Requirements Not Explicitly addressed

- **Attitude Measurement Error (AME)**
  - Instantaneous angular separation between the actual and the estimated pointing direction.
  - Previously in the MRD, now removed.
- **Pointing Drift Error (PDE)**
  - Angular separation between the short time average pointing direction during the RPE reference time interval and a similar average at a specified later time, where the same nominal direction is commanded.
  - At present the longest observation foreseen will last 10 hours
- **Earth pointing capability**
  - Depends on the strategy for TC/TM link
- **Fuel consumption and parasitic delta-Vs**
  - In the RCS based modes the fuel consumption and the parasitic delta-Vs have to be limited

Main assumption about the S/C

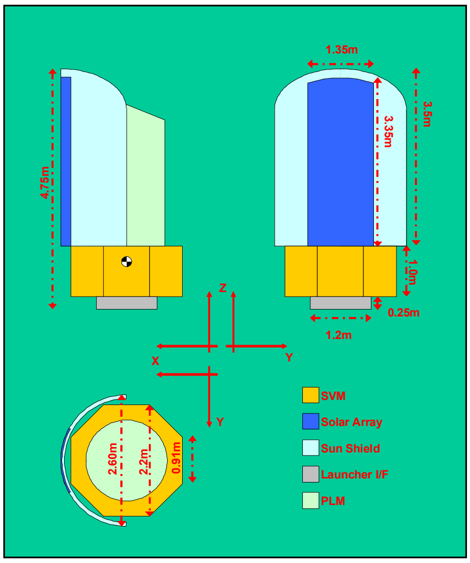
- **The S/C behaves as a rigid body wrt. the AOCS fine pointing modes**
  - Sun shield and solar array do not bend or vibrate
  - Control bandwidth decoupled from the sloshing mode natural frequency
  - This could not be true for the RCS based modes, especially during the large delta-Vs
- **Main characteristics**
  - Mass = 2160Kg
  - Jxx, Jyy = 3500Kgm^2
  - Jzz = 2000Kgm^2
  - COM = [0.00 0.00 0.95]m (about 1/5 of the S/C length)
  - COM migration < 5% (assuming ≈100Kg of RCS propellant)

Solar Pressure Torque about Y-axis

		Dim.* (bxh) m^2	Ca	Cr	Cd
SVM		2.20x1.00	55%	4%	40%
SSH**		2.60x3.50	20%	50%	30%
SA		1.35x3.35	70%	6%	24%
LNC I/F		1.20x0.25	20%	30%	50%
PLM		*Not Relevant*			

**Wrt. the +X direction*
*** The effective area has to be reduced because of the SA*

Solar pressure @ 1.01AU	4.6µPa
Solar torque about the Y axis	169µNm



Torque requests

- **Minimum torque for large slews**
  - Max Slew = 180deg
  - Max time = 30min
    - *Take 1min to settle down after the slew is complete*
  - ➔ Minimum acceleration/deceleration torque = 15mNm
- **Attitude Control during delta-Vs**
  - Orbit control thrusters mounting
    - *Cant angle optimised for MoL*
    - *CoM migration 5% ≈ 5cm*
      - BOL = [0.00 0.00 0.95]m
      - EOL = [0.00 0.00 1.00]m
    - *Mounted close to the Launcher I/F lower rim along the X-axis*
    - *Max force 20N*
  - ➔ Max disturbance torque = 249mNm (about Y-axis)

Trade off: MBRW Vs μThrusters

- **Both actuator system are a potential risk in terms of their development and qualification**
- **The main advantage of Magnetic Bearings RW versus μThrusters is the capability to cope with the large torque requests**
  - μThrusters typically deliver no more than 1mN as max thrust, i.e. roughly 10 times less than requested
  - MBRW can provide up to 400mNm
    - *Adequate for attitude control also during small delta-Vs (routine orbit maintenance)*
- **Magnetic Bearings RW are the baseline**
  - The μThursters option remains open in case a suitable MBRW could not be developed in time
  - In this case large slew should be dine using the RCS or a dedicated set of RW

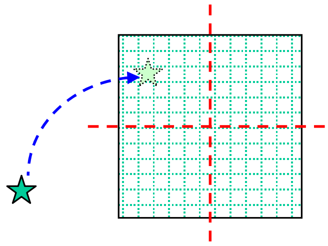
Trade off: Fine Gyro selection

- **Fine Gyro Candidates**

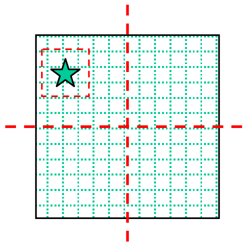
Model	Manufacturer	Bias Stab [deg/h]	ARW [deg/ √Hz]
Astrix 120	EADS	0.01	0.0025
Astrix 200	EADS	0.002	0.0002
FOG 24	Cielo	0.001	0.0002
Scalable SIRU™	Northorp/Grumman	0.0003	0.00001

- **At present it is not assumed that the Fine GYRO should be used with the FGS ➔ No need for a very high performance unit**
- **Astrix 120 (or any with similar performances) is the baseline**

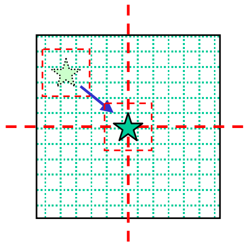
Target Pointing Strategy



1 Slew
From any attitude to the target (direct or Sun safe trajectory).
AOCS Ctrl loop based on STR and GYRO.
Ctrl B/W away from the sloshing frequency.
Settling 1min max.



2 Acquisition/Tracking
Acquisition of the star in the FGS FoV.
Pointing stability (RPE) better than 0.01”over 100ms
Same AOCS Ctrl loop; the FGS is ON, but not in the loop.

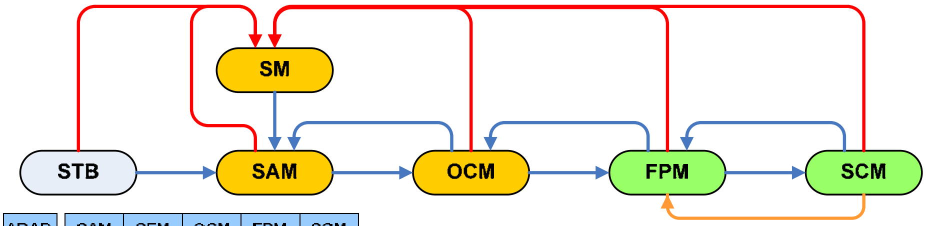


3 Locking
Bring the star to the centre of the FGS, ideally aligned with the main instrument.
Two AOCS ctrl loop
-X/Y fast (10Hz) using FGS (baseline) or FGS and GYRO (option)
- Z slow (4Hz) using STR and GYRO

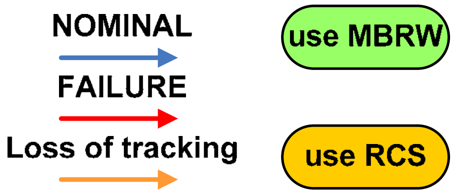
Sensors and Actuators Baseline

- **Sensors**
  - Attitude Anomaly Detector (AAD, TNO-TPD)
  - Sun Acquisition Sensor (SAS, TNO-TPD)
  - Coarse Gyro Sensor (SiREUS, Slex/Galileo)
  - Fine Gyro Sensor (Astrix 120, EADS)
  - Star Tracker (A-STR, Selex/Galileo OR Hydra, Sodern)
    - *Trade off on the configuration, not the performances*
  - FGS (custom made, ref. FGS presentation)
- **Actuators**
  - 1N thursters RCS (CHT1, EADS)
  - Magnetic Bearing Reaction Wheels (MWI 30/400/37, RCD)

AOCS Units vs Modes



	N. of units	ARAD	SAM	SFM	OCM	FPM	SCM
AAD	1+1	X					
CGYR	1+1	X	X	X			
SAS	1+1		X	X			
STR	1+1				X	X	X
FGYR	1+1				X	X	X
FGS	1+1					Out Of Loop	X
OCT	2+2				X		
RCS	4+4		X	X	X		
MBRW	4					X	X



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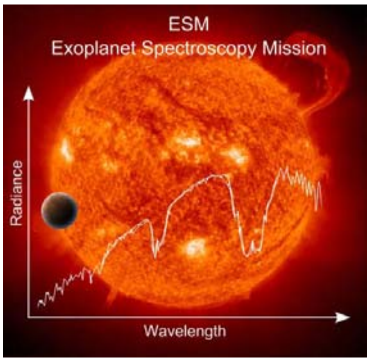
Configuration

Internal Final Presentation

ESTEC, 26th March 2010

Prepared by the ESM/ CDF* Team



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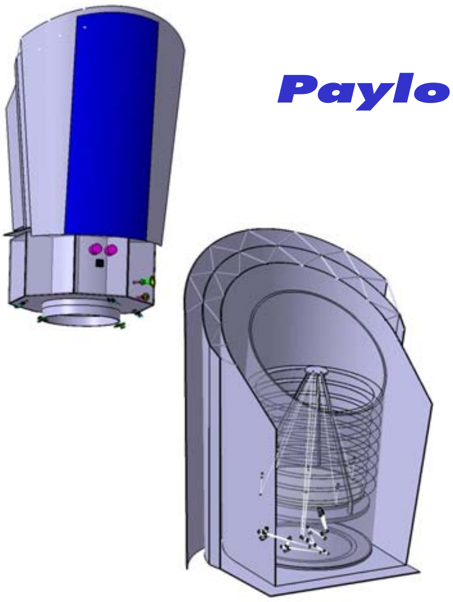
Requirement

- Use of SOYUZ-Fregat ST fairing
- Accommodate subsystem units to meet their requirements
- Accessibility during test and verification phase
- Avoidance mechanisms

Design Driver

- Available payload envelope in the SOYUZ ST-fairing
- Telescope size ➔ 1195mm I/F diameter central cylinder
- Propellant tank => 1000mm SVM-height
- Thermal requirement

Payload Module (PLM)



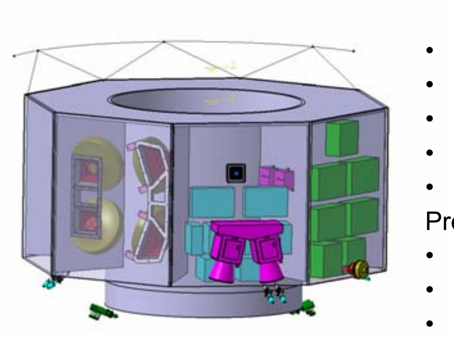
Telescope:
- Primary Mirror
- Secondary Mirror
- FGS
- SWS (shortwave)
- MWS (midwave)
- LWS (longwave)

Structure:
- TOB (50K)
- IOB (30K)
- SM support structure
- Baffle (50K?)
- Shields support structure

Thermal:
- Thermal shield (80K)
- Thermal shield (120K)
- FGS

Note:
TOB I/F with SVM (struts)
IOB I/F with TOB (struts)

Service Module (SVM)



Structure – octogonal shape with outer diameter of 2.2 m → side to side ≈ 2.07m
- Central cylinder (1195mm)
- Bottom panel
- Top panel
- Outer Panel
- Shear Panel (0.5m width)

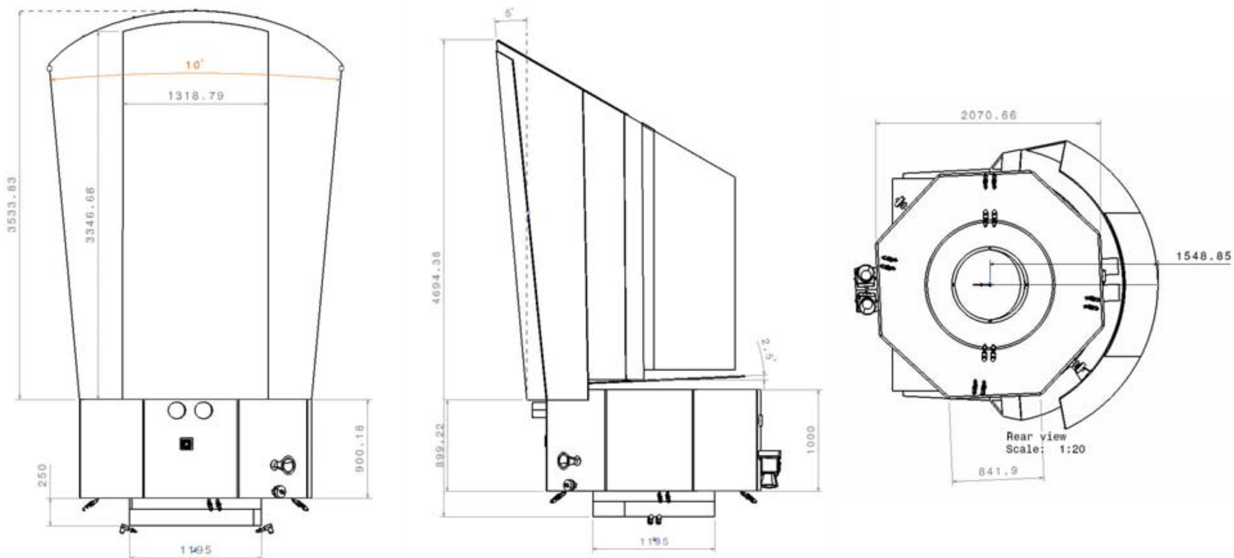
Propulsion:
- Propellant tank
- 4x2 1N thruster (Ampac)
- 2x2 20N thruster (Herschel)

Data Handling
- 2x AOCS & platform computer
- 2x Payload & Memory computer
- 6x IO concentrator

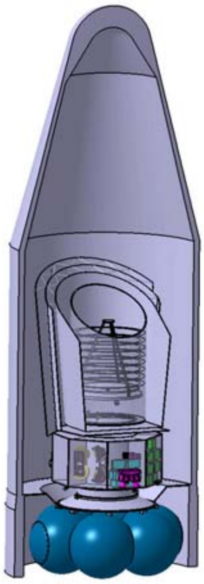
AOCS:
- Attitude Anaomly Detector
- 2x Star tracker
- Sun Sensors
- Coarse Gyro
- Fine Gyro
- Reaction Wheels

Communication
- 2x Transmitter
- 2x Receiver
- 2x TWTA
- 2x LGA
- 1x MGA
- 1x RFDU

Overall dimension



ESM in SOYUZ



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Structures

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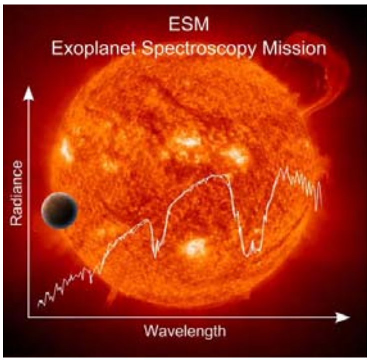

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Requirements/Assumptions

- Soyuz Launch from Kourou
  - Stiffness:
    - Lateral >15Hz
    - Longitudinal >33Hz
- No Analysis performed as part of this study.
- Telescope optical bench to support Instrument Optical Bench and interface to SVM.
- Telescope Optical bench to SVM supports to support Thermal shields and Sunshield

Baseline design

- 1194-IF adapter
- Simple load path
- Hexagonal SVM With Central cylinder
  - although accommodation is tight – hence central cylinder of SVM extended by 100mm
  - Known technology (e.g. Herschel/Planck)
  - Many options for component accommodation
- PLM
  - Initial design to have GFRP connection to SVM (for Thermal decoupling, although CFRP assumed for structures spreadsheet mass)
  - CFRP connection may be required for better Strength
  - Telescope Optical Bench assumed to be Ceramic
  - Instrument Optical Bench assumed to be Aluminium Alloy.
  - Instrument OB to Telescope OB connectivity (struts) assumed to be CFRP.

Baseline design

- Baffle
  - Baffle to be CFRP/Aluminium cylinder.
  - CFRP/Aluminium stringers (8) spaced internally to provide additional stiffness.
  - Baffle to support thermal shields and Sunshield.

Baseline design

- Sunshield and Thermal Shield
  - The Thermal shields interface to each other and baffle via titanium struts/spacers (for thermal isolation)
  - Sunshield interfaces to Thermal shields via Aluminium Alloy struts/spacers.
  - Sunshield interfaces to SVM via Titanium struts.

PLM – component/mass breakdown

Create a New Design Sheet / Add a new unit / Item	Nr.	Item mass [kg]	M_struct [kg]	Material	Maturity	Unit Margin [%]	Unit mass with margin [kg]
EXAMPLE	2	4.081	6.37	STEEL	Modification	10	7.01
Secondary_Mirror_support_panel	1	0.145	0.15	sandwich	New dev.	20	0.17
Secondary_Mirror_support_structure	3	1.939	1.94	SiC	New dev.	20	2.33
Primary_Mirror_Iso_static_supports	6	0.584	0.58	ALUMINUM	New dev.	20	0.70
Primary_Mirror_Iso_static_supports_end_fittings	12	0.584	0.58	ALUMINUM	New dev.	20	0.70
Telescope_Optical_Bench	1	36.938	36.94	SiC	New dev.	20	44.33
Telescope_OB_to_instrument_OB_supports	8	0.402	0.40	M55J Laminate	New dev.	20	0.48
Telescope_OB_to_instrument_OB_supports_end_fittings	16	1.088	1.09	TITANIUM	New dev.	20	1.31
Instrument_Optical_Bench	1	39.160	39.16	ALUMINUM	New dev.	20	46.99
Telescope_OB_to_Baffle_Support_Beams	8	1.070	1.07	ALUMINUM	New dev.	20	1.28
Telescope_OB_to_Baffle_Support_Beams_end_fittings	16	0.113	0.11	ALUMINUM	New dev.	20	0.14
Baffle	1	57.599	57.60	sandwich	New dev.	20	69.12
Baffle stiffener (ribs)	8	1.022	1.02	sandwich	New dev.	20	1.23
Baffle_support_ring	1	36.549	36.55	ALUMINUM	New dev.	20	43.86
Secondary_Sunshield_Support_Structure_1	20	0.050	0.05	TITANIUM	New dev.	20	0.06
Secondary_Sunshield_Support_Structure_2	20	0.050	0.05	TITANIUM	New dev.	20	0.06
Secondary_Sunshield_Support_Structure_3	20	0.050	0.05	TITANIUM	New dev.	20	0.06
Sunshield	1	26.173	26.17	sandwich	New dev.	20	31.41
Optical_Bench_optics_support_structure	1	20.000	20.00	ALUMINUM	New dev.	20	24.00
OB_Thermal_blanket_support	1	5.000	5.00	ALUMINUM	New dev.	20	6.00
Misc.	1	15.000	15.00	0	New dev.	20	18.00
20			**295.06**			**20.0**	**354.07**

SVM – component/mass breakdown

Create a New Design Sheet / Add a new unit / Item	Nr.	Item mass [kg]	M_struct [kg]	Material	Maturity	Unit Margin [%]	Unit mass with margin [kg]
EXAMPLE	2	4.081	6.37	STEEL	Modification	10	7.01
Central_cylinder	1	24.021	24.02	sandwich	New dev.	20	28.83
Shear_wall	8	1.815	1.82	sandwich	Modification	10	2.00
Outer_Panel	8	2.114	2.11	sandwich	Modification	10	2.33
Top_Panel	1	8.723	8.72	sandwich	New dev.	20	10.47
Bottom_Panel	1	8.723	8.72	sandwich	New dev.	20	10.47
Sunshield_support	8	0.156	0.16	TITANIUM	New dev.	20	0.19
IF_ring_LVA-SVM	1	23.496	23.50	ALUMINUM	New dev.	20	28.20
SVM-PLM_connection(via_sun/thermal_shields)	16	0.167	0.17	M55J Laminate	New dev.	20	0.20
Tank_Support_Struts	8	0.101	0.10	M55J Laminate	New dev.	20	0.12
Tank_support_Strut_ends	8	0.139	0.14	TITANIUM	New dev.	20	0.17
Tank_support_panel	1	5.539	5.54	sandwich	New dev.	20	6.65
Misc.	1	15.000	15.00	0	New dev.	20	18.00
12			122.77			17.4	144.18

Conclusions/Proposals

- Based on prior knowledge and studies it is expected that the structure will meet the stiffness requirements
- Total Structure mass currently 498kg
  - SVM – 144.18kg
  - PLM – 354.07kg
- An initial Finite Element Analysis is required to:
  - Determine preliminary stiffness
  - Provide preliminary strength assessment
- An initial Thermo-elastic distortion Analysis is required to:
  - Confirm material selection (OB support struts etc)
  - Provide preliminary data for pointing errors

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Thermal - SVM

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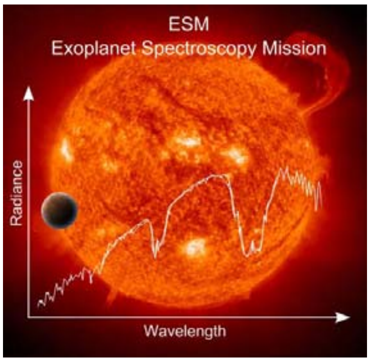

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Requirements and Design Drivers (1/2)

- Three main constraints drove the design:
  - Maintain the units in their operational and non operational thermal range during the mission lifetime (classical).
  - Guarantee the “thermoelastic stability” of the SVM (hard to quantify and verify at this stage).
  - Guarantee “acceptable conductive I/F” with the PLM (<20°C).

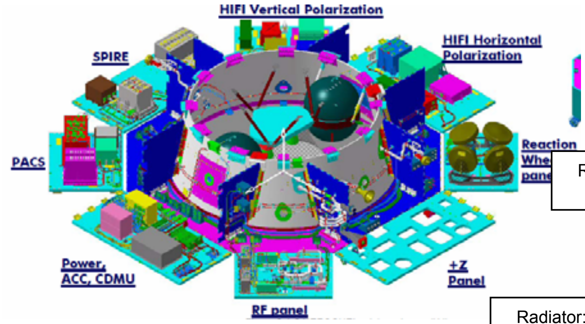
Requirements and Design Drivers (2/2)

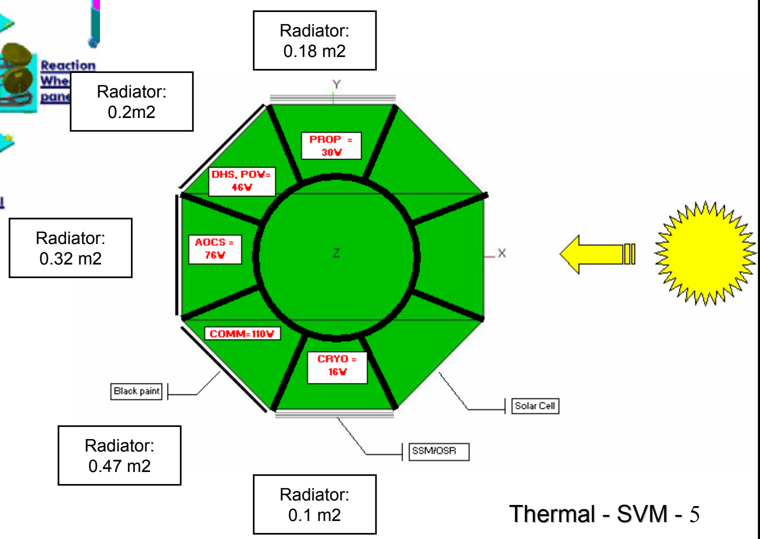
- The following inputs were necessary to size the TCS:
  - L2 orbit with a sun-pointing allowing +/-30° +/-10° slews.
  - Electrical dissipation of around 300W.

Baseline Design (1/3)

- The following ‘design point’ was chosen:
  - SVM maintained at constant temperature thanks to compensation heating during operational mission phases.
  - The SVM temperature was set to be at 0°C for all the enclosures.
- Classical thermal control solutions are foreseen (MLI, radiators, Heaters).

Baseline Design (2/3)





Baseline Design (3/3)

- Compensation heating:
  - Variation of external thermal environment (due to slews).
  - Variation of the dissipations of units.
- Results:

	Launch Mode - SVM	Initialisation Mode - SVM	Cruise Mode - SVM	Observation Mode	Manoeuvering Mode - SVM	Safe Mode - SVM	TC/TM - SVM	Slew Mode - SVM
Compensation Heating (W)	**0**	**159**	**131**	**186**	**123**	**93 ***	**96**	**173**

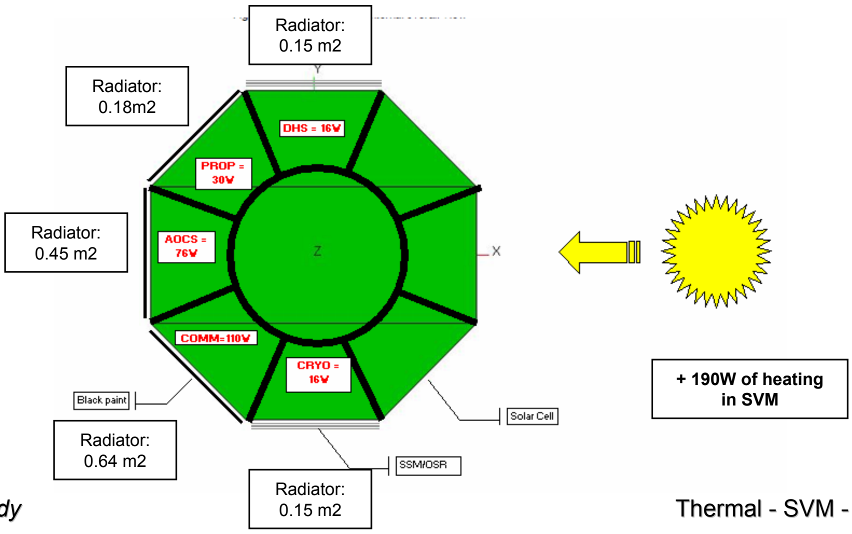
**In Safe Mode: heating to maintain SVM>-20°C*

Budgets

Element 2	Payload Module			MASS [kg]			
Unit	Unit Name Click on button above to **insert new unit**	Part of subsystem	Quantity	Mass per quantity excl.	Maturity Level	Margin	Total Mass incl. margin
1	MLI		1	6.9	To be developed	20	8.2
2	Heaters		1	0.6	To be modified	10	0.6
3	Black Painted Radiators		0.92	0.3	Fully developed	5	0.3
4	SSM Radiators		0.20	0.3	Fully developed	5	0.1
5	Misc (thermal washers, filler…)		1	1.0	Fully developed	5	1.1
-	Click on button below to insert new unit			0.0	To be developed	20	0.0
SUBSYSTEM TOTAL			**5**	**8.8**		**17.1**	**10.3**

Options

- SVM maintained at -20°C:



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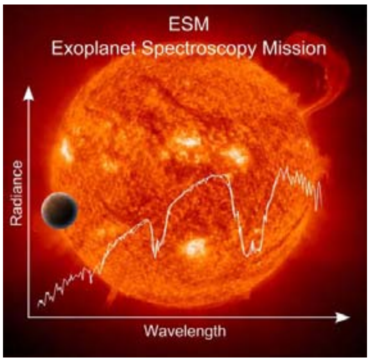
<Cryogenics>



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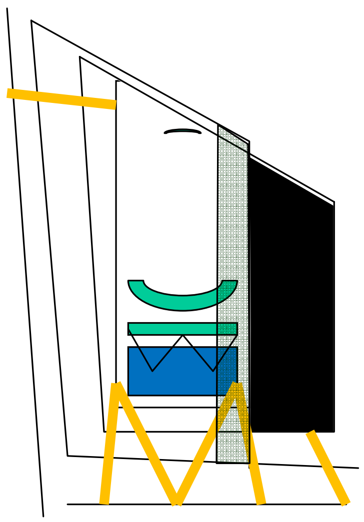
Cooling Requirements

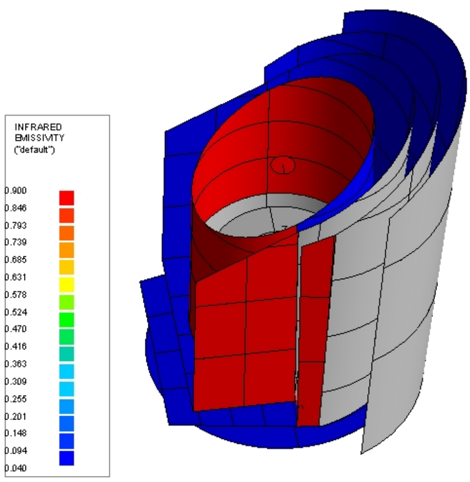
- Telescope and Baffle needs to be cooled below 50K
- Detector cooling at 30K, accomodation of FGS on Optical Bench
- Minimised exported vibrations to guarantee long term stability
- ➔ passive cooling of telescope
- ➔ Sorption cooler for detector cooling, reducing exported vibrations since there are no moving parts
- ➔ cooling of IOB down to 30K for co-alignment of detetctors

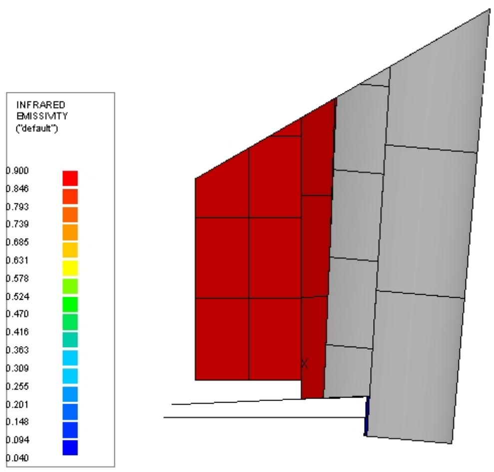
PLM configuration



- 2 Thermal shields with MLI insulation
  - Shield 1 cylindrical part tilted 5 deg vs Baffle
  - Shield 2 bottom part tilted 2.5 deg vs Shield 1
  - ➔ V-Groove effect improves performance
- Large Radiators (open honeycomb) on Baffle and Shield 1 for Sorption cooler
- GFRP support structure as on Planck (8 stuts for telecope support, additional struts for Shield support)
- IOB supported via CFRP struts on TOB
- 1000 Manganin wire harness
- Aluminium Honeycomb panels for Shields similar to Planck cryostructure

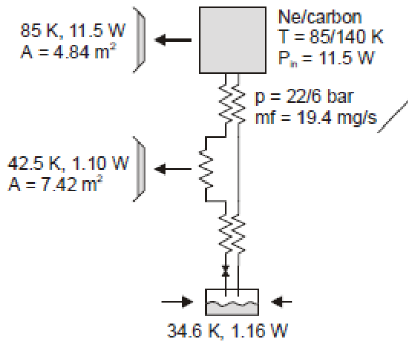
PLM ESARD model





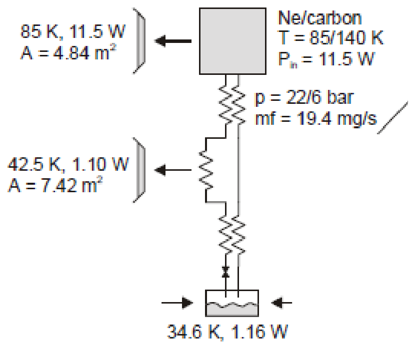
Neon Sorption cooler

- Based on 4K JT sorption cooler a H2 sorption cooler under devlopment for Darwin
- Vibrationfree, no moving parts
- Initial sizing for 280mW at 30K
- Requires large Radiator areas at low temperatures



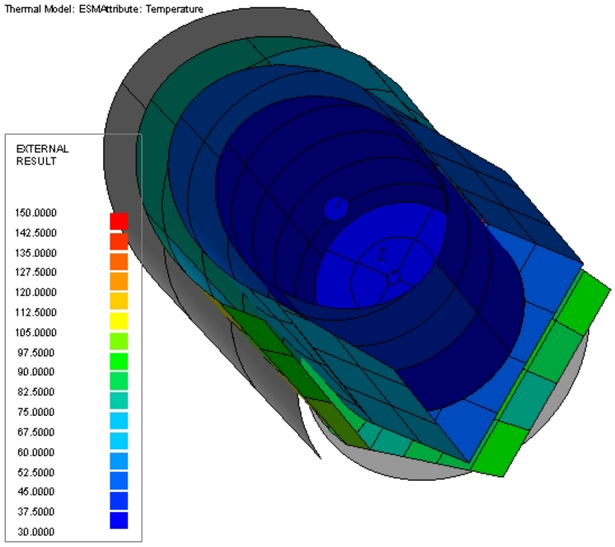
Neon Sorption cooler

- Based on 4K JT sorption cooler and H2 sorption cooler under development for Darwin
- 'Vibrationfree', no moving parts
- Initial sizing for 280mW at 30K
- Dissipation at low temperatures ➔ large radiator area
  - 300mW below 42K
  - 2.8W below 85K



Results

- Telescope and Baffle below 40K
- Shield 1 below 80K
- Parasitic heatload to IOB ~30mW, leaving 150mW availabe for Detector dissipations
- ➔ sufficient margins available, further optimisations might allow ar increase of detector dissipation (if needed)



Mass/power

Element 1	Payload Module			MASS [kg]					
Unit	Unit Name Click on button above to insert new unit	Part of subsystem	Quantity	Mass per quantity excl. margin		Maturity Level	Margin		Total Mass incl. margin
1	Ne sorption Cooler		2	5,0		To be modified	10		11,0
2	Radiators & Shield		1	120,0		To be developed	20		144,0
3	Tel Decontamination		1	1,0		To be modified	10		1,1
-	Click on button below to insert new unit			0,0		To be developed	20		0,0
	SUBSYSTEM TOTAL		3	131,0			19,2		156,1

Power:

- 50W for cooler and Cryogenic sensors readout during nominal operations (safemode = 0W)
- 50W (tbc) during initial Phase after launch for Telescope de-contamination at 180K (as for Herschel)

Option: Detector cooling at 7K

- Radiator sizing allows to use H2 sorption cooler to cool down IOB to 20K (200mW cooling power)
- From 20K to 7K, the Planck 4K cooler can be used (mass~40kg, 120W input power), which would be located in the SVM
- Low margin in Shield1 and Baffle temperatures, further optimisations would be required

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Propulsion

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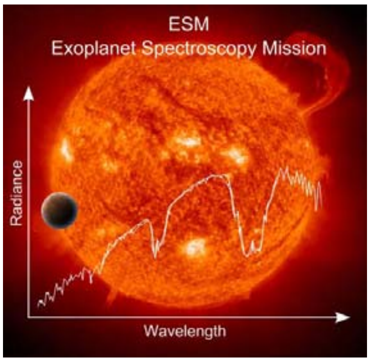

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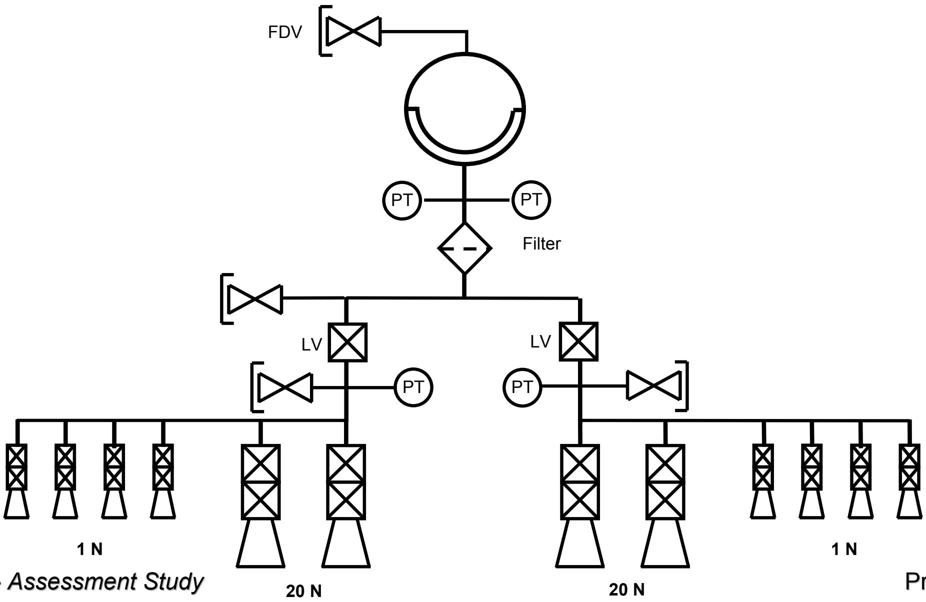
Baseline design



Baseline design

- Component Selection

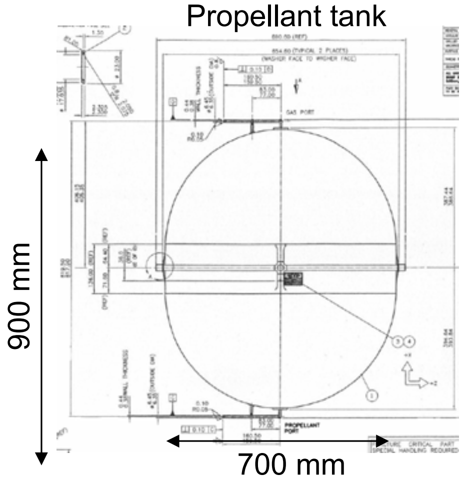
Options	Model	Supplier	Status
Propellant tank	Herschel-Planck	MTSP (UK)	TRL 6
Thruster	MONARC-1	AMPAC (US/UK)	TRL 9
Thruster	CHT-20N	EADS-ST (D)	TRL 9
Fill and Drain Valve	3-barrier	EADS-ST (D)	TRL 9
Pressure transducer	SAPT	BRADFORD (NL)	TRL 9
Filter	RA01808A	SOFRANCE (FR)	TRL 9
Latch Valve	51-166	MOOG (US)	TRL 9

The propellant tank selected has the advantage of not inducing further degradation of the thruster by propellant contamination. Currently under final qualification of the diaphragm only (the rest of the parts are qualified from previous programmes)

Baseline design

- Accommodation

Propellant tank



Thrusters (1N)

Thrusters (20N)

Baseline design

- Propellant Mass budget

Mission Phase		Delta-V budget [m/s]	Thrust [N]	Isp [s]	Acc. Propellant consumption [kg]
Launcher Dispersion	Init	0	21.89	225.7	0
	Fin.	38.28	16.15	219.5	39.0
Station keeping	Init	38.28	0.74	185.8	39.0
	Fin.	59.84	0.63	182.6	66.2
12 Safe Modes + 12 Safe Acquisition Mode	Init	59.84	1.0	203	66.2
	Fin.	64.36	0.59	180.5	72.7
EOL Propellant Residuals + 10% Margin					9.0
TOTALS					**81.7**

- Main inputs:
  - S/C Max. Mass = 2165 kg
- Constraints
  - 20 N Thrusters cannot operate continuously for more than 1 hour.

Baseline design

- Thruster cycles

Mission Phase		20N Thrusters	1N Thrusters
Launcher Dispersion	Estimated	200	14600
Station keeping	Estimated	0	45000
12 Safe Modes + 12 Safe Acquisition Mode	Estimated	0	78020
TOTAL		200	137620
Qualification (AMPAC)		-	315000
Qualification (ASTRIUM)		93130	59000

Initial ASTRIUM 1N Thruster replaced by the AMPAC 1N Thruster (ITAR restricted component)

Baseline design

Components	Units/ Sets	Mass budget (with margin) [kg/unit]	Reliability [FITS/unit]	Recurrent Cost [k€/unit]
Propellant tank	1	16.2	0.0	300
Thruster Assembly (20N)	2	1.5	918	100 (thrusters only)
Thruster Assembly (1N)	4	0.9	271	60 (thrusters only)
Fill and Drain Valve	4	0.08	56	10
Pressure transducer	4	0.3	196 (function) 0.6 (leak)	15
Filter	1	0.08	1.0	10
Latch Valve	2	0.4	160	40
Piping	1	1.1	7.0	6
Bracketing	1	4.3	N/A	15
TOTAL		31.0	N/A	936

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POWER SUBSYSTEM

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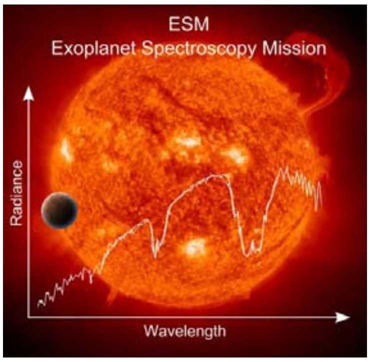

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Power Subsystem Main Lines (1/2)

- L2 operation with fixed panels / stable illumination (see comment)
- Very low power budget ~370W max (sustained)
  - The sizing mode is the communications with Earth.
    (with correction of pro. power budget for CBH TBC)
    The observation mode is only a little less demanding.
- However
- Very high peak power demand ~ 1900W (theoretical)
- This peak includes mainly:
  - 1200W peak power request for the 4 RW in failure case
  - A 400W peak nominal for RW
  - ⇒ power peak need is ~200% to 500% the max average power

Power Budget

Mode	Conditions		Thermal	AOCS	Comms	Propulsion	DHS	Cryogenics	Mech	AOCS - FGS	Te le sc o	S W S sp	M W S sp	L W S sp	Harness (excl. PSS)	TOTAL CONSUMPTION	Power Provided By	Paverage during Sunlight
Eclipse Mode :			linked	linked	linked	linked	linked	linked	linked	linked	t ust ust ust ust ust ust ust ust used							
Launch Mode - SVM	40.3495	Ppeak	242 W	1251 W	110 W	142 W	16 W	104 W	0 W	0 W					37 W	1902 W		
Launch Mode - SVM	Solar Flux 0 W/m^2	Pon	0 W	13 W	110 W	2 W	16 W	0 W	0 W	0 W					3 W	143 W	Battery	
Eclipse Mode	(0 if Solar Array not used)	Pstdby	0 W	13 W	0 W	2 W	16 W	0 W	0 W	0 W					1 W	31 W		
	Remaining Battery Capacity	Duty Cycle	0 %	0 %	18 %	0 %	0 %	0 %	0 %	0 %						18%		
	100%	Paverage	0 W	13 W	20 W	2 W	16 W	0 W	0 W	0 W					1 W	52 W		
Tref 47 min	Eclipse Mode NOT Included	Total Wh	0 Wh	10 Wh	16 Wh	1 Wh	13 Wh	0 Wh	0 Wh	0 Wh					1 Wh	40 Wh		
Initialisation Mode - SVM	Solar Flux 1295 W/m^2	Pon	206 W	13 W	110 W	114 W	16 W	50 W	0 W	0 W					10 W	520 W	Solar Arrays	378 W
	(0 if Solar Array not used)	Pstdby	0 W	13 W	0 W	42 W	16 W	50 W	0 W	0 W					2 W	123 W		
	Remaining Battery Capacity	Duty Cycle	66 %	0 %	100 %	5 %	0 %	0 %	0 %	0 %						64%		
	100%	Paverage	136 W	13 W	110 W	46 W	16 W	50 W	0 W	0 W					7 W	378 W		
Tref 90 min	Eclipse Mode NOT Included	Total Wh	204 Wh	20 Wh	165 Wh	68 Wh	24 Wh	75 Wh	0 Wh	0 Wh					11 Wh	567 Wh		
Cruise Mode - SVM	Solar Flux 1295 W/m^2	Pon	170 W	76 W	110 W	93 W	16 W	50 W	0 W	0 W					10 W	524 W	Solar Arrays	353 W
	(0 if Solar Array not used)	Pstdby	0 W	76 W	0 W	42 W	16 W	50 W	0 W	0 W					4 W	187 W		
	Remaining Battery Capacity	Duty Cycle	66 %	0 %	45 %	0 %	0 %	0 %	0 %	0 %						49%		
	100%	Paverage	112 W	76 W	50 W	42 W	16 W	50 W	0 W	0 W					7 W	353 W		
Tref 43200 min	Eclipse Mode NOT Included	Total Wh	80855 Wh	54360 Wh	36000 Wh	30227 Wh	11520 Wh	36000 Wh	0 Wh	0 Wh					4979 Wh	253941 Wh		
Observation Mode	Solar Flux 1295 W/m^2	Pon	242 W	116 W	110 W	46 W	16 W	54 W	0 W	1 W					12 W	596 W	Solar Arrays	360 W
	(0 if Solar Array not used)	Pstdby	0 W	76 W	0 W	27 W	16 W	54 W	0 W	1 W					3 W	177 W		
	Remaining Battery Capacity	Duty Cycle	66 %	0 %	18 %	0 %	0 %	0 %	0 %	0 %						44%		
	100%	Paverage	160 W	76 W	20 W	27 W	16 W	54 W	0 W	1 W					7 W	360 W		
Tref 300 min	Eclipse Mode NOT Included	Total Wh	799 Wh	378 Wh	100 Wh	136 Wh	80 Wh	270 Wh	0 Wh	3 Wh					35 Wh	1800 Wh		
Manoeuvering Mode - SVM	Solar Flux 1295 W/m^2	Pon	160 W	36 W	110 W	46 W	16 W	50 W	0 W	0 W					8 W	426 W	Solar Arrays	351 W
	(0 if Solar Array not used)	Pstdby	0 W	36 W	0 W	27 W	16 W	50 W	0 W	0 W					3 W	131 W		
	Remaining Battery Capacity	Duty Cycle	66 %	0 %	100 %	0 %	0 %	0 %	0 %	0 %						75%		
	100%	Paverage	106 W	36 W	110 W	27 W	16 W	50 W	0 W	0 W					7 W	351 W		
Tref 35 min	Eclipse Mode NOT Included	Total Wh	62 Wh	21 Wh	64 Wh	16 Wh	9 Wh	29 Wh	0 Wh	0 Wh					4 Wh	205 Wh		
Safe Mode - SVM	Solar Flux 1050 W/m^2	Pon	187 W	13 W	110 W	46 W	16 W	0 W	0 W	0 W					7 W	379 W	Solar Arrays	265 W
	(0 if Solar Array not used)	Pstdby	0 W	13 W	0 W	27 W	16 W	0 W	0 W	0 W					1 W	57 W		
	Remaining Battery Capacity	Duty Cycle	50 %	0 %	100 %	0 %	0 %	0 %	0 %	0 %						64%		
	100%	Paverage	93 W	13 W	110 W	27 W	16 W	0 W	0 W	0 W					5 W	265 W		
Tref 5760 min	Eclipse Mode NOT Included	Total Wh	8952 Wh	1248 Wh	10560 Wh	2605 Wh	1536 Wh	0 Wh	0 Wh	0 Wh					498 Wh	25400 Wh		
TC/TM - SVM	Solar Flux 1295 W/m^2	Pon	125 W	116 W	110 W	2 W	16 W	50 W	0 W	0 W					8 W	426 W	Solar Arrays	368W
	(0 if Solar Array not used)	Pstdby	0 W	76 W	0 W	2 W	16 W	50 W	0 W	0 W					3 W	146 W		
	Remaining Battery Capacity	Duty Cycle	66 %	0 %	100 %	0 %	0 %	0 %	0 %	0 %						70%		
	100%	Paverage	83 W	76 W	110 W	27W	16 W	50 W	0 W	0 W					7 W	368W		
Tref 120 min	Eclipse Mode NOT Included	Total Wh	165 Wh	151 Wh	220 Wh	3 Wh	32 Wh	100 Wh	0 Wh	0 Wh					13 Wh	685 Wh		
Slew Mode - SVM	Solar Flux 1295 W/m^2	Pon	240 W	436 W	110 W	46 W	16 W	54 W	0 W	1 W					18 W	920 W	Solar Arrays	415 W
	(0 if Solar Array not used)	Pstdby	0 W	76 W	0 W	27 W	16 W	54 W	0 W	1 W					3 W	177 W		
	Remaining Battery Capacity	Duty Cycle	50 %	26 %	18 %	0 %	0 %	0 %	0 %	0 %						32%		
	100%	Paverage	120 W	169 W	20 W	27 W	16 W	54 W	0 W	1 W					8 W	415 W		
Tref 15 min	Eclipse Mode NOT Included	Total Wh	30 Wh	42 Wh	5 Wh	7 Wh	4 Wh	14 Wh	0 Wh	0 Wh					2 Wh	104 Wh		

Power Subsystem Main Lines (2/2)

- A peak at x5 the base power (RW command failure) cannot be handled by a standard regulated (or unregulated) bus architecture without a major over sizing (bus impedance).
- Even the nominal x2 peak (nominal RW) requires specific verification and adaptation.

RW Peak Power Handling trade off (1/3)

Solution	Main features
"Usual" Regulated Bus	• ✋ 1200W BDR + R ⇒ 2kW EPS
Battery Bus with fixed "28V+"' operation in L2 and Cruise (e.g. LISA Pathfinder)	• PF units ON at launch and initialisation shall be compatible 23/37V unregulated bus operation. • Battery switch (sized for 1200W+) • The 1200W peak implies a > 4V bus voltage drop, ✋ and the 400W peak implies a > 1V bus voltage drop with a battery not too much oversized (2C 8C discharge).
28V Regulated Bus but with the RW supplied directly from the battery	• PCDU main elements are sized as a 400W EPS • Nominal as fault RW peak power handled by the battery without intermediate loss or interaction with the P/F • The battery need a permanent "charge" of up to 80W+R to compensate RW normal consumption
Use an active filter in each RW supply line	• Interesting only if pulse duration + worst case repetition rate keep super capacitor size within reason: TBC presently. • ✋ Studied for radar / lidar applications, but low TRL.
All solution	• The battery needs a specific qualification. • The RW cannot be protected by usual LCL. A long 400W power demand cannot be allowed.

RW Peak Power Handling trade off (2/2)

- RW supplied directly from the battery
  - The magnetic bearing RW are designed for LEOP application: i.e. 23/37V unregulated bus (e.g. MWI 30-4000/37).
- Second level trade-off / issues shall be addressed:
  - Battery voltage: below or above (equal ?) the bus?
  - SA power routing to the 2 bus: BDR, BCR, both?
  - Battery sizing (w.r.t. peak discharge current)?
  - DOD alarm (real versus transient drop due to a RW peak)?

Inputs for the architecture trade-off around the battery

- In case of a 1200W power call, the voltage drop on the battery (+harness) is likely to trig the battery DOD protection: for a classical design, this means a DNEL action by PCDU and an HW alarm which initiates a system reconfiguration.
- Considering that the event is linked to a major AOCS failure, this may be the proper to handle the situation. However, assessing this would need a detailed FMECA analysis (beyond CdF scope).
- A safe approach is to provision a specific battery “DOD” protection which is able to filter between a sustained DOD, and a transient correlated to a current call from the RW. Such a filter is in fact complementary to the need of a specific protection on the RW power lines: i.e. against sustained 400W power demand.

- At constant battery energetic size ($s_x p$), and at first order, the DOD protection and battery surge current issue are independent from the chosen battery voltage.
- In case of a 1200W power call, if a battery “below” the bus is used, the voltage drop is likely to goes below the 23V minimum RW supply voltage.
- In turn, if a battery “above” the bus is used, a 1200W power call is likely to cause a battery voltage drop bellow the bus voltage.

- A double bus architecture (unregulated + regulated) architecture with a battery “above” the (regulated) bus is the solution which is used for the radar / lidar missions on small platform (e.g. AEOLUS).
- However, in the IFP case, the mean RW power consumption remains low w.r.t. the main by one (dislike radar / lidar case). This architecture would imply for IFP, that most of the S/C power transits <u>permanently</u> through the BDR (thermal dissipation).

Power Subsystem Architecture (1/3)

- Closing the technical battery voltage trade-off is difficult in the CdF frame.
- However, this trade-off is somehow internal to the EPS design, as it can be expected to be rather neutral on the mass and unit shape point of view. Cost shall consider NRE and analysis in all cases.
- The proposed baseline is to consider a battery voltage below the bus, with a BDR + BCR interface to the main (regulated) bus, with the SA supplying the main bus.
  - This solution favor the global efficiency
  - But with an identified risk w.r.t. the intricate RW/PCDU FMECA
  - It is however still TBC that it is not possible to exclude the failure case in the first place: i.e. at RW command I/F circuit level.
  - This choice gives a good basis for the CdF, but with need of further detailed studies in close relation with a RW pre-selection process.

Power Subsystem Architecture (2/3)

- The proposed baseline architecture is based on a S3R solar array power conditioning.
  - Taking a (nominal) pitch limit of ±30° and roll limit of ±1° (Herschel), implies an SA illumination modulation of ~14%.
  - With IFP baseline of ±5°, and an additional SA kant of 5° to fit the sunshield shape, the SA illumination rises up 26%.
  - Furthermore the ±5° roll implies to consider a higher lateral SA panel temperature: on the edge for needing 1 more series cell (i.e. ~5% efficiency loss).
- A recommendation would be to limit the roll requirement.
- Else, the use of an MPPT could be considered.

Power Subsystem Architecture (3/3)

- With an MPPT case
  - The SA surface could be a little reduced (10%).
  - The 3 panels kant configuration needs 3 MPPT, i.e. 6 converters at least to add to the 2 BDR and 2 BCR needed to manage the double bus.
  - However, this would be a field of application of the new B3R technology patented by ESA (buck buck-boost regulator) for lidar/radar mission (double bus), and which combines the MPPT/BDR/BRC functions in one single converter.
  - This is not the baseline (TRL-1), but shall be part of the option to be keep under consideration.

Power Subsystem Architecture

- The propose baseline is so:
  - 400W, 28V Regulated Power Bus
  - With S3R SA power conditioning (20 sections).
  - A 400W+R BDR battery power conditioning for launch
  - A 100W+R BCR for battery recharge, and RW power consumption balancing.
  - A 39Ah (nameplate) 6s26p battery (Herschel) sized for the 1500W RW / 1900W w.c. peak (8C/10C).
  - A 4.4m2 solar array (1.2+2x1.6)
  - i.e. a scale down (SA, S3R, S4R, PDU) Herschel architecture with an added BCR and specific RW interface (protection)

Power Subsystem Mechanical Data

- PCDU
  - 26.3Kg
  - 520x360x200mm
- Solar Array
  - 16.1Kg (4.4+2x5.9)
  - 0.8x1.5m + 0.8x2m (N.B ~0.82 would simplify the layout)
  - 21 strings length for the centre panel, 19 for the lateral ones
- Battery
  - 7.4Kg
  - 340x210x130mm

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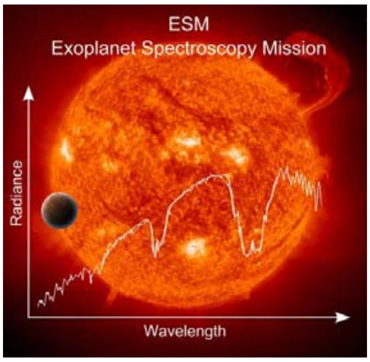
Avionics and Data Systems



Internal Final Presentation

ESTEC, 26th March 2010

Prepared by the ESM/ CDF* Team

(*) ESTEC Concurrent Design Facility

Data System requirements

- Single payload mission
- Complex AOCS
- High degree of autonomy
- Radiation
- Reuse

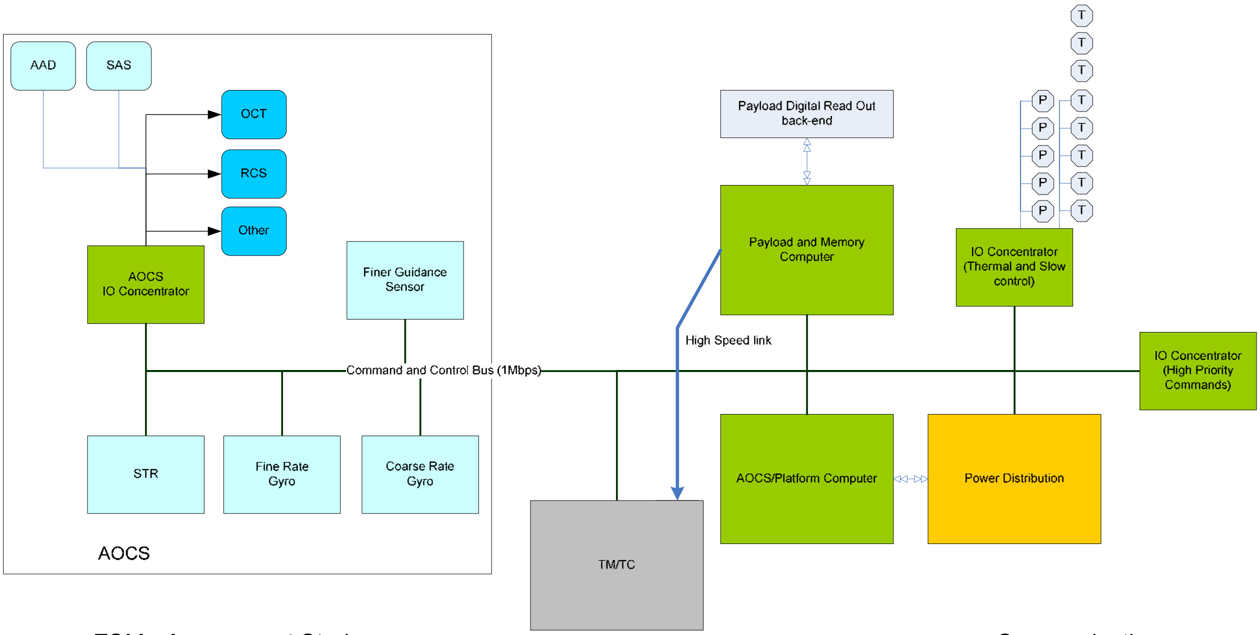
Radiation environment

- At L2 solar protons dominate the total radiation dose, thus dose may depend on the launch date vs actual solar cycle.
- Preliminary SPENVIS analysis with the assumption of 1 ‘quiet’ year and 2 ‘stormy’ years shows that electronic behind shielding requires a tolerance of not more than 20 krad(Si).
- With this inputs use of upscreened COTS devices for some non critical digital functions, with the aim of reducing budgets is achievable.
  - Mass Memory
  - (> 80K) Thermal control

Distributed intelligence

- To achieve the autonomy requirements without having a too complex on board SW we shall slightly increase the level of intelligence of single avionic units.
- Simple AOCS units are managed by a data concentrator
- Thermal control is managed by an autonomous system
- Housekeeping traffic shall be automatically channeled by onboard command and control bus following its priority
- Mass memory (flash based) has inner file system and file management capabilities based and is grossly oversized with respect to mission needs.

Avionic & Data System block Scheme



Model's Budgets

- Processor Module(s) (x2+2)
  - Power budget: 5.5W (@50% bus load
  - Mass: 5.6 Kg (including CVM)
- Memory Module (x6+12)
  - Each holding ~ 128 GiB of raw data
  - Blocks are organized with redundant block-level striping with parity data distributed across all active modules (2 concurrent failures w/o data loss), spare blocks are hot plugged in case of failures.
  - Active memory configurable, proposed ~ 0.5 TiB
  - Total mass ~ 1 Kg + possibly some shielding
  - Power < 2 W
- I/O concentrators
  - Can be separate boxes or integrated in computers
  - At least 3 (functionally)
  - For AOCS: oversampling of AOCS sensors and acquisition time decoupling
  - For Thermal: autonomous thermal control
  - For High Priority commands: capability to control the spacecraft w/o CPU intervention.

Autonomy capabilities

- Proposed C&C bus is CAN+CANOpen (as per ECSS-E-ST-50-15)
  - Redundant, 1 Mbps, multi-master, contention based (supports isocronous and asyncronous traffic)
- Each bus connected unit shouts loud when she fells like.
- Each bus connected unit may use any portion of traffic
- Synchronization is guaranteed by periodic heartbeats sent by the bus time master

- This allows a very intelligent management of the combined AOCS+slow control+HK data traffic, SW-less high priority data/commands management, autonomous thermal control and most important of all, a much simpler OBSW and a level of functional redundancy.

For other systems:

- Complex AOCS units (FGS, STR, CRG FRG) shall have (2x) bus interface

- Transponder unit shall have (2x) bus interface and command decode capability

Mass budget

AOCS/Platform/Payload Computer			
Unit Name Click on button above to insert new **unit**	**Part of custom subsystem**	**Quantity**	Mass per quantity excl. margin
AOCS/Platform Computer		2	5.6
Payload and Memory Computer		2	6.6
IO Concentrator		6	1.2
Click on button below to insert new unit			
SUBSYSTEM TOTAL		**3**	**31.6**

New Developments to support Exoplanet mission

- None (specific to Data Systems)
  - All presented items are in 2011-1014 workplans
- For comms:
  - ‘Intelligent’ TM/TC transponder
- For Operations
  - Full integration of a file management protocol in actual infrastructure

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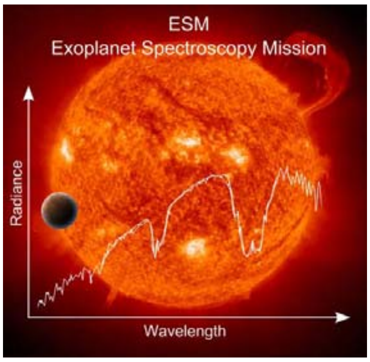
Ground Stations and Operations



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Operations Characteristics

- L2 mission with wide amplitude orbit (Halo)
- LEOP and transfer similar to IXO, Plato, and Euclid
- Preplanned operations in observation phase with moderate number of repointings
- Monthly orbit correction manoeuvre
- Low science data volume allows to reduce coverage to 2 times per week

Operations Approach

- An ESA **"Standard"** services operations concept is applied. It is similar as for other other planned L2 missions (e.g. PLATO and EUCLID, SPICA) in terms of performance, availability and low risk requirements.
- Re-use of components of the design from Herschel- Planck and GAIA is assumed. The concept employs minimised ground contact, systematic use of standards, fast development times and use of ESOC infrastructure.
- Family of mission concept: Sharing of control room with other L2 mission assumed.
- Operations Concept to be similar to PLATO

Data Rate (high rate downlink)

Assumptions:
- 1 Gbit/day Science data
- 2 * 2 h passes per week
- 1.5h available for high data rate
- 0.5 h ranging not compatible with high data rate)

- Required:

Science Generation Rate		HK Generation Rate		Contacts	Pass Duration	Downlink Data Rate
[kb/s]	[Mbit/day]	[kb/s]	[Mbit/day]	[/week]	[h]	[kb/s]
11.6	1000	5	432	2	2	933

- Available:

Antenna	Gain [dBi]	RF Power [W]	Coding	Ground Station	Data Rate [kb/s]
Herschel MGA 10° off	16	32	Concatenated	New Norcia 35m	1500

Data Rates

- Uplink: 4 kb/s (compatible with ranging and with MGA as well as LGA)
- Uplink: 64 kb/s as option during high data rate downlink (to cope with short uplink time and with CFDP protocol)
- Downlink during ranging: ~ 500 kb/s
- Downlink compatible with 15m stations: ~ 150 kb/s
- Downlink LGA: ~ 20 kb/s

Minimum Coverage Nominal Operations

- Navigation requires ~ 3h coverage per week TBC
- Checking + minor software updates etc. requires ~ 4h per week
- Command uplinks feasible with short coverage if high level commands are used.
- Coverage 2 times per week good compromise to keep impact of problems at bay
- Orbit maintenance and larger checks require 8h/day at regular intervals
- No close to real time task that drive short feedback

Communications Concept

- 2 passes per week
- Herschel antenna reuse (and possibly also RF setup in general)
- Fixed MGA in general requires interruption of science during pass, but wide MGA beam width might allow for continuation of science for selected targets
- For safe mode and manoeuvres data rates compatible to LGA to be implemented
- Use of 15m station not recommended as baseline station, but recommended to add respective data rates to increase operational feasibility

Coverage Overview

Activity	Duration	Coverage	Operations Type	Comments
LEOP	2 - 3 days	2 stations each 8h/day	Two shifts, on line	Autonomy assumed to be in line with 2 stations only, LEOP ends with first correction manoeuvre
Transfer + Outgassing	~ 4 weeks	1 station 8h/day, 2 stations selected passes	SPACONs + selected passes with engineer and FD on line	Includes: Touch up manoeuvre ~ L+ 12 commissioning steps as far as possible
Commissioning	2 months TBC	1 station 8 - 10 h/day	8 - 10h/day real time	PIs colocated
Initial Operations	6 months TBC	1 station 4h/day 7 days/week	SPACONs + selected passes with engineer	Less busy schedule proposed, usually full efficiency is only achieved after 1/2 year of operations
Nominal operations	2.5 years + 3 years extension	1 station 2h/day 2 days/week + 1 * 8h /month	SPACONS	Engineers on call

Special Features (1)

- Use of File Delivery protocol proposed
- State of the art for uplink
  - Very useful for software updates and timeline uplinks
- Recommended by ESOC working group for general application

Special Features (2)

- ESOC working group recommendation
  - CFDP (CCSDS File Delivery Protocol) for point to point communications (spacecraft ↔ MOC)
  - Uses encapsulation into CCSDS packets
  - Implementation of file management techniques on board
- File management on board is promising, but requires developments beyond current PUS standard.

Cost Considerations

- Cost expected similar to PLATO, because very similar Flight Operations team
- Overall slightly lower cost than Plato:
  - lower cost due to:
    - less ground station usage
    - less SPACON time
  - but:
    - slightly higher Flight Dynamics cost due to more manoeuvres
    - Data transfer protocol setup
  - uncertainty:
    - how many L2 missions in family of mission control room

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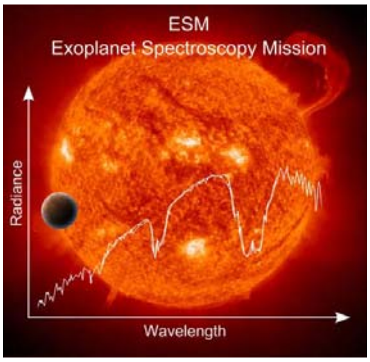
Communications



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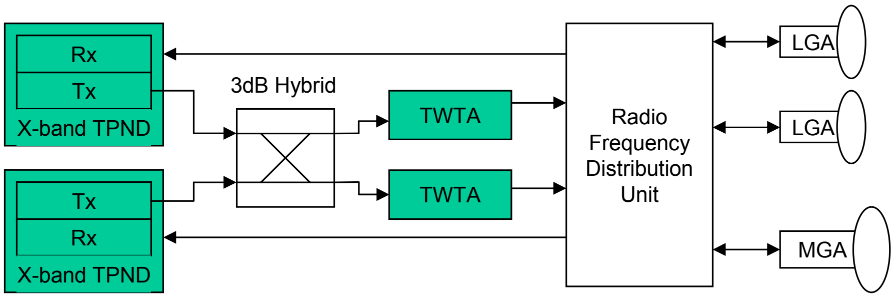
Requirements and design drivers

- Requirements:
  - Follow de ECSS standards
  - Provide telemetry telecommands and ranging simultaneously during all missions and regardless of the attitude.
  - Margin shall be at least 3 dB
  - Receivers in hot redundancy / Transmitters in cold redundancy.
- Design drivers:
  - L2 orbit. Maximum distance Earth-S/C = 1.7e6 km
  - 35 m X-band antenna in New Norcia. G/T=50 dBK
  - Two passes of 2 hours each per week (only 1.5 hours for TM)

Subsystem design

- The whole H-P communications architecture will be reused:
  - 2 x X-band transponders
  - 2 x TWTA
  - 1 x RDFU
  - 2 x LGA and 1 x MGA

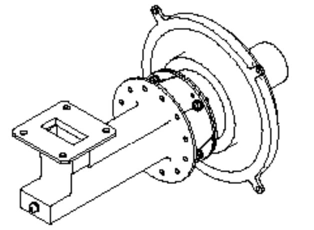


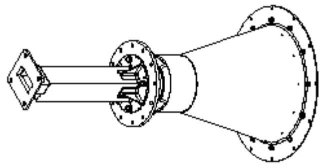
Subsystem design

- 2 x X-band transponders:
  - Transmitters in cold redundancy and receivers in hot redundancy
  - TC up to 4 kbps
  - TM up to 1.5 Mbps (3.4 Msps with Concatenated code)
  - Coder has to be implemented in the OBDH
  - Power: 15 W transmitter / 10 W receiver
- 2 x TWTA
  - Output power: 32 W
  - Power: 75 W
- Total power consumption: 110 W in Tx / 20 W in Rx

Subsystem design

- 2 x Low Gain antennas
  - Pattern: Omnidirectiona
  - Choked horn type
  - Gain: (-3,+3) dBi
- 1 x Medium Gain antenna
  - Pattern: Directional
  - Spacecraft pointed
  - Type: Horn
  - Gain: +16 dBi





Link budgets

- MGA
  - Data rate: 1.5 Mbps
  - Margin: 7 dB

Frequency	8.475	GHz
Information data rate	1500	kbps
Tx Power	32.00	W
Tx losses	-1	dB
Antenna gain	16.00	dBi
Tx EIRP	**30.05**	**dBW**
Elevation	10	deg
Slant range	1705253	km
Total propagation loses	**-236.32**	**dB**
Antenna G/T	50.64	dB/K
Total losses	-0.54	dB
Eb/No information	10.67	dB
Implementation losses	-1	dB
Eb/No req. inf.	2.50	dB
Margin	**7.17**	**dB**

- LGA
  - Data rate: 5 kbps
  - Margin: 10 dB

Frequency	8.475	GHz
Information data rate	5	kbps
Tx Power	32.00	W
Tx losses	-4	dB
Antenna gain	-3.00	dBi
Tx EIRP	**8.05**	**dBW**
Elevation	10	deg
Slant range	1705253	km
Total propagation loses	**-236.32**	**dB**
Antenna G/T	50.64	dB/K
Total losses	-0.54	dB
Eb/No information	13.44	dB
Implementation losses	-1	dB
Eb/No req. inf.	2.50	dB
Margin	**9.94**	**dB**

Data budget

- Generated data:
  - PLTM: 11.6 kbps (1 Gb per day)
  - HKTM: 5 kbps
  - Data generation time: 4 days
  - Total generated data: **5.7 Gb**
- Transmitted data
  - Data rate: 1.5 Mbps
  - Transmission time: 1.5 hours
  - Total transmitted data: **8.1 Gb**

- **70 % of link occupation**

Mass budget

Element 2	Service Module		MASS [kg]	
Unit	Unit Name Click on button above to **insert new unit**	Quantity	Mass per quantity excl. margin	Total Mass incl. margin
1	X-band transmitter	2.00	2.00	4.2
2	X-band receiver	2.00	2.00	4.2
3	X-band TWTA	2.00	5.00	10.5
4	X-band LGA	2.00	1.00	2.1
5	X-band MGA	1.00	1.50	1.6
6	RFDU	1.00	1.00	1.1
7	Cables and Harness	1.00	1.00	1.1
-				
SUBSYSTEM TOTAL		**7**	**23.5**	**24.7**

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AIV/Programmatics

IFP

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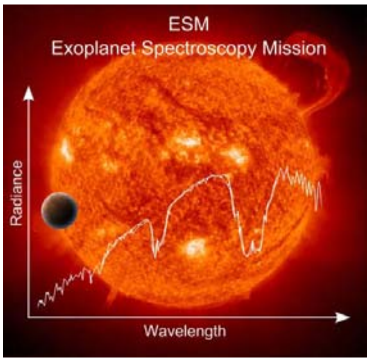

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Programmatic constraints

- Possible Future Cosmic vision proposal (M-class)
- End of definition phase (B1) first quarter 2014
  - Corrected to first quarter 2015
- Launch before 2020
- ≥TRL 5 for most critical technologies by end of definition phase (B1)
- FM payloads delivered 18 months before launch

TRL overview

- ESA&NASA Technology Readiness Levels (TRL)

- **TRL 1** Basic principles observed and reported
- **TRL 2** Technology concept and/or application formulated
- ***TRL 3*** *Analytical and experimental critical function and/or characteristic proof-of concept*
- ***TRL 4*** *Component and/or breadboard validation in laboratory environment*
- ***TRL 5*** *Component and/or breadboard validation in relevant environment*
- **TRL 6** System/subsystem model or prototype demonstration in a relevant environment (ground or space)
- **TRL 7** System prototype demonstration in a space environment
- **TRL 8** Actual system completed and “flight qualified” through test and demonstration (ground or space)
- **TRL 9** Actual system “flight proven” through successful mission operations

Critical technologies

	Description	Technology readiness level
AOCS	Reaction wheels with magnetic bearings	TRL 4
	CMOS for fine guidance sensor	TRL 4
	FEEP (optional) adaptation	TRL 4
TCS	Neon sorption cooler	TRL 4
EPS	MPPT (optional)	TRL 3
Payloads	Detectors	TRL 3

Detector pre-development

Baseline detector technology:

HgCdTe
Available solutions do not provide required dynamic range

Fields of development needed:
A. Readout electronics ROIC (increase ratio of flux measurement to readout noise by factor of 10): TRL 3, min. 2.5 years
B. Detector material (extension of possible wavelengths (>10µm) with acceptable dark current at 30K): TRL 3, min. 2 years

Combined development (A. -> B.): min. 3 years

same technology for the 3 detectors/wavelength ranges -> similar development issues

Optional detector technology:

Si:As
US: commercial technology does not meet requirements
In Europe: still in predevelopment state, e.g. problems with stability/consistency of output signal for different pixel
-> TRL 2, min. 6-7 years of development

Proposed Model philosophy

Phase B1/B2:

- PSF / AILF (AOCS)
- E(Q)M (Cryo-Cooler, reaction wheel magn.)
- DM (Detector/ROIC, Cryo-Cooler, FGS CCD, FEEP (optional))
- Optical bench

Phase C/D

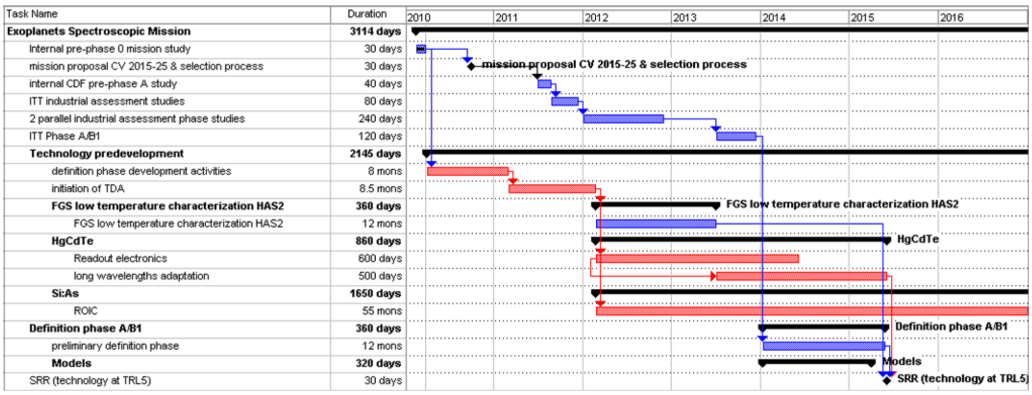
- STM telescope
- SM
- CQM, later refurbished as STM
- QM reaction wheel magn.
- EQM (DHU, PCDU, FEEP (optional))
- Optical bench
- PFM

Phase durations

	duration	Main drivers
Phase A/B1	18 months	Given by Cosmic Vision programmatics
Phase B2	12 months	Technology development
Phase C	18 months	Technology development, complexity thermal design, CQM, telescope STM
Phase D	30 months	Specific Qual. (system STM / subsystem QM) followed by PFM
Launch cpgn.	4 months	

Schedule Phase A/B1

- Start of Phase A/B1 defined by CV selection process: Jan. 2014 (duration: 18 months -> mid 2015)
- Development time for detectors:
  - minimum 3.5 years expected
  - definition of technical development activities (TDA): 1 year
  - 5.5 years until mid 2015 -> 1 year “margin”: e.g for TDA assessment cycles, additional dev. time



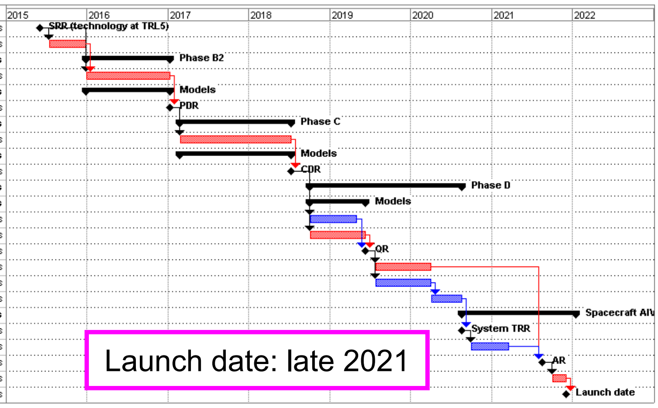
Schedule Phase B2 - launch

- Payload FM delivery L-18 months on critical path:

  Possible mitigation:

  - relaxation of requirement to 12 months -> PL still able to be ready for system environmental testing
  - earlier production start for PL (implying earlier subsystem QR)

Task Name	Duration
SRR (technology at TRL5)	30 days
ITT Phase B2/C/D	120 days
Phase B2	**270 days**
preliminary design phase	270 days
Models	**270 days**
PDR	30 days
Phase C	**360 days**
detailed definition phase	360 days
Models	**360 days**
CDR	30 days
Phase D	**490 days**
Models	**180 days**
STM (partially refurbished from CQM & telescope STM)	150 days
QM (FEEP, DHU, PCDU, Payloads,...)	180 days
QR	30 days
FM Payloads	180 days
PFM procurement and assembly	180 days
System AIV and functional test	100 days
Spacecraft AIV campaign	**367 days**
System TRR	30 days
Environmental test campaign PFM	120 days
AR	30 days
Launch campaign	47 days
Launch date	30 days



Conclusions (1/2)

AOCS
- Reaction wheels with magnetic bea...s
- Fine guidance sensors
- FEEP (optio...

Cry...
- He-sorption cooler

Predevelopment within normal project phases

Payloads
- Detectors
  - Uncertainty of dark current at 30K
  - ROIC & dynamic range

Early start necessary

Lead time needed for commencing new research activity has to be considered due to annual assessment cycles

Conclusions (2/2)

- Decision point for B2/C/D in mid 2015
  - Until then: detectors on the critical path
  - mitigation by definition and initiation of TDA within 2011

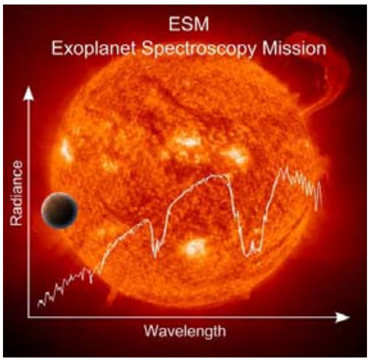
- Approach to Phase B2/C/D at the moment conservative, more detailed prediction possible in later project phases

- PL delivery L-18 months on critical path, may be relaxed by earlier subsystem QR (to be investigated)

- Expected launch date in 2021

ESM
Exoplanet Spectroscopy Mission

<Risk>



Internal Final Presentation

ESTEC, 26th March 2010

Prepared by the ESM/ CDF* Team

(*) ESTEC Concurrent Design Facility

Outline

- Dependability and Safety Requirements
- Qualitative Risk Assessment
  - Risk Management Policy
  - Risk Log
- Reliability Assessment
- Conclusions

PA Req. MRD Update

Requirement ID	Title	Statement
PA: Product Assurance Requirements		
R-PA-10	ECSS product assurance	Product Assurance (PA) requirements provided by ECSS-Q-00A and the detailed requirements provided by lower level standards defined in ECSS-Q-00A for each of the PA disciplines shall apply.
R-PA-20	Tailoring of ECSS requirements	Detailed requirements from the applicable Level 2 and Level 3 ECSS standards shall be tailored according to the characteristics of the mission and the input required to perform an effective risk assessment process.
R-PA-30	Tailoring of PA requirements	Tailoring of PA requirements standards shall be performed according to ECSS-M-00-02A.
R-PA-40	Risk assessment	Tailoring of detailed requirements with regard to risk assessment shall assure that all PA tasks necessary to provide the required qualitative and quantitative input for the risk assessment process are provided.
R-PA-50	Single point failures 1	Single Point Failures (SPF) with catastrophic and critical consequences as defined in ECSS-Q-40A and ECSS-Q-30A are a subset of critical items to be identified in the scope of the risk assessment process. Risk assessment and control shall be performed in compliance with ECSS-Q-00A, clause 3.3.5. Risk assessment according to ECSS-Q-00A contributes to the overall project risk management process according to ECSS-M-00-03b. In particular safety and dependability critical items identification and control shall comply with: • ECSS-Q-30A, clause 5.3 - Dependability Critical Items. • ECSS-Q-40A, clauses 3.3 (Functions) and 5.6 (Items) - Safety Critical Functions and Items. • Launch site Safety Regulations Safety critical items and operations (system and ground support equipment) in the scope of ESM are relevant with regard to AIT/AIV activities and any activities at the launch site. Thus compliance to specific requirements related to the level of fault tolerance will be mandatory according to launch site safety regulations.
R-PA-60	Single point failures 2	Identification and control of SPFs as defined above applies to: all interfaces between payload instruments and the spacecraft module, including mechanical, thermal, electrical (power, data, EMC/EMI, pyrotechnics), radiation, as far as applicable.

R ID	Reference	Updated reference
R-PA-10	ECSS-Q-ST-00A	ECSS-S-ST-00C clause 5.3.4 Product Assurance (Q-branch)
R-PA-30	ECSS-M-00-02A	ECSS-S-ST-00C clause 7.3
R-PA-50	ECSS-Q-40A	ECSS-Q-ST-40C
R-PA-50	ECSS-Q-30A	ECSS-Q-ST-30C
R-PA-50	ECSS-Q-00A clause 3.3.5	ECSS-Q-ST-10C clause 5.2.4 (Critical items control and PA interfaces to project risk management)
R-PA-50	ECSS-Q-00A	ECSS-Q-ST-10C clause 5.2.4 (Critical items control and PA interfaces to project risk management)
R-PA-50	ECSS-M-00-03-B	ECSS-M-ST-80C
R-PA-50	ECSS-Q-ST-30A clause 5.3	ECSS-Q-ST-30C clause 4.5
R-PA-50	ECSS-Q-ST-40A clauses 3.3 (functions) , 5.6 (Items)	ECSS-Q-ST-40C clauses 6.5 (functions) and 5.6 (items)

Update to version C of ECSS-Q-ST series

Dependability and Safety Requirements

- **Dependability**
  - High System Reliability Goal (probability of mission success) **>85%.**
  - Design lifetime of **3 years.**
  - No failure propagation, minimize or remove Single Point Failures (SPFs)
  - Appropriate FDIR Req.'s
  - Reliable Safe Mode
  - Fault Tolerance Approach:
    - 1 Failure tolerant system for critical consequences
    - 2 Failure tolerant system for catastrophic consequences (safety critical)
  - Reliability Assurance:
    - Designs to be validated with appropriate Reliability Analyses such as FTA, FMECA, Reliability Prediction, PRA, …
- **Safety**
  - Safety goal: Identify, reduce to acceptable levels or eliminate all possible safety hazards during all mission phases

Qualitative Risk Assessment: Risk Policy

- **Maximize** the probability of **achieving ESM's** intended goals and to contribute to the Science Directorate integrated risk management.
- The CDF risk management policy for **ESM** aims at **handling** risks which may cause serious cost, schedule, technical, and science value impacts on the project.
- **Risk Management Process**

An organized, systematic decision making process that efficiently identifies, analyzes, plans, tracks, controls, communicates, and documents risk to increase the likelihood of achieving program/project goals.

Mission Success Criteria

SRE	• The ESM mission is to analyse and determine the composition of the atmosphere of known transiting exoplanets (primary objective), non-transiting exoplanets (secondary objective), and could also observe transiting binary stars or brown dwarves.
Technical	• Payload and platform shall perform correctly during all mission phases for the required lifetime at least 3 years.
Schedule	• Launch by the end of 2020 on Soyuz-ST from CSG. • Minimum TRL 5 by PDR for critical technologies.
Cost	• ESA Cost at Completion (2008) shall be ≤ 450 M€ (SRE M-class mission budget)

Risk Policy: Severity/Likelihood Categorization & Risk Index

Severity	Schedule	Science	Technical (ECSS-Q-30 and ECSS-Q-40)	Cost
Catastrophic 5	Launch opportunity lost	Failure leading to the impossibility of fulfilling the mission's Scientific objectives	Safety : Loss of system, launcher or launch facilities. Loss of life, life-threatening or permanently disabling injury or occupational illness; Severe detrimental environmental effects.	Cost increase result in project cancellation
Critical 4	Launch delayed (TBD) months	Failure results in a major reduction (70-90%) of mission's Science return	Dependability: Loss of mission. Safety: Major damage to flight systems, major damage to ground facilities; Major damage to public or private property; Temporarily disabling but not life- threatening injury, or temporary occupational illness; Major detrimental environmental effects.	Critical increase in estimated cost
Major 3	Launch delayed (TBD) months	Failure results in an important reduction (30-70%) of the mission's Science return	Dependability: Major degradation of the system. Safety: Minor injury, minor disability, minor occupational illness. Minor system or environmental damage.	Major increase in estimated cost
Significant 2	Launch delayed (TBD) months	Failure results in a substantial reduction (<30%) of the mission's Science return	Dependability: Minor degradation of system (e.g.: system is still able to control the consequences) Safety: Impact less than minor	Significant increase in estimated cost
Minimum 1	No/ minimal consequences	No/ minimal consequences.	No/ minimal consequences.	No/ minimal consequences.

Score	Likelihood	Definition
E (5)	Maximum	Certain to occur, will occur once or more times per project.
D (4)	High	Will occur frequently, about 1 in 10 projects Pf=0.1 R=0.9
C (3)	Medium	Will occur sometimes, about 1 in 100 projects Pf=0.01 R=0.99
B (2)	Low	Will occur seldom, about 1 in 1000 projects Pf=0.001 R= 0.999
A (1)	Minimum	Will almost never occur, 1 in 10000 projects Pf=0.0001 R=0.9999

Severity					
5	5A	5B	5C	5D	5E
4	4A	4B	4C	4D	4E
3	3A	3B	3C	3D	3E
2	2A	2B	2C	2D	2E
1	1A	1B	1C	1D	1E
	A	B	C	D	E
					Likelihood

Risk Drivers

- New Technology
  - MB RW, Detectors, ROIC, FGS, etc.
- Environmental Factors
  - Radiation, contamination, micrometeoroid, extreme temperature gradients, etc.
- Design Challenges
  - Optics, Detectors, Cryogenics
- Reliability Issues
  - Electronics, software
- Major Mission Events
  - Launch, orbit insertion

Risk Log: Ground, Launcher, Mission

Risk Type	Risk Index (Final)	Risk scenario	Classification (Severity-Impact)	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Ground							
★	3A	Possible lack of availability of ground stations.	Science	Conflict with other ESA missions.	Coverage 4h , 2 times per week is a good compromise to minimize schedule impact problems.	Baseline New Norcia Ground station DSA 1 (Deep Space Antenna 1).	Larger on-board data storage.
Launcher							
	5D	Launcher failure. Delivering insufficient impulse for correct orbit insertion trajectory. Impact on safety.	Technical	Propulsion, staging, avionics, electrical or structural failure.	Soyuz-ST is a highly reliable launch vehicle based on the successful Soyuz launch vehicle which is the most frequently used and most reliable launch vehicle in the world.	Good launch success record until 03/2010: 7 launches, 6 successes and 1 partial failure (Meridian 2 payload 21/5/2009).	
	3D	Unavailability of launch vehicle	Schedule	Previous launch failure, schedule delays or launcher technical issues.	Contingency strategy in case of delayed launch date.	Design compatibility with several launch vehicles.	
Mission							
★	5C	Insufficient number of science targets to justify ESM mission.	Science	Currently (2010) only ~10 exoplanet targets have been identified.	Additional exoplanet targets are expected to be discovered during ESM's development timeframe.	10 year margin until schedule 2020 launch date.	
★	4D	Operational complexity of direct injection trajectory	Technical	Demanding course correction operations in very limited time.	Action taken: Option highly elliptical orbit trajectory.		
	2E	Increase in total ΔV requirements.	Technical	Baseline change from MBRW to BBRW + FEEP micro thruster system with consequent increase in overall propellant mass.	Consider increase in ΔV factor in trade-off before changing AOCS baseline design.		

Risk Log: Payload

Risk Type	Risk Index (Final)	Risk scenario	Classification (Severity-Impact)	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Payload							
★	4D	MgCdTe technology uncertainties at LW IR wave lengths (15 microns)	Technical	Dark current impact at 30K operating temperature.	Acceptable reduction in performance.	Employ alternative SiAs technology. However, technology development is required in Europe which may have other mission impacts as development time is expected to be > 4 years and must operate at < 7 K.	
★	4D	Detector read out fit requirements for ESM not achieved with current technology (2010).	Technical	Noise and integration capacity of current detector technology is off by a factor of 10 as compared to ESM's requirements.	Invest in technology and testing.	Apply development margins in schedule.	Accept reduction in requirements.
★	4D	Detector technology development impact on schedule. ITAR restrictions & delays may apply for US procured detectors. Criticality of APS supplier.	Schedule	Single or limited number of APS suppliers. MWIR-LWIR Si:As Impurity Band Conduction (IBC) detector technology development required in Europe. ROIC & material development required.	Limit scope of detector technologies considered to European manufacturers e.g. Sofradir (EU): HgCdTe; Xenics (EU): HgCdTe, InSb.	Invest in European Si:As detector technology if it is required for ESM.	Consider having several APS suppliers to run parallel procurements.
	4C	Loss of cryogenic cooler/cooling chain. Impact on telescope observations.	Science/technical	Technical complexity. Non redundant last cooling stage.	Establish appropriate design margins and back up operational modes.	High reliability requirements to ensure successful mission completion.	

Risk Log: Payload

Risk Type	Risk Index (Final)	Risk scenario	Classification (Severity-Impact)	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Payload							
★	4C	Loss of instrument detectors and/or readout electronics	Science/technical	Failure in APS electronics due to radiation environment. The main radiation components at L2 consist of: Galactic cosmic rays, solar particle events and solar and Jovian electrons.	The L2 environment (and orbits around it) is relatively benign compared to those in geostationary (GEO), or low Earth (LEO) orbits.	Maintain low operating temperatures and use appropriate shielding.	Consider 11-year solar activity cycle in setting mission launch date. The last solar minimum occurred around March 2006.
★	4C	Telescope performance degradation due to optics contamination during manufacturing, assembly, testing, transport, launch campaign or flight.	Science/technical	Optical instruments mounted on space platforms may be subject to performance degradation due to condensation of gases, debris contamination, dust particles or plume impingement from AOCS thrusters.	Appropriate cleanliness requirement specification and cleanliness and contamination control plan covering all project phases.	Configuration layout such that the sources of contamination cannot impact on sensitive surfaces.	Apply XMM/Herschel experience and lesson's learnt.
	4B	Loss/degradation of science return due to EMI.	Science	EMI with telescope instruments from electromagnetic sources.	Stringent EMI/EMC test levels to minimize/eliminate risk to the telescope	System level testing with engineering model instruments will mitigate.	EMI shielding.
★	3D	Single event upset (SEU) experienced by FGS detectors with impact on science return.	Science/technical	Extreme radiation environment. The main radiation components at L2 consist of: Galactic cosmic rays, solar particle events and solar and Jovian electrons.	Consider 11-year solar activity cycle. The last minimum occurred around March, 2006.	Fine Guidance Sensor (FGS) is internally redundant with a beam split and 2 detectors.	Filtering not necessarily important if hybrized with Gyro through one Kalman filter.

Risk Log: Payload

Risk Type	Risk Index (Final)	Risk scenario	Classification (Severity-Impact)	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Payload							
★	3D	Complex cryogenic cooling chain development, manufacturing, assembly, integration and testing.	Schedule/technical	Low TRL of the cryogenic cooling chain. Technology development is required. Complex testing environment.	Plan schedule accordingly considering complexity in assembly, integration and testing.	Increase schedule margins.	Invest in technology.
★	3D	Stray light impact on telescope observations.	Science	Light from unwanted sources reaching detectors. Micrometeoroid impacts on telescope baffle.	Consider all possible sources of straylight including: sources outside FoV, inside FoV and self emission.	Straylight analysis for the orbit configuration.	Implement adequate baffle requirements.
★	3C	Custom European Fine Guidance Sensor (FGS) detector development is required for use at low temperatures. Impact on schedule.	Schedule/technical	European Fine Guidance Sensor (FGS) detector considered needs to be tested/qualified for use at low temperatures (ESM)	Invest in technology and testing.	In case the testing/qualification activity for the European detector is unsuccessful there is a possibility to switch to a US manufacturer. However, this might have other project impacts such as schedule delays due to ITAR or increased cost.	
	3C	Complex mirror manufacturing, integration and alignment. Optics test and calibration. Delays in schedule.	Schedule	High precision machining/grinding, mirror polishing, reflective coating application, integration, alignment and testing.	Smaller mirror dimension and reduced manufacturing complexity as compared to Herschel.	Apply ESA's lesson's learned from experience in previous space telescope observatories.	Plan schedule accordingly considering complexity in assembly and integration.
★	3C	Micro-vibration disturbances/jitter impact on telescope observations.	Science/technical	Cryogenic cooler. Reaction wheels: Static and dynamic imbalances produced by a non uniform mass distribution within the flywheel. Bearing/motor disturbances are also possible sources.	Minimize the amplitude of the vibrations by, for example, placing equipment on appropriate mountings.	Along the vibration paths, modifications of structural elements or equipment relocation can be attempted with the aim of reducing the mechanical coupling between vibration sources and receivers.	Use of magnetic bearing reaction wheels rather than ball bearing reaction wheels which reduce microvibrations by a factor of 10. Action taken.

Risk Log: Platform

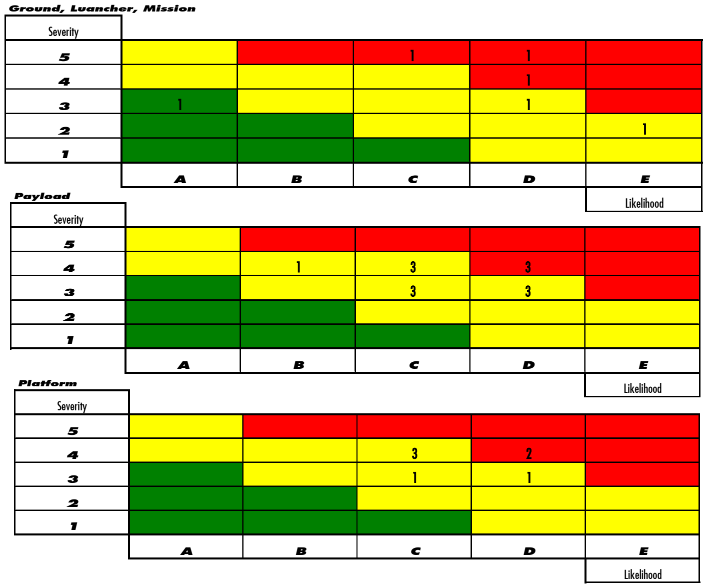
Risk Type	Risk Index (Final)	Risk scenario	Classification (Severity-Impact)	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Platform							
	4D	DHS LEON3 baselined processor unavailability with impact on schedule.	Schedule	The LEON3 processor is not available as a radiation-hardened component/chip (e.g. LEON2 from Atmel (AT697 and AT7913) took 10 years development).	Follow closely on LEON3 chip development activities.	Baseline an already existing processor available as a rad hard component.	
★	4D	Low-noise Magnetic Bearing Reaction Wheels TRL issues.	Schedule	Uncertainties in the design maturity.	Invest in technology and testing. Assess design maturity.	Option consisting of ball bearing reaction wheels in combination with electric micro-thrusters.	Electromagnetic FEEPs are in general ahead in development wrt. Magnetic Bearing -RW.
	4C	Loss of thermal control with impact on instrument operations/science return.	Science/technical	Extreme thermal environment. Complex instrument module thermal control.	Design for worst case cold and worst case hot.	Appropriate material selection, insulation and thermal control.	Appropriate testing capabilities.

Risk Log: Platform

Risk Type	Risk Index (Final)	Risk scenario	Classification (Severity-Impact)	Cause	Mitigating Action 1	Mitigating Action 2	Mitigating Action 3
Platform							
	4C	Loss of ESM attitude control with impact on science return.	Science/technical	Complex AOCS system.	Fully redundant AOCS system.	Reliable safe mode.	
	4C	Complete or partial loss of power subsystem with impact on science return.	Science/technical	Demanding power requirements driven by the cryogenic assembly and to a lesser extent the magnetic bearing RWs.	One solar array string/battery cell redundancy.	PCDU internally redundant.	
	3D	Temporary loss of DHS with impact on the availability of science return.	Science/technical	Single event upset (SEU) caused by high energy ionizing particles, mainly solar protons.	Reliable safe mode. DHS high reliability redundant architecture.	Preliminary SPENVIS analysis shows that the electronics behind shielding requires a tolerance of no more that 20 Krad assuming 1 quiet year and 2 stormy years.	Consider solar activity cycle in setting mission launch date. Total radiation dose may depend on actual launch date vs. actual solar cycle.
★	3C	Compatibility issues of the file management system proposed, CFDP (CCSDS File Delivery Protocol), with the PUS (Packet Utilization Standard).	Schedule/technical	Mappability issues with the 'message type' interface PUS between ground and the onboard applications.	CFDP messaging mechanism can replicate some of PUS services at 'file' level rather than at 'packet' level.	Invest time and resources in solving potential compatibility issues.	CFDP implementation activity is planned at ESOC.

Risk Index Chart

- High risks are typical of a Pre-Phase A Project. Areas with lack of definition or little previous experience pose a priori more risk to the mission and therefore are the ones with more risk reduction potential.
- Experience shows that all risk items with a critical risk index (red/yellow area) must be analyzed and proposals for risk treatment actions elaborated.
- For the remaining risk items there is an alert with respect to a possible increase of the Risk Index.
- In the end, ideally all risk items should reach a level of justifiable acceptance.
- The risk management process should be further developed during the project definition in order to analyze the entire system, refine the risk identification and classification, and provide evidence that all the risks have been effectively controlled.



Reliability Assessment: Assumptions

- Mission lifetime of 3 years.
- Component lifetimes follow the **exponential distribution**.
- The following are considered **non-credible single point failures** SPF:
  - Structural and non-moving mechanical components
  - Short or open on power bus
  - Propulsion tank or manifold bursts or leaks (upstream of isolation valves)
  - Heat pipe failure
- **Software** and procedural failures are **not included** in the analysis (Flight Software modeled as reliability of 1)
- Harness modeled with R=1.
- **Duty Cycles:** Propulsion (LV ~700 cycles, 20N ~200 cycles, 1N ~140000 cycles), Operational Heaters – 70%, battery 10%, all other components – 100%
- **Event Probabilities**: Launch – 98%.
- Failure rate allocation at unit level based on ESA-PSS-01-302 and CDR Reliability prediction reports of similar units.
- Stand- by $\lambda s = \lambda/10$

Reliability Assessment (1/2)

• **AOCS:**
AAD ½ hot, SAS ½ hot, Coarse Gyro ½ hot, STR ½ cold, Fine Gyro internal, MBRW ¾ hot.

• **Communication:**
X Band Tx ½ cold, X band Rx ½ hot, TWTA ½ cold.

• **DHS:**
Payload Computer ½ cold, Platform Computer ½ cold, I/O concentrators 3x ½ cold.

• **Propulsion:**
½ thruster branch in cold redundancy (1LV, 1 PT, 1 FDV, 4 1N T, 2 20N T)

Subsystem	Equipment	no. of units	Redundancy Scheme	Operating time (hrs-cycles)	Failure Rate (FIT)	Failure Rate (FPH-FPC)	Unit Reliability	Reliability (R)
AOCS	Attitude Anomaly Detector	2	1/2 hot	26280	80	0.0000000800	0.9979	1.0000
AOCS	Sun Acquisition Sensor	2	1/2 hot	26280	100	0.0000001000	0.9974	1.0000
AOCS	Coarse Gyrometer	2	1/2 hot	26280	1000	0.0000010000	0.9741	0.9993
AOCS	Star Tracker	2	1/2 cold	26280	1500	0.0000015000	0.9613	0.9992
AOCS	Fine Gyrometer	1	Internal?	26280	2000	0.0000020000	0.9488	0.9488
AOCS	Magnetic Bearing Reaction Wheel	4	3/4 hot	26280	350	0.0000003500	0.9908	0.9995
AOCS TOTAL								**0.9469**
COMMS	X-band transmitter	2	1/2 cold	26280	900	0.0000009000	0.9766	0.9997
COMMS	X-band receiver	2	1/2 hot	26280	1100	0.0000011000	0.9715	0.9992
COMMS	X-band TWTA	2	1/2 cold	26280	500	0.0000005000	0.9869	0.9999
COMMS	X-band LGA	2	None	26280	10	0.0000000100	0.9997	0.9995
COMMS	X-band MGA	1	None	26280	100	0.0000001000	0.9974	0.9974
COMMS	RFDU	1	None	26280	30	0.0000000300	0.9992	0.9992
COMMS	Cables and Harness	1	N/A	N/A	N/A	N/A	N/A	N/A
Comms TOTAL								**0.9949**
DHS	AOCS/Platform Computer	2	1/2 cold	26280	2000	0.0000020000	0.9488	0.9985
DHS	Payload and Memory Computer	2	1/2 cold	26280	2000	0.0000020000	0.9488	0.9985
DHS	IO Concentrator	6	3x 1/2 cold	26280	137	0.0000001370	0.9964	1.0000
DHS TOTAL								**0.9971**
PROPULSION	Propellant Tank	1	None	26280	0	0.0000000000	1.0000	1.0000
PROPULSION	Service Valve	2	None	700	56	0.0000000560	1.0000	0.9999
PROPULSION	Pressure Transducer	1	None	26280	200	0.0000002000	0.9948	0.9948
PROPULSION	Propellant Filters	1	None	26280	10	0.0000000100	0.9997	0.9997
PROPULSION	Thruster Branch							0.8542
PROPULSION	Latch Valves	1	None	700	160	0.0000001600	0.9999	0.9999
PROPULSION	Service Valve	1	None	700	56	0.0000000560	1.0000	1.0000
PROPULSION	Pressure Transducer	1	None	26280	200	0.0000002000	0.9948	0.9948
PROPULSION	Thrusters (1N)	4	None	140000	271	0.0000002710	0.9628	0.8592
PROPULSION	Thrusters (20N)	2	None	200	918	0.0000009180	0.9998	0.9996
PROPULSION	Thruster Branch	2	1/2 cold				0.8542	0.9878
PROPULSION	Piping	30	N/A	N/A	N/A	N/A	N/A	N/A
PROPULSION	Bracketing	1	N/A	N/A	N/A	N/A	N/A	N/A
Propulsion TOTAL								**0.9823**

Reliability Assessment (2/2)

•**Power:**
144 battery cells (6s 24p). 1 string redundant. 17 solar array strings of 21 cells (center panel) & 26 strings of 21 cells each side panel. 69 S/A strings total. 1 SA string redundant. Internally redundant PCDU, S3R section level (1/1+n hot) and BCR 2/3 hot.

• **FGS:**
FGS Module ½ cold, FGS Detector ½ cold.

• **Cryogenics:**
Cooler and electronics ½ cold.

• **Instruments:**
Instrument reliability allocation of 0.975 @ 3 years for VNIR, SWIR & MWIR. Telescope assembly modeled with R=1.

Subsystem	Equipment	no. of units	Redundancy Scheme	Operating time (hrs-cycles)	Failure Rate (FIT)	Failure Rate (FPH-FPC)	Unit Reliability	Reliability (R)
THERMAL	MLI	1	N/A	N/A	N/A	N/A	N/A	N/A
THERMAL	Heaters	1	Internal?	18396	150	0.0000001500	0.9972	0.9972
THERMAL	Black Painted Radiators	1	None	N/A	N/A	N/A	N/A	N/A
THERMAL	SSM Radiators	1	None	N/A	N/A	N/A	N/A	N/A
THERMAL	Misc (thermal washers, filler…)	1	N/A	N/A	N/A	N/A	N/A	N/A
Thermal TOTAL								**0.9972**
POWER	PCDU	1	internal (section level)	26280	206	0.0000002055	0.994613036	0.9946
POWER	Batterie	1	23/24 hot (6s cell string)	2628	271	0.0000002708	0.999288486	0.9999
POWER	Solar Array, centre panel	1	16/17 hot (21s cell string)	26280	5	0.0000000049	0.999870317	1.0000
POWER	Solar Array, side panel	2	None, 26/26 (21s cell string)	26280	5	0.0000000049	0.999870317	0.9933
POWER TOTAL								**0.9878**
FGS	FGS Module	2	1/2 cold	26280	1500	0.0000015	0.9613	**0.9992**
FGS								**0.999**
Harness TOTAL								**1.000**
SVM TOTAL								**0.9080**
CRYOGENICS	Ne sorption Cooler	2	1/2 cold	26280	2000	0.000002	0.948797392	0.9985
CRYOGENICS	Radiators&Shield	1	N/A	N/A	N/A	N/A	N/A	N/A
CRYOGENICS	Tel Decontamination	1	N/A	N/A	N/A	N/A	N/A	N/A
CRYOGENICS								**0.9985**
FGS	Detector FGS	2	1/2 cold	26280	100	0.0000001	0.9974	1.0000
FGS								**1.0000**
TELESCOPE								**1.0000**
VNIR SPEC.								**0.9750**
SWIR SPEC.								**0.9750**
MWIR SPEC.								**0.9750**
INSTRUMENTS								**0.9269**
PLM TOTAL								**0.925**
Launch & Deploy								**0.9800**
Mission Total								**0.8236**

Conclusions

- Risk Areas
  - **Mission:** Insufficient number of science targets. **Platform:** Detector tech. development, cryogenics.
  - **Payload:** AOCS tech. development, including MB-RW.
- ESM CDF Reliability Prediction:

82% @ 3 years

Detailed information is provided in the CDF Report