M5 SPICA

CDF Study Executive Summary

Prepared by ESA Study and the CDF* Teams

(*) ESTEC Concurrent Design Facility

Introduction

Background & Mission Objectives

- Request of SCI-FM/FI to perform a preliminary mission design for SPICA, one of the three M5 candidates.

- SPICA:
  - joint European-Japanese project
  - offers significant improvement in far-infrared spectroscopic and survey capabilities over NASA's Spitzer and ESA's Herschel space observatories, ensure continuing advances in this field.
  - complement the capabilities of existing and foreseen major observatories, such as the ground-based Atacama Large Millimetre/submillmetre Array and the space-based Webb telescope.

- Launch 2032 with JAXA's new H3 launcher.

Responsibilities

ESA

- Mission Prime
- SVM
- Science Instrument Assembly (SIA), incl. Telescope
- Mission Operations Centre + Ground Segment (with JAXA Ground Station – TBC)
- Science Operations

JAXA

- Payload Module
  - Cryogenics Assembly (JAXA)
  - SIA (ESA)
  - Instruments (SMI = JAXA, Safari = SRON, POL = SCEA)
- Launch
- Ground Station for Mission Operations (TBC)
- Share in Science Operations

Systems

Requirements and Design Drivers

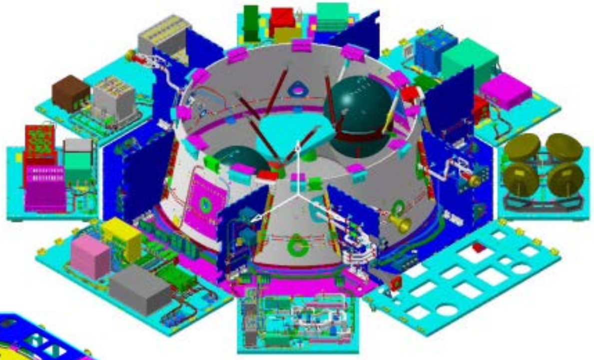
- General Mission and System requirements
  - Launch in 2032
  - Orbit around Sun-Earth L2 point
  - 3 years nominal mission lifetime, with 5 years goal
- Design drivers
  - Telescope diameter of 2.5m
  - Active cooling of the telescope below 8K (instrument heads down to 4.8K and 1.8K), passive cooling to 40K
  - Launcher: H3-22L from Tanegashima Space Center (JP) provided by JAXA
  - Procurement and AIV/AIT responsibilities shared among JAXA, ESA and Instrument Consortia
  - Compatibility with an M-size mission
  - TRL5 by mission selection and TRL6 by mission adoption

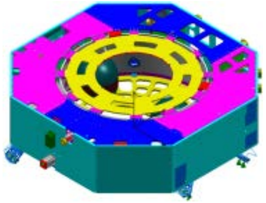
Reference Studies and Heritage

- CDF NG-CryoIRTel Study, Ref: CDF-152(A) from Dec 2014
  - Telescope, thermal cryo, AOCS and communications trade-offs
  - Baseline design for both PLM and SVM
- SPICA M5 proposal
  - Baseline design in line with NG-CryoIRTel study
  - Telescope diameter increased from 2m to 2.5m
  - Cryogenic cooling relaxed from <6K to <8K
  - Pointing requirements, both absolute and relative, relaxed
  - Added camera/polarimeter instrument – POL
- JAXA’s Conceptual Design Study (Ref: SPICA-PP-15007-2)
- Herschel / Planck and Gaia heritage
  - Herschel and Planck heritage applicable to both, instruments and platform
  - Planck’s configuration and approach to Cryo cooling incl. testing
  - Gaia’s refocusing mechanism for the telescope secondary mirror

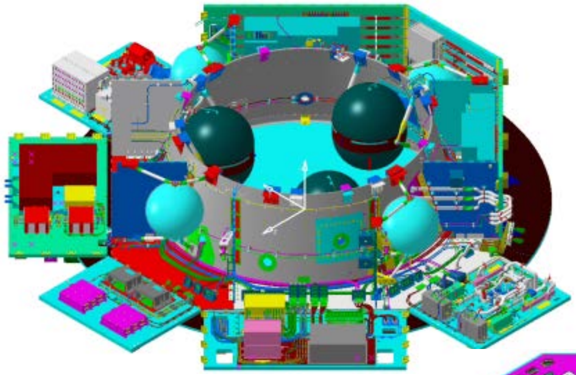
Herschel-Planck SVM Heritage

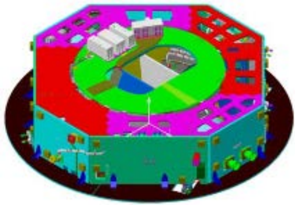
Herschel Configuration





Planck Configuration





Relevant Commonalities

- House avionics equipment and servicing subsystems, as well as the "warm" units of the payload instruments
- Support the PLM Cryogenic system
- Provides mechanical interface to the launcher adapter

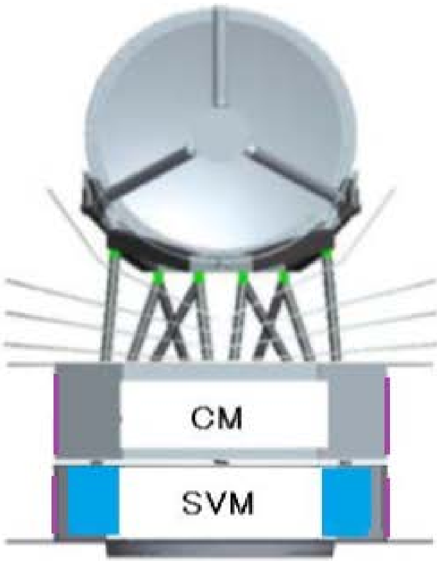
System Level Trade-offs

- Telescope: Ritchey-Chretien vs On-axis or off-axis Korsch
  - Impact on optical characteristics at focal plane
- Operational orbit: Halo vs Lissajous
  - Reduction of Earth illumination constraints
  - Minimize impact on delta-V and propellant mass
- Conventional AOCS vs need for a dedicated Attitude Sensor
  - Critically assess pointing requirements
  - Minimize impact on cost and complexity
- Accommodation of cryo-units: level of integration with/in the SVM
  - Reduction of mass and volume
  - Minimize impact on procurement and AIV/AIT plans

System Options

1st

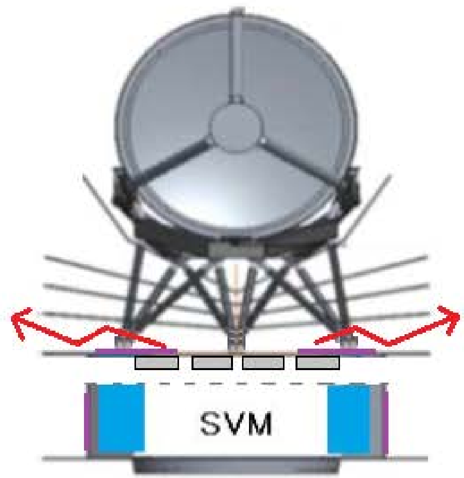
M5 Proposal



Extended PLM

Cryo-coolers and Instrument warm units in CM (PLM radiators in PLM)

4th

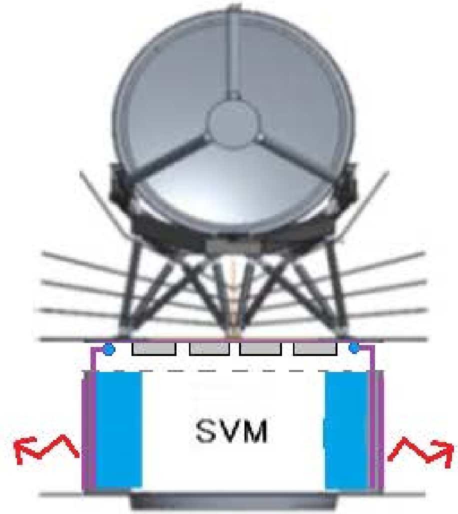


Compact PLM

Cryo-coolers in PLM and Instrument warm units in SVM (PLM radiators in PLM)

3rd

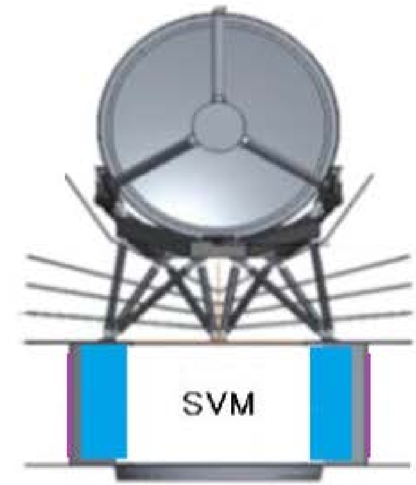
CDF Baseline



Hybrid PLM

Cryo-coolers mounted on PLM bottom panel and Instrument warm units in SVM (PLM radiators in SVM with LHP I/F)

2nd



Modified PLM

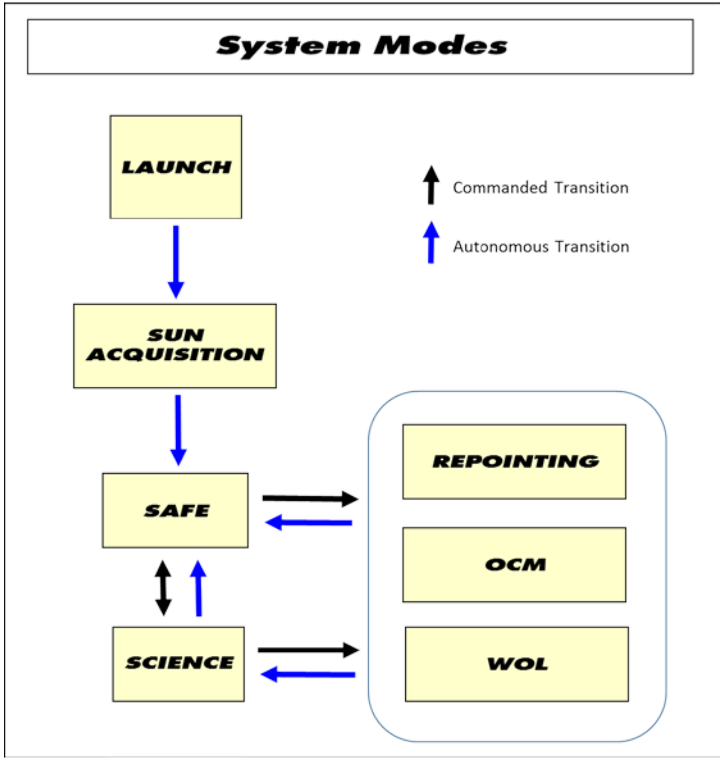
Cryo-coolers and Instrument warm units fully integrated in SVM (all radiators in SVM)

Mission Phases

- Launch & Early Operation Phase (less than 1 day, max. 2 days)
- Transfer to L2 and insertion in Halo orbit
  - Transfer correction manoeuvre (max. 2 days after launch)
  - Commissioning (max. 3 months, after max. 1 week decontamination)
  - Cryo-cooling of SIA (to be finished max. 6 months after launch)
- Instrument performance verification (to be finished max. 6 months after launch)
- Nominal Operation (2.5 years)
- Extended Operation (2 years)
- Decommissioning (2 weeks)

System Modes

- Launch
- Sun Acquisition
  - Attitude control on RCS
- Safe*
  - Sun pointing (attitude control on RCS)
  - Comms via HGA
- Science
  - Instrument calibration and nominal operation
  - Comms via LGA only
- Science with Comms
  - Same as Science plus comms via HGA
- Repointing
  - Slew between targets
- Orbit Correction Manoeuvre (OCM)
- Wheels Off-Loading (WOL)



* Additional Stand-by and Survival modes could be considered to, respectively, use RW instead of RCS (to minimize propellant use) or lower cryo-coolers duty cycle (to minimize power needs).

Instruments' Budgets

Resources \ Modes	SAFARI	POL	SMI	
Volume				
Focal-plane unit(s)	1200x1200x500	465x720x450	LR-CAM: 1030x520x230 MR-HR: 1040x790x230	mm^3
Warm unit(s)	ICU: 380x330x270 DPU: 380x330x250 WFEE: 380x330x100	DPU: 250x260x200 BOL WFEE:390x290x340	LR-CAM: 400x300x280 MR-HR: 400x300x280	mm^3
Mass				
Focal-plane unit(s)	125	20	50.8	kg
Warm unit(s)	36	25	37	kg
Duty cycle				
Mission share	65.45%	4.55%	30.00%	
Within a 24h cycle				
RECYCLING/ANNEALING	7.2	4	4	h/day
CALIBRATION + OBSERVATION	16.8	20	20	h/day
Observation efficiency	100.00%	100.00%	84.00%	
Power Consumption (best estimates w/o margins)				
Warm unit(s)				
OFF	0	0	0	W
STAND-BY	140	68	35	W
RECYCLING/ANNEALING	140	83	35	W
CALIBRATION + OBSERVATION	140	70	35	W
Data Generation				
Housekeeping				
OFF	0	0	0	kbps
STAND-BY	128	15	15	kbps
CALIBRATION + OBSERVATION	128	15	15	kbps
Science				
OFF	0	0	0	Mbps
STAND-BY	0	0	0	Mbps
CALIBRATION + OBSERVATION	4	1	5.67	Mbps
Peak to DHS	4	1	20	Mbps

	SAFARI	POL	SMI	
Thermal				
2ST / Mid-temp (20K, TBC) stage				
OFF	0	0	8.3	mW
STAND-BY	0	0	8.3	mW
RECYCLING/ANNEALING	0	0	8.3	mW
CALIBRATION + OBSERVATION	0	20	26.8	mW
4K-JT stage				
OFF	-0.24	0.45	0.32	mW
STAND-BY	-0.24	0.45	0.32	mW
RECYCLING/ANNEALING	14	10.4	10	mW
CALIBRATION + OBSERVATION	14	1.23	3.14	mW
1K-JT stage				
OFF	2	0.69	0.29	mW
STAND-BY	2	1.1	0.29	mW
RECYCLING/ANNEALING	5.5	4.2	3.1	mW
CALIBRATION + OBSERVATION	5.5	1.1	2.83	mW

	MAXIMUM	CYCLE AVERAGE	MISSION AVERAGE	
Resources				
Power Consumption	258	247.1666667	243.1893939	W
Data Generation: Housekeeping	158	158	158	kbps
	N/A	13.6512	13.6512	Gbit/day
Data Generation: Science	5.67	3.969	3.061306061	Mbps
	N/A	342.9216	264.4968436	Gbit/day
2ST stage	28.3	24.96666667	13.68257576	mW
4K-JT stage	14.77	14.77	11.14465152	mW
1K-JT stage	6.89	6.89	6.479893939	mW

NOTE: These values are based on best estimates, i.e. with no maturity/system margins, as provided by the PI consortia for the sole purpose of the CDF study.

Instruments’ Pointing Requirements

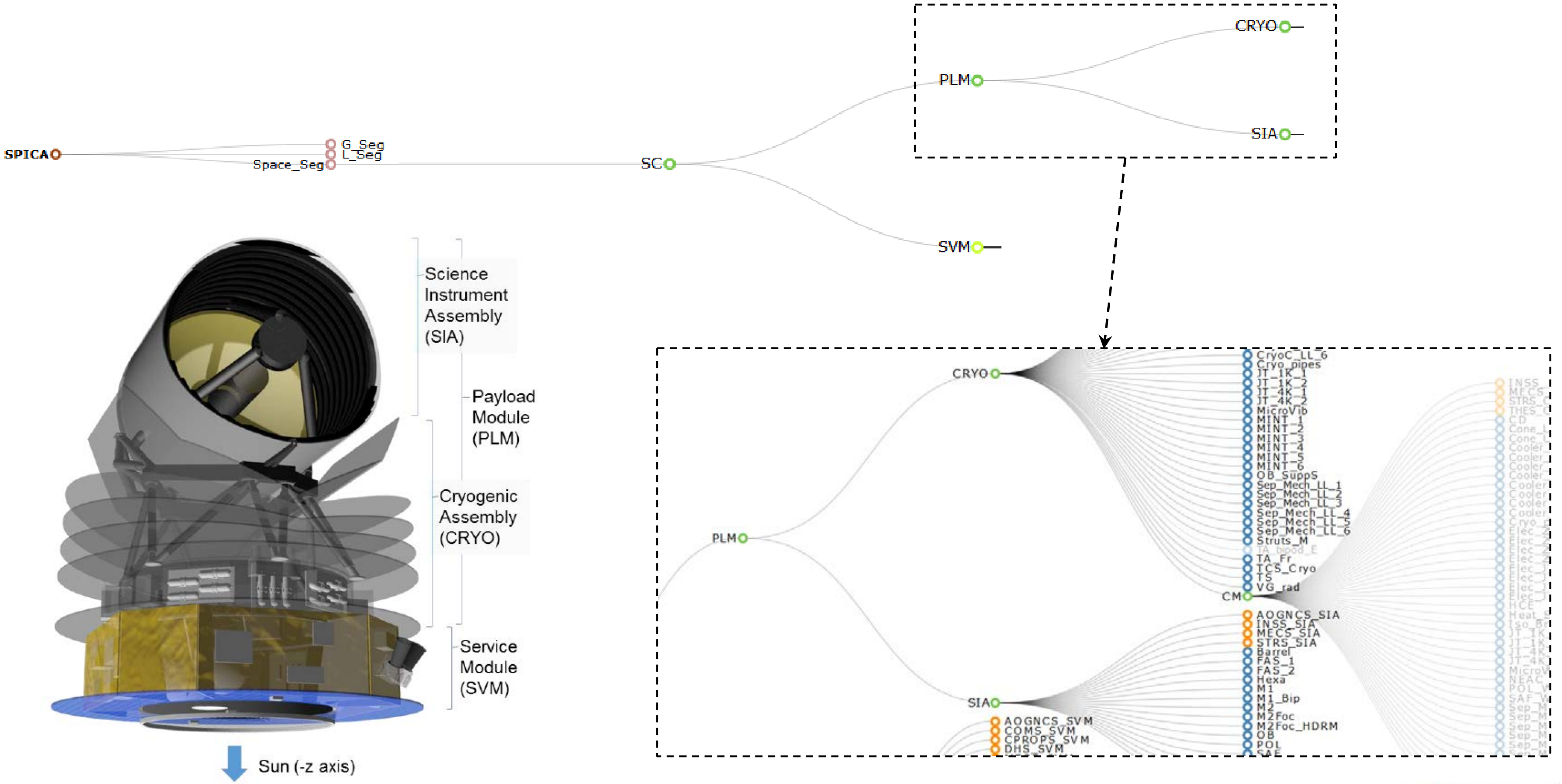
Values provided at start of CDF study (changes since M5 proposal in red):

Instrument	Slit Width	MPE (3σ)	RPE (0-p,3σ)	AKE (3σ)
SMI/LR	3.7”	0.92”	0.79” (>600 s)	0.37”
SMI/MR	3.7”	0.92”	0.84” (>600 s)	0.37”
SMI/HR	1.7”	0.44”	0.44” (>600 s)	0.17”
SAFARI	**4.5”**	1.5”	0.15” (>200 s)	0.15”
POL	N/A	1.0”	0.3” (>3600 s)	0.30”
System level		0.44”	0.15” (>200 s)	0.15”

During the CDF study an effort has been made to better understand and characterize the relevant pointing accuracy figures, both relative and absolute, required by each instrument based on their specs and observation modes.

Further detailed information has been gathered from all PI consortia to support the AOCS dedicated Attitude Sensor trade-off, although the full consolidation of these figures has not being fully achieved within the time and scope of the study.

System Architecture (OCDT Model)



Mass Budget (CDF Baseline option / H-PLM)

		Element properties		Level 4
Element Definition short name:		PLM		
Element Definition long name:		Payload Module		
Subsystem	**Switch**	**PLM Mass Budget**		**Mass [kg]**
AOGNC	Product	Attitude, Orbit, Guidance, Navigation Control		16.80
COM	Not used	Communications		0.00
CPROP	Not used	Chemical Propulsion		0.00
DH	Not used	Data-Handling		0.00
EPROP	Not used	Electric Propulsion		0.00
INS	Product	Instruments		234.96
MEC	Product	Mechanisms		49.29
STR	Product	Structures		911.17
SYE	Not used	System Engineering		0.00
TC	Product	Thermal Control		263.71
		Harness	5%	73.80
		Dry Mass w/o System Margin		**1549.73**

		Element properties		Level 4
Element Definition short name:		SVM		
Element Definition long name:		Service Module		
Subsystem	**Switch**	**SVM Mass Budget**		**Mass [kg]**
AOGNC	Product	Attitude, Orbit, Guidance, Navigation Control		81.94
COM	Product	Communications		25.55
CPROP	Product	Chemical Propulsion		56.35
DH	Product	Data-Handling		32.03
EPROP	Not used	Electric Propulsion		0.00
INS	Product	Instruments		117.60
MEC	Product	Mechanisms		7.70
PWR	Product	Power		85.67
STR	Product	Structures		535.20
SYE	Not used	System Engineering		0.00
TC	Product	Thermal Control		176.37
		Harness	10%	111.84
		Dry Mass w/o System Margin		**1230.24**

S/C Mass Budget		**Mass [kg]**
Dry Mass PLM		**1549.73**
Dry Mass SVM		**1230.24**
System Margin	20%	555.99
Dry Mass incl. System Margin		**3335.96**
CPROP Fuel Mass		341.77
CPROP Fuel Margin	2%	6.84
CPROP Pressurant Mass		0.77
CPROP Pressurant Margin	2%	0.02
Total Wet Mass		**3685.35**
Target Wet Mass		3700.00
Below Target Mass by		14.65

PLM Assemblies (CDF Baseline option / H-PLM)

		Element properties	Level 5
Element Definition short name:		CRYO	
Element Definition long name:		Cryogenic Assembly	
Subsystem	**Switch**	**CRYO Mass Budget**	**Mass [kg]**
AOGNC	Not used	Attitude, Orbit, Guidance, Navigation Control	0.00
COM	Not used	Communications	0.00
CPROP	Not used	Chemical Propulsion	0.00
DH	Not used	Data-Handling	0.00
EPROP	Not used	Electric Propulsion	0.00
INS	Not used	Instruments	0.00
MEC	Product	Mechanisms	39.69
STR	Product	Structures	377.77
SYE	Not used	System Engineering	0.00
TC	Product	Thermal Control	263.71
		Harness 0%	0.00
		Dry Mass w/o System Margin	**681.17**

		Element properties	Level 5
Element Definition short name:		SIA	
Element Definition long name:		Science Instrument Assembly	
Subsystem	**Switch**	**SIA Mass Budget**	**Mass [kg]**
AOGNC	Product	Attitude, Orbit, Guidance, Navigation Control	16.80
COM	Not used	Communications	0.00
CPROP	Not used	Chemical Propulsion	0.00
DH	Not used	Data-Handling	0.00
EPROP	Not used	Electric Propulsion	0.00
INS	Product	Instruments	234.96
MEC	Product	Mechanisms	9.60
STR	Product	Structures	533.40
SYE	Not used	System Engineering	0.00
TC	Not used	Thermal Control	0.00
		Harness 0%	0.00
		Dry Mass w/o System Margin	**794.76**

Mass Budget (M5 proposal option / E-PLM)

Element properties			Level 4
Element Definition short name:		PLM	
Element Definition long name:		Payload Module	
Subsystem	**Switch**	**PLM Mass Budget**	**Mass [kg]**
AOGNC	Product	Attitude, Orbit, Guidance, Navigation Control	16.80
COM	Not used	Communications	0.00
CPROP	Not used	Chemical Propulsion	0.00
DH	Not used	Data-Handling	0.00
EPROP	Not used	Electric Propulsion	0.00
INS	Product	Instruments	352.56
MEC	Product	Mechanisms	57.69
PWR	Not used	Power	0.00
STR	Product	Structures	1320.13
SYE	Not used	System Engineering	0.00
TC	Product	Thermal Control	408.67
		Harness 5%	107.79
		Dry Mass w/o System Margin	**2263.64**

Element properties			Level 4
Element Definition short name:		SVM	
Element Definition long name:		Service Module	
Subsystem	**Switch**	**SVM Mass Budget**	**Mass [kg]**
AOGNC	Product	Attitude, Orbit, Guidance, Navigation Control	81.94
COM	Product	Communications	25.55
CPROP	Product	Chemical Propulsion	56.35
DH	Product	Data-Handling	32.03
EPROP	Not used	Electric Propulsion	0.00
INS	Not used	Instruments	0.00
MEC	Product	Mechanisms	7.70
PWR	Product	Power	85.67
STR	Product	Structures	434.28
SYE	Not used	System Engineering	0.00
TC	Product	Thermal Control	18.22
		Harness 10%	74.17
		Dry Mass w/o System Margin	**815.91**

S/C Mass Budget		**Mass [kg]**
Dry Mass PLM		**2263.64**
Dry Mass SVM		**815.91**
System Margin	20%	615.91
Dry Mass incl. System Margin		**3695.46**
CPROP Fuel Mass		341.77
CPROP Fuel Margin	2%	6.84
CPROP Pressurant Mass		0.77
CPROP Pressurant Margin	2%	0.02
Total Wet Mass		**4044.85**
Target Wet Mass		3700.00
Below Target Mass by		-344.85

PLM Assemblies (M5 proposal option / E-PLM)

Element properties			Level 5
Element Definition short name:		CRYO	
Element Definition long name:		Cryogenic Assembly	
Subsystem	**Switch**	**CRYO Mass Budget**	**Mass [kg]**
AOGNC	Not used	Attitude, Orbit, Guidance, Navigation Control	0.00
COM	Not used	Communications	0.00
CPROP	Not used	Chemical Propulsion	0.00
DH	Not used	Data-Handling	0.00
EPROP	Not used	Electric Propulsion	0.00
INS	Product	Instruments	117.60
MEC	Product	Mechanisms	48.09
PWR	Not used	Power	0.00
STR	Product	Structures	786.73
SYE	Not used	System Engineering	0.00
TC	Product	Thermal Control	408.67
		Harness 0%	0.00
		Dry Mass w/o System Margin	**1361.09**

Element properties			Level 5
Element Definition short name:		SIA	
Element Definition long name:		Science Instrument Assembly	
Subsystem	**Switch**	**SIA Mass Budget**	**Mass [kg]**
AOGNC	Product	Attitude, Orbit, Guidance, Navigation Control	16.80
COM	Not used	Communications	0.00
CPROP	Not used	Chemical Propulsion	0.00
DH	Not used	Data-Handling	0.00
EPROP	Not used	Electric Propulsion	0.00
INS	Product	Instruments	234.96
MEC	Product	Mechanisms	9.60
PWR	Not used	Power	0.00
STR	Product	Structures	533.40
SYE	Not used	System Engineering	0.00
TC	Not used	Thermal Control	0.00
		Harness 0%	0.00
		Dry Mass w/o System Margin	**794.76**

Element properties			Level 6
Element Definition short name:		CM	
Element Definition long name:		Cooler Module	
Subsystem	**Switch**	**CM Mass Budget**	**Mass [kg]**
AOGNC	Not used	Attitude, Orbit, Guidance, Navigation Control	0.00
COM	Not used	Communications	0.00
CPROP	Not used	Chemical Propulsion	0.00
DH	Not used	Data-Handling	0.00
EPROP	Not used	Electric Propulsion	0.00
INS	Product	Instruments	117.60
MEC	Not used	Mechanisms	0.00
PWR	Not used	Power	0.00
STR	Product	Structures	379.20
SYE	Not used	System Engineering	0.00
TC	Product	Thermal Control	408.67
		Harness 0%	0.00
		Dry Mass w/o System Margin	**905.47**

System Mass Breakdown History Comparison

			CDF NGCRYO	JAXA			CDF SPICA		
			M-PLM	E-PLM	M-PLM	Delta	E-PLM	H-PLM	Delta
SVM			1193	776	1088	312	816	1230	414
	POW		90	90	90		86	86	
	COM		22	22	22		26	26	
	DHS		33	33	33		32	32	
	AOCS*		71	71	71		82	82	
	PROP		89	89	89		56	56	
	STR		375	298	412	114	434	535	101
	THE		354	64	138	74	18	176	158
	MEC		12	12	12		8	8	
	INST*		59	0	124	124	0	118	118
	SVM Harness		88	97	97		74	112	
PLM			1060	2287	1823	-464	2264	1550	-714
	SIA		N/A	950	950		795	795	
		AOCS					17	17	
		STR					533	533	
		MEC					10	10	
		INST	120	240	240		235	235	
	CRYO		N/A	1337	873	-464	1361	681	-680
		STR					787	378	-409
		THE					409	264	-145
		MEC					48	40	
		INST*	0	124	0	-124	118	0	-118
	PLM Harness						108	74	
Dry mass w/ maturity margins			2252	3063	2911	-152	3080	2779	-300
System margin (ESA: 20%, JAXA: 15%)			450	459	437		616	556	
Total dry mass			2703	3522	3348		3696	3335	
Propellant & Pressurant w/ margins			313	353	335		349	349	
Total wet mass			3016	3875	3683	-193	4045	3684	-361
Target launch mass			3500	3700	3700		3700	3700	
Below mass target			484	-175	17	193	-345	16	361

Payload Mass Breakdown History Comparison

	SAF	POL	SMI	TOTAL w/o margins	TOTAL w/ margins	
	CDF NG-Cryo					
	SAF	POL	SMI	TOTAL w/o margins	TOTAL w/ margins	
Optic units	55.0	0.0	45.1	100	120	
Warm units	25.0	0.0	24.0	49	59	
					179	
	M5 Proposal					
	SAF	POL	SMI	TOTAL w/o margins	TOTAL w/ margins	
Optic units	125.0	12.0	47.9	185	222	
Warm units	43.0	16.0	35.0	94	113	
					335	
	JAXA					
	SAF	POL	SMI	TOTAL w/o margins	TOTAL w/ margins	With FAS*
Optic units	125.0	12.0	50.8	188	225	240
Warm units	36.0	16.0	36.7	89	106	124
					332	**364**
	CDF SPICA					
	SAF	POL	SMI	TOTAL w/o margins	TOTAL w/ margins	
Optic units	125.0	20.0	50.8	196	235	
Warm units	36.0	25.0	37.0	98	118	
					353	

FAS electronics already included in NGCryo/SVM/AOCS, so it was counted twice (ESA: 20kg, JAXA: 17kg).

System Budgets Breakdown per Ownership

- The system product tree model has been populated with ownership information
  - This includes ESA and JAXA agencies, and SAFARI, POL and SMI Consortia
  - This allows generating budget breakdown reports for each module or assembly filtering per ownership

JAXA	Total Mass		Parameter	ownership
	96		Value	JAXA
Equipment	**Mass (kg)**		**Row Labels**	
Cooler_2ST_1 (CryoCooler_2ST #1)	12		Cooler_2ST_1 (CryoCooler_2ST #1)	
Cooler_2ST_2 (CryoCooler_2ST #2)	12		Cooler_2ST_2 (CryoCooler_2ST #2)	
Cooler_2ST_3 (CryoCooler_2ST #3)	12		Cooler_2ST_3 (CryoCooler_2ST #3)	
Cooler_2ST_4 (CryoCooler_2ST #4)	12		Cooler_2ST_4 (CryoCooler_2ST #4)	
Cooler_2ST_5 (CryoCooler_2ST #5)	12		Cooler_2ST_5 (CryoCooler_2ST #5)	
Cooler_2ST_6 (CryoCooler_2ST #6)	12		Cooler_2ST_6 (CryoCooler_2ST #6)	
Cooler_2ST_7 (CryoCooler_2ST #7)	12		Cooler_2ST_7 (CryoCooler_2ST #7)	
Cooler_2ST_8 (CryoCooler_2ST #8)	12		Cooler_2ST_8 (CryoCooler_2ST #8)	

Mission Analysis

Mission Analysis

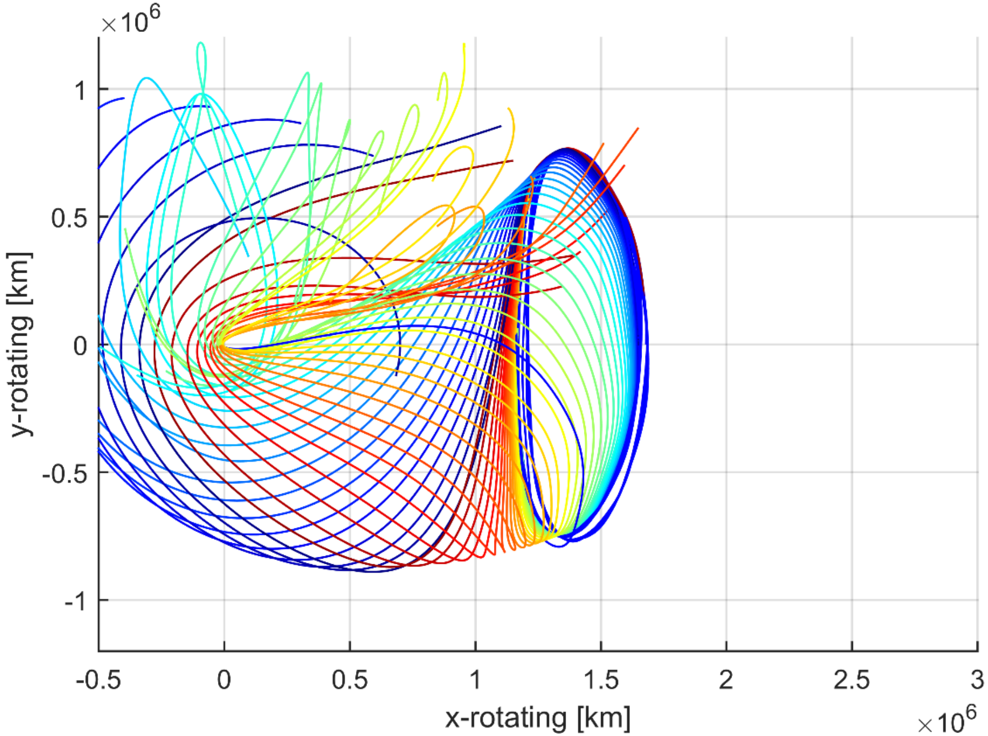
- Requirement: Find the appropriate science orbit and the associated DeltaV budget

- Science Orbit Trades:
  - Free transfer Large Amplitude Quasi Halo Orbit (JWST, Euclid, Herschel, Plato, etc.)
  - Small amplitude Lissajous Orbit (Gaia, Gaia NIR, Planck, etc.)
  - Orbit size is defined by Sun-S/C-Earth angle (SSCE)

- DeltaV budget will strongly depend on the assumptions for the launcher and spacecraft

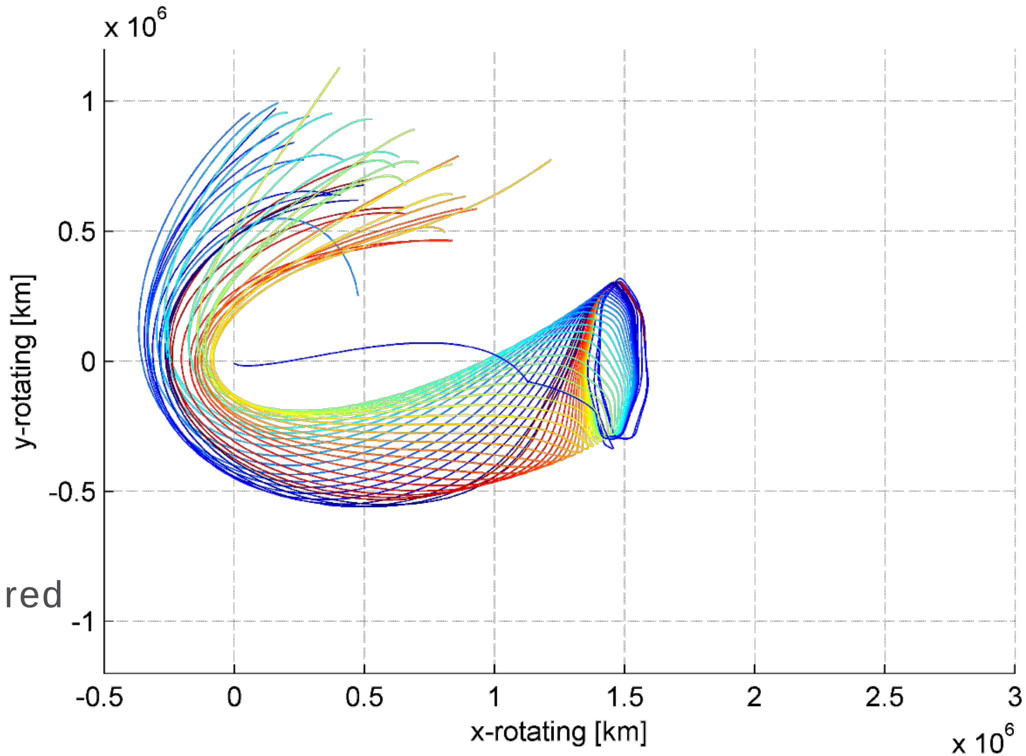
Orbit Option 1: Large Amplitude Quasi-Halo Orbit

- No orbit injection manoeuvre required
- Stable manifold of the orbit intersects with the near Earth environment
- Direct ascent trajectory can usually provide an all year launch window if argument of perigee value is correct
- Orbits are eclipse free



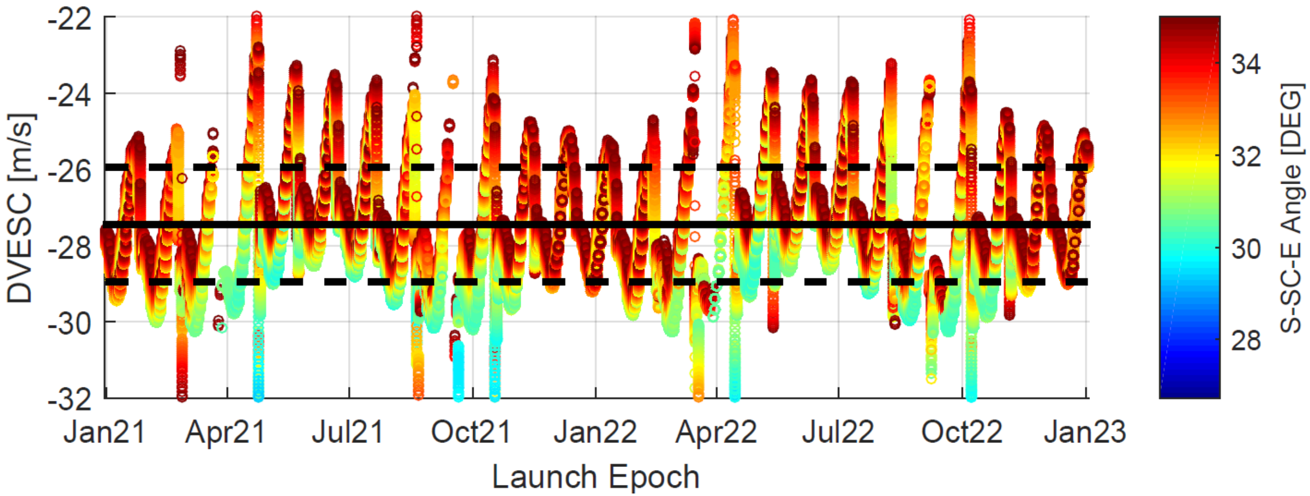
Orbit Options 2: Small Amplitude Lissajous Orbit

- Orbit injection manoeuvre required, size depends on required amplitude reduction
  - Stable manifold does not intersect with the Earth
  - Fast and slow transfer options available
- For an all year launch window a circular parking orbit is required with the option to select the drift duration (gives free choice in argument of perigee)
- Eclipse avoidance manoeuvres required Frequency depends on size



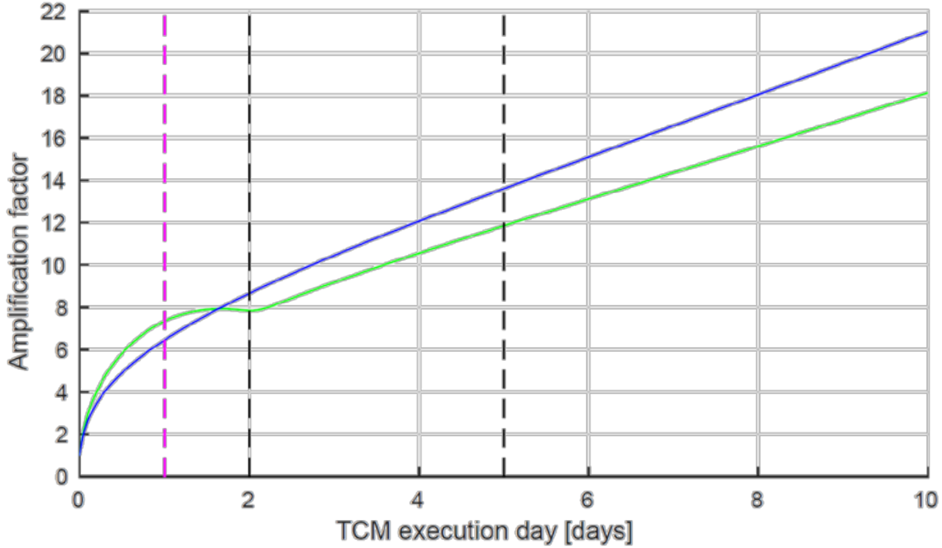
Injection onto Stable Manifold

- Perigee velocity is usually pre-programmed into the launcher
- Actual stable manifold velocity depends on the phasing with the moon
- Deviation between pre-programmed and required velocity must be corrected by the S/C
- Additionally the launcher dispersion must be corrected



Transfer Correction Manoeuvre 1

- The pre-programmed perigee velocity as well as the launcher dispersion need to be corrected as soon as possible due to the amplification of the error
  - ESOC assumes a correction at day-1, 24 hours after separation
  - The DeltaV budget assumes a correction at day-2, 48 hours after separation (perigee errors will be amplified by a factor of 9)



Station-Keeping

- Orbit maintenance or station-keeping DeltaV requirements will heavily depend on the noise environment of the S/C
- Typical values range from 0.7-7 m/s/year
- The actual value will depend on the residual acceleration environment of the S/C as well as the predictability of the direction of the residual acceleration
  - Balanced thruster configuration with no residual acceleration for attitude vs. unbalanced thruster configuration
  - Well known attitude profile and well characterized propulsion system (e.g. Gaia)
  - Venting of Helium into space with no a-priori defined direction (e.g. Herschel)
- Drastic Station Keeping cost reduction to around 1 m/s/year requires
  - a constraint on the residual acceleration of the S/C
  - or make the accelerations completely predictable in the long term (no target of opportunity).

Simplified DeltaV Budget

Lissajous orbit DV is optional – Quasi Halo is baseline

	Example values – Ariane 5/6, Large amplitude Quasi Halo, noisy S/C	Suggested margin	Double on biased trajectory
• Flight program correction			
– 1.5 m/s * 9	13.5 m/s	10%	Yes
• Launcher dispersion correction			
– 3-4.5 m/s * 9 (JAXA 5.28 m/s)	40.5 m/s (JAXA 47.56 m/s)	0%	Yes
• Correction of TCM#1			
– 0.1 * TCM#1	5.4 m/s (JAXA 6.1 m/s)	10%	Yes
• Lissajous orbit insertion			
– 12 m/s/(DEG SSCE)	168 m/s (28->14 Deg)	10%	NO
• Station-Keeping			
– 0.7-7 m/s/year	35 m/s	50%	Yes
• Disposal			
– 10 m/s	10 m/s	10%	Yes
• Eclipse avoidance			
– 15 m/s	15 m/s	10%	Yes

Propulsion System Design Trade

- Biased vs. non-biased trajectory
- In some cases the thruster layout is desired to not point towards the payload module to avoid contamination
  - Thrust can only be provided into the anti-Sun direction
  - The trajectory can be biased that manoeuvres are executed only into the anti-sun direction
- Applied e.g. on JWST and Gaia (although due to propulsion system reasons)

- Consequence: The entire DeltaV budget must be doubled with the exception of the Lissajous orbit insertion manoeuvre

- Mission Analysis provides geometric DeltaV values – efficiencies must be taken into account by propulsion

Optics

Telescope requirements

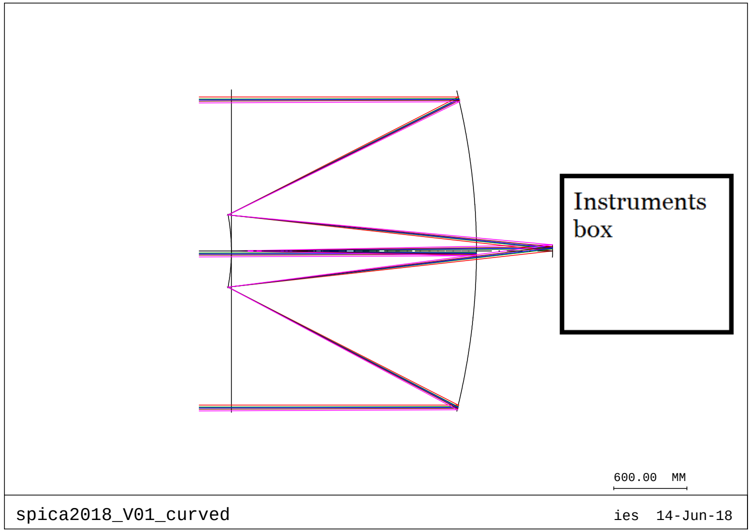
From proposal:

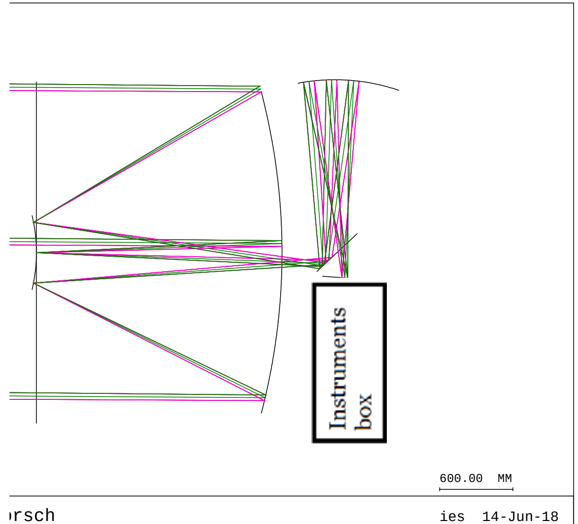
- Entrance pupil diameter 2.5 m
- Infrared light, baseline for requirements 20 µm
- FoV ± 900 arc sec
- Image quality Strehl>0.8 at instrument detector
- Image surface curvature > 600 mm radius

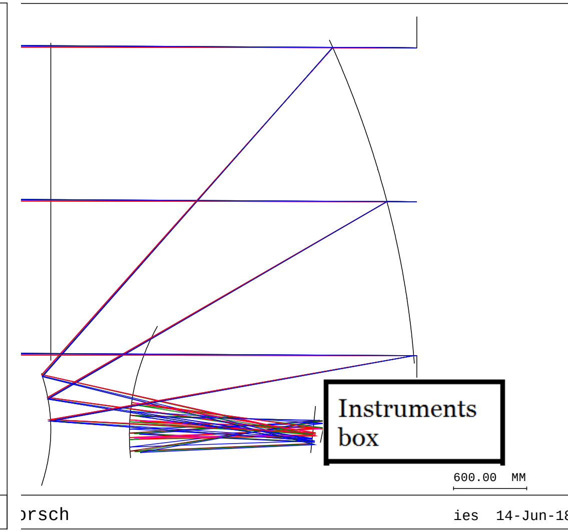
Questions:

- EFL?
- Polarisation?
- Can PSF be elliptical?

Telescope concept options







1
Ritchey-Chretien

2
On axis Korsch
(off axis FoV)

3
Off axis Korsch
(off axis FoV)

TOP VIEW

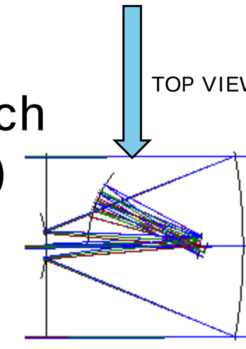
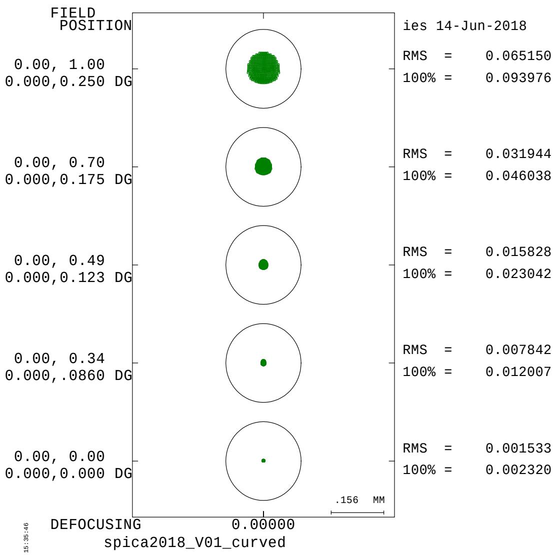
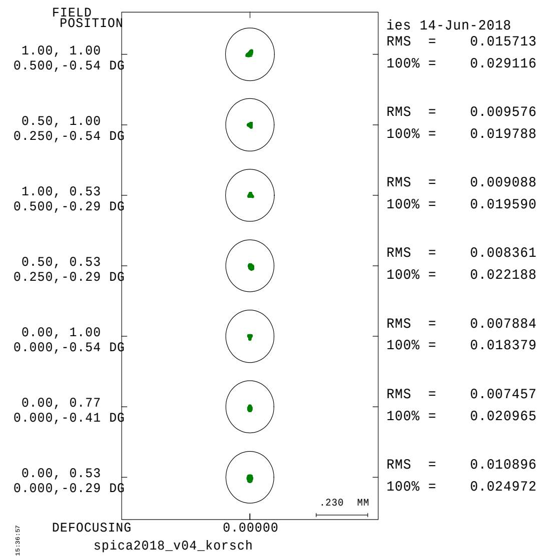


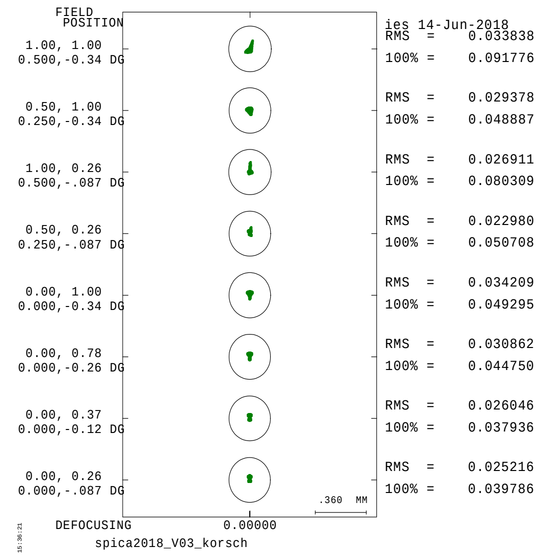
Image at telescope focus



Option 1



Option 2



Option 3

Telescope concepts characteristics

Parameter	Option 1	Option 2	Option 3
EFL (mm)	11415	10958	14960
Field curvature	640	Flat	Flat
FoV	± 0.25°	0.25°x 1°	0.25°x 1°
Strehl ratio	> 0.898	> 0.995	> 0.990
Exit pupil-focus distance (mm)	2636	1228	1036

Proposed trade off

Criterion	Option 1	Option 2	Option 3
Strehl/Field curvature	proposal?	> 0.995/ flat	> 0.990/flat
M1 manufacture	Baseline	Easier manufacture &test	More difficult manufacture/ complex test metrology
Polarisation	No	Some	Some more
Instrument design			
Throughput	Baseline	Worse	Better
Accommodation			

Proposed trade off parameters

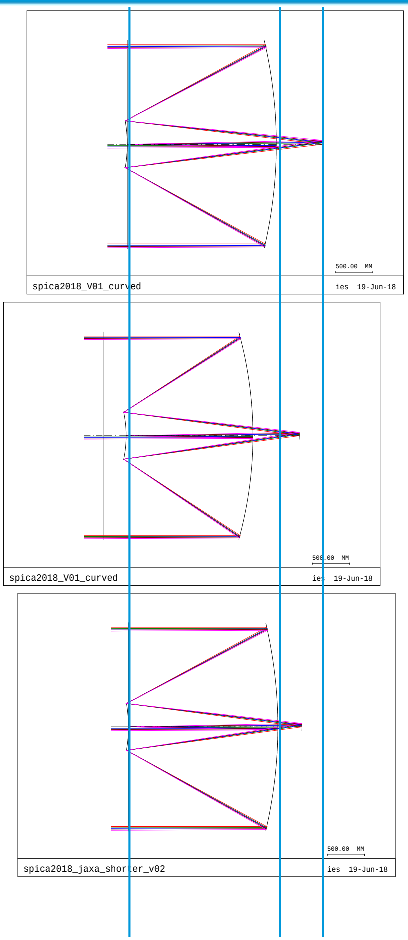
Criterion	Option 1 (M5 Baseline)	Option 2 (on-axis Korsch)	Option 3 (off-axis Korsch)
Strehl/Field curvature	>0.898/ 642 mm	> 0.995/ flat	> 0.990/flat
M1 manufacture	Baseline	Easier manufacture / similar test difficulty	More difficult manufacture/ complex test metrology
Polarisation	No	Some	Some more
Instrument design			
Throughput	Baseline	Worse	Better
Accommodation	M2 visible to the sides		
Mass	Baseline	Show-stopper?	Show-stopper?

Telescope requirements open questions

Possible changes with respect to JAXA baseline design:

1. EFL and f/no – preference for f/5.4 => impacts location of instruments in focal plane
2. Polarisation – looked at it for POL
3. Can PSF be elliptical – not further considered

Ritchey –Chretien length analysis (300 mm shorter)



Option 1:
Jaxa

Option 4:
M1-M2 shorter

Option 5:
M2-focus shorter

If Ritchey-Chretien remains baseline,

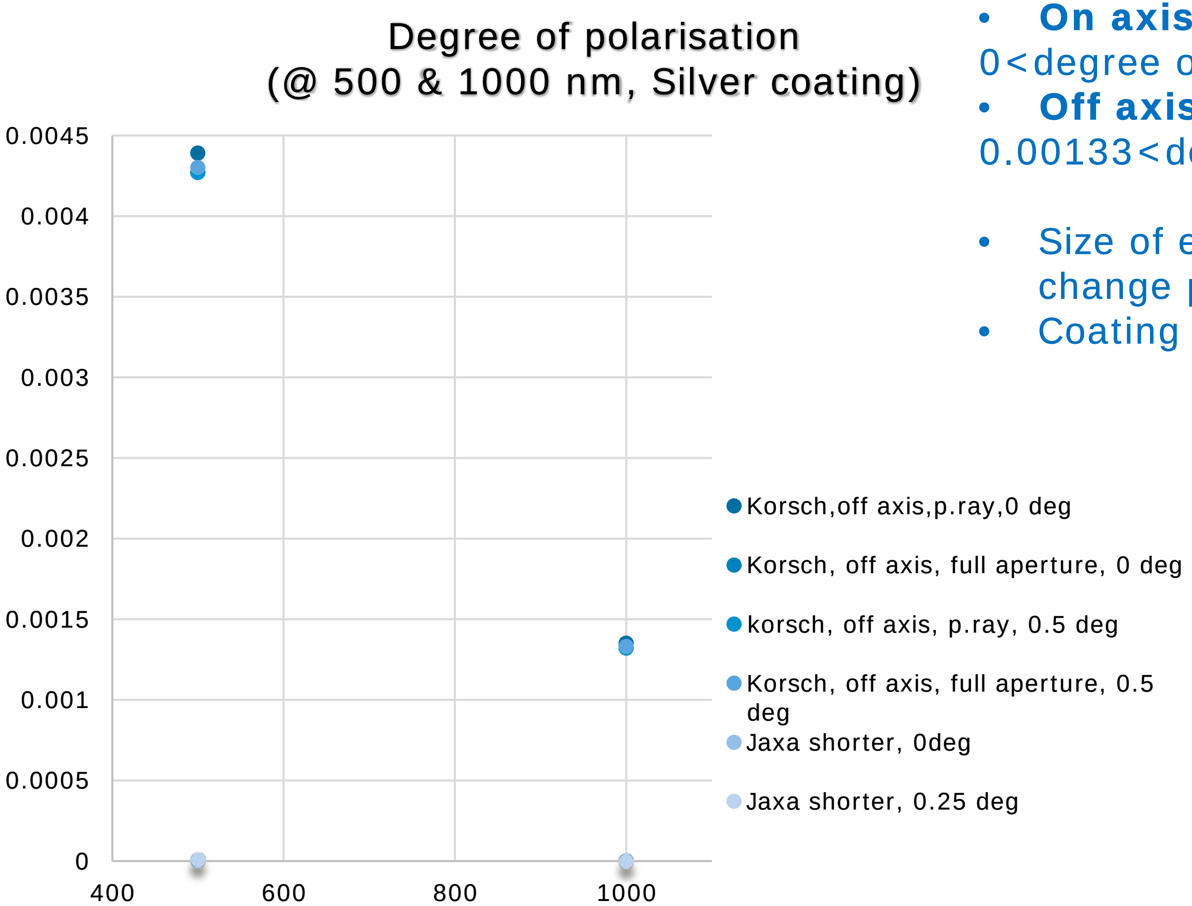
- issues to solve ?
- complications of solutions ?

Parameter	**Jaxa** (Option 1)	**M1-M2 shorter** (Option 4)	**M2-focus shorter** (Option 5)
M2 semi-aperture	294 mm	294 mm	294 mm
M1 radius/K (conic constant)	5229.7 mm/ -1.0323	**4445 mm/ -1.029515**	5229.7 mm/ -1.041
Strehl	>0.898	>0.873	>0.876
Image surface curvature radius	642 mm	550 mm	632 mm
EFL	11415 mm	10150 mm	10116 mm
Instruments accommodation	Baseline (f/4.57)	f/4.06	f/4.05
Fit in shadow cone (Tel. baffle)	No	?	?

Proposed trade off parameters

Criterion	Option 1 (M5 Baseline)	Option 2 (on-axis Korsch)	Option 3 (off-axis Korsch)
Strehl/Field curvature	>0.898/ 642 mm	> 0.995/ flat	> 0.990/flat
M1 manufacture	Baseline	Easier manufacture / similar test difficulty	More difficult manufacture/ complex test metrology
Polarisation	No	Some	Some more
Instrument design			
Throughput	Baseline	Worse	Better
Accommodation	M2 outside shadow cone		
Mass	Baseline	Show-stopper?	Show-stopper?

Degree of polarisation



- **On axis telescope:**

0<degree of polarisation <0.00001

- **Off axis telescope:**

0.00133<degree of polarisation <0.0044

- Size of entrance aperture and field do not change polarisation noticeably
- Coating and λ affect polarisation

Ag, s & p reflectance at 1.937 micron vs AOI

Reflection calculator

Angle of incidence (0~90°): 0

Direction: ◉ in ○ out

Reflectance (at 1.937 µm) [i]

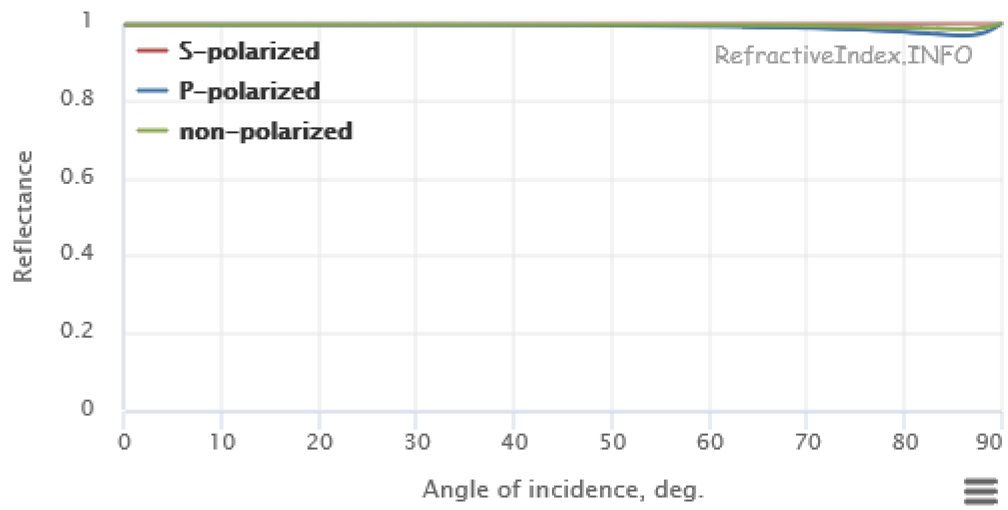
$R = 0.99519$

Reflection phase [i]

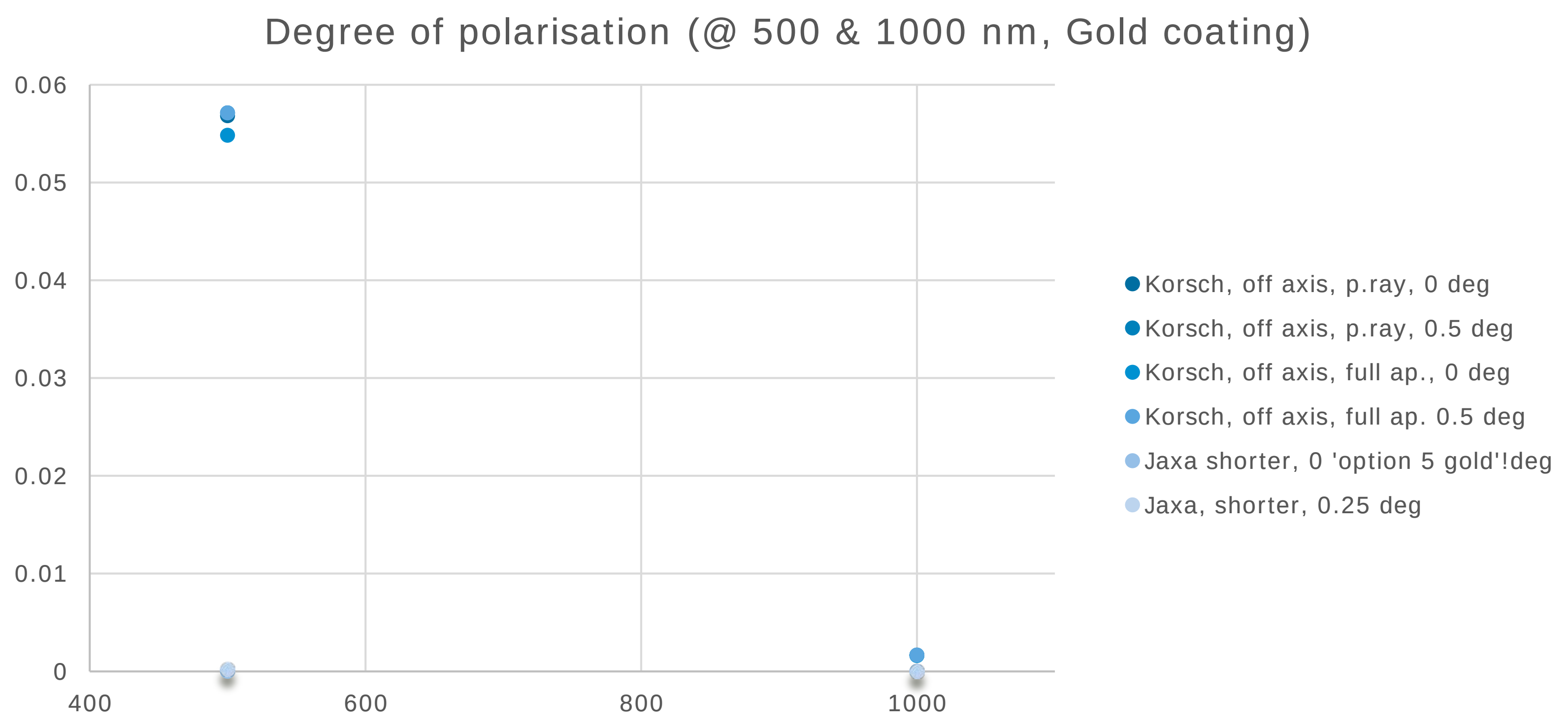
$\phi = -171.877°$

Brewster's angle [i]

$\theta_B = 85.938°$



Degree of polarisation with Au coating



Au- Gold, s & p Reflectance vs AOI

Reflection calculator

Angle of incidence (0~90°): 0

Direction: (•) in ( ) out

Reflectance (at 1.937 µm) [i]

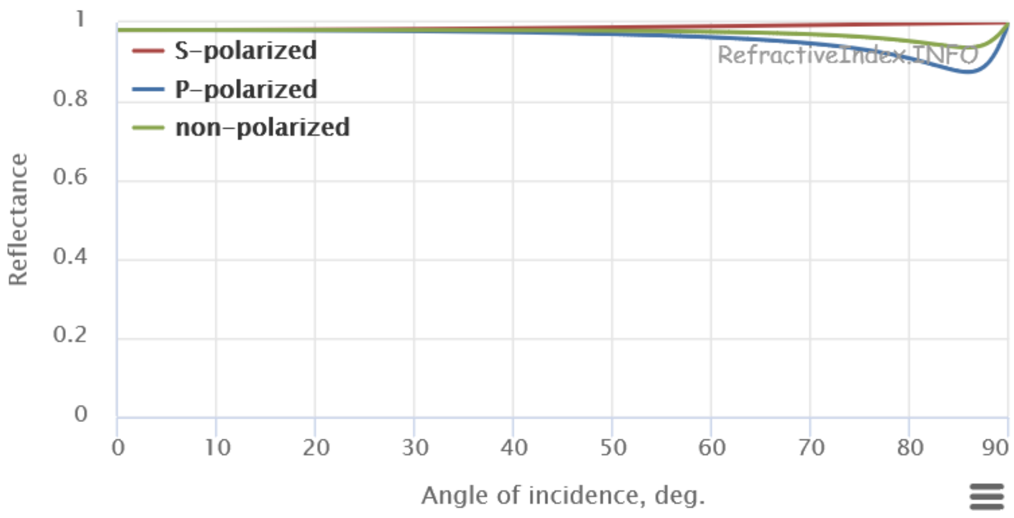
$R = 0.98099$

Reflection phase [i]

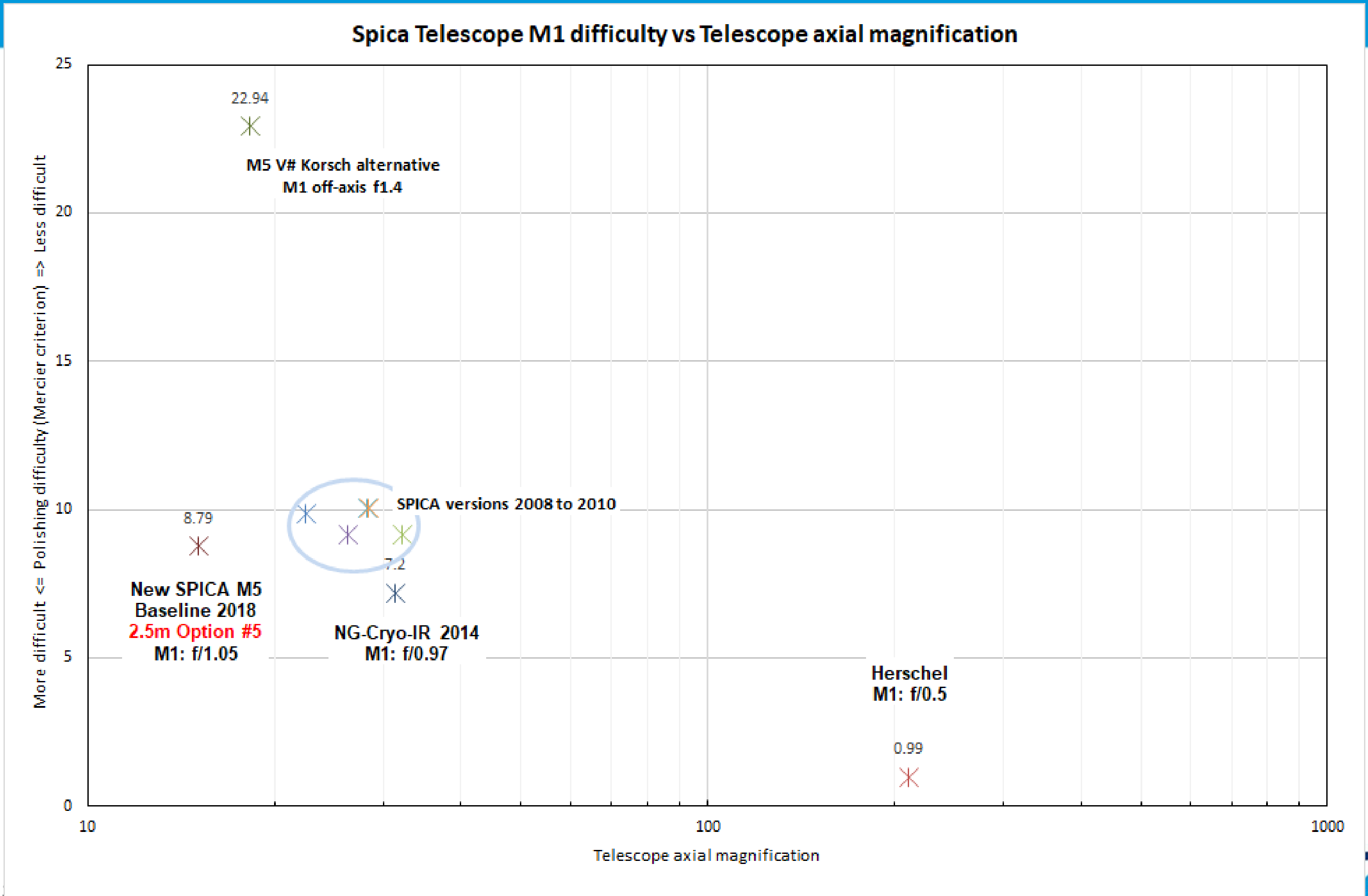
$\phi = -171.735°$

Brewster's angle [i]

$\theta_B = 85.859°$



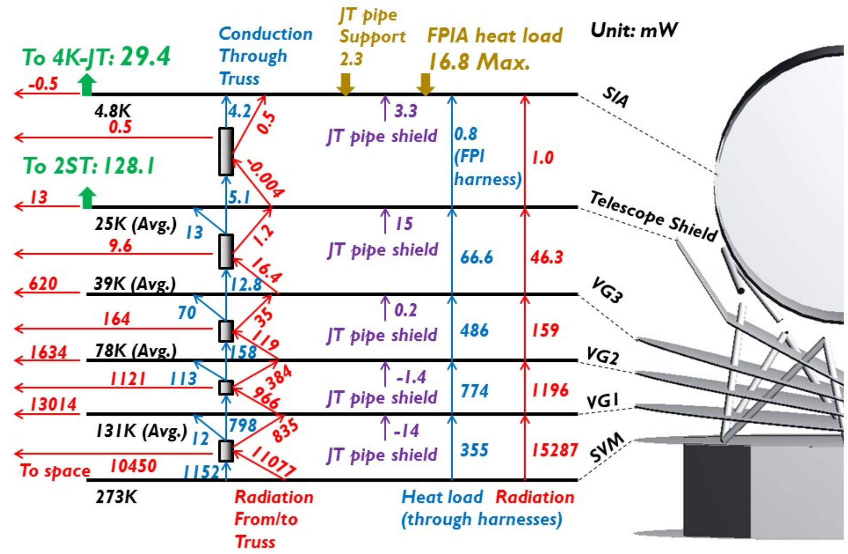
Telescope M1 difficulty space



Thermal

- Focus on the ‘regular’ Thermal Control of the PLM.

- Assumed that the V-Grooves and Cryo-chain design has been sufficiently covered by past studies.

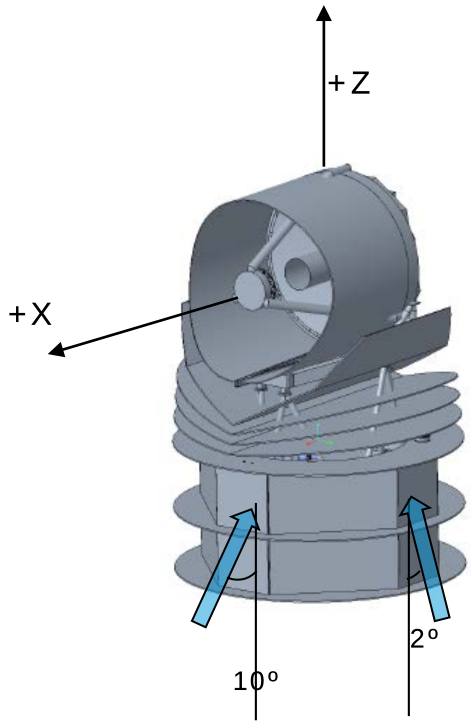


Driving parameters and assumptions

- Thermal Control of the Electronics Boxes
  - Dissipation: 763W
    - 82Wx4 (4 CDE controlling 2x2ST coolers)
    - 47Wx2 (2 CDE controlling 1x1KJT)
    - 54Wx2 (2CDE controlling 1x4KJT)
    - 180W SAFARI
    - 35W SMI
    - 18W FAS
  - Maximum temperature (design): 50degC
- Thermal Control of the Cryocoolers
  - Dissipation: 948W
    - 75Wx8 2ST (3x1KJT PC, 3x4KJT PC, 2xSC)
    - 80Wx2 1KJT
    - 94Wx2 4KJT
  - Maximum temperature (design): **30degC**

(Total dissipation = 1711W)

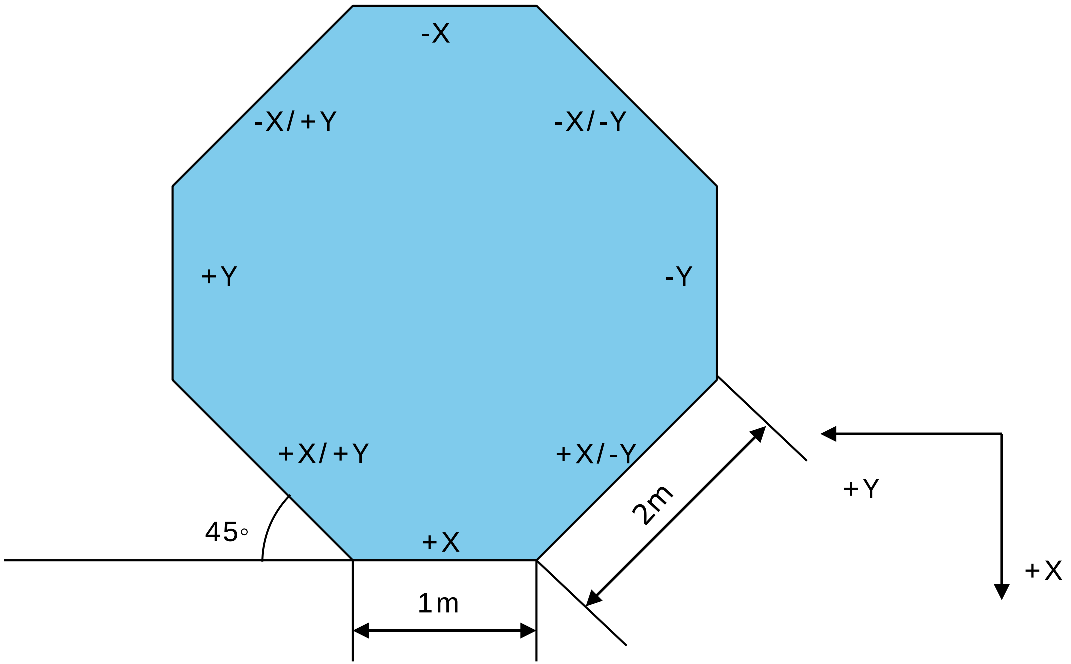
- Thermal Control of the SVM units:
  - Dissipation: 544W
    - POW: 180W (temperature range [9degC, 30degC])
    - COMMS: 116W
      DHS: 41W
    - AOCS: 133W
    - PROP: 74W
  - Maximum temperature (design): 50degC



Sun Aspect Angles

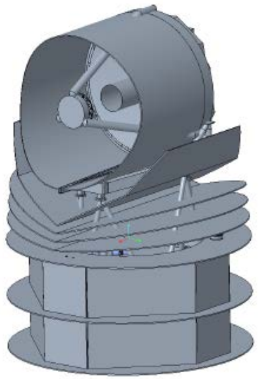
Assumption for the dimensions of the Cryocooler Module and SVM

- Note: it makes sense to have the 'small sides' in the +/-X axis to have 2 'big sides' toward –X for the PL.

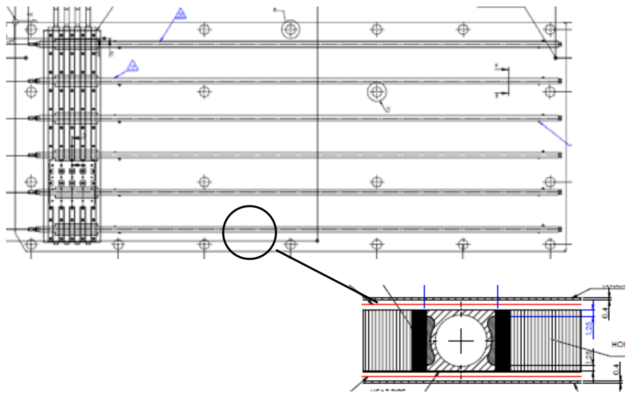


E-PLM Option

- General Architecture:
  - Mechanical Coolers, Cooler Drive Electronics and Instrument Electronics are in a separated module on top of the SVM.
  - 'Simple' Thermal architecture preferred for both SVM and CCM:
    - Units mounted directly on the panels coated to serve as radiators (white paint preferred).
    - Heat Pipes are preferred to spread the heat, but for Coolers panels due to the fact that they have to be mounted on the upper half of the panels, Aluminum doublers are necessary to increase the radiator efficiency of the lower part.
    - MLI for radiative insulation, and kapton foil heaters for active thermal control



General view SVM+CCM



All radiator panels have embedded heat pipes

E-PLM Option

- Sizing of the Radiators of the CryoCooler Module:

Lower radiator efficiency due to the use of doublers

Item	Location	Dissipation	Max Temperature (K)	Gradient (K)	Uncertainties (K)	Temperature Radiator (K)	Emissivity	Absorptivity	Sun Aspect angle (deg)	Sink Temp (K)	Radiator efficiency	Trimming Margin	Minimum Rad surface (m2)	Minimum Height (m)
3x2ST + 2xJT4K	-X/-Y	413	303	15	15	273	0.9	0.3	2º around X, 10º around Y	179.42	0.8	0.9	2.49	**1.24**
2x2ST	-X	150	303	15	15	273	0.9	0.3	10	194.02	0.8	0.9	0.99	0.99
3x2ST + 2xJT1K	-X/+Y	385	303	15	15	273	0.9	0.3	2º around X, 10º around Y	179.42	0.8	0.9	2.32	1.16
2(2x2ST) CDE + 2xJT1K CDE	+Y	258	323	10	15	298	0.9	0.3	2	129.91	0.9	0.9	0.82	0.82
SAFARI	+X/+Y	180	323	10	15	293	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.64	0.32
N/A	+X													
SMI+FAS	-X/+Y	53	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.19	0.09
2(2x2ST) CDE + 2xJT4K CDE	-Y	272	323	10	15	298	0.9	0.3	2	129.91	0.9	0.9	0.87	0.87

Better gradients assumed for Eboxes (large baseplate)

The height of the CCM shall be 1.3m

E-PLM Option

- Sizing of the Radiator of the SVM:

Item	Location	Dissipation	Max Temperature (K)	Gradient (K)	Uncertainties (K)	Temperature Radiator (K)	Emissivity	Absorptivity	Sun Aspect angle (deg)	Sink Temp (K)	Radiator efficiency	Trimming Margin	Minimum Rad surface (m2)	Minimum Height (m)
AOCS	-X/-Y	133	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.47	0.23
	-X													
POW	-X/+Y	180	303	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.88	0.44
	+Y													
COMMS	+X/+Y	116	323	10	15	293	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.41	0.21
DHS	+X	41	323	10	15	293	0.9	0.3	10	194.02	0.9	0.9	0.15	0.15
PROP	-X/+Y	74	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.26	0.13
	-Y													

The height of the SVM not driven by thermal, unused panels

E-PLM Options

- Mass Budget
  - CCM: 42.9kg

Item	Surface/Number	Mass per Unit/m2 (kg or kg/m2)	Total mass (kg)
Radiator coating (SG121FD)	8.30 m2	0.30	2.49
MLI	6.70 m2	0.40	2.68
Doublers (2mm Alu)	2.32 m2	5.40	12.51
Heat Pipes	54.07 m	0.35	18.92
Heaters	6.60 m2	0.80	5.28
Misc	1.00	1.00	1.00

Heating power necessary if no dissipation in the CCM: **1237W**

  - SVM: 15.18kg

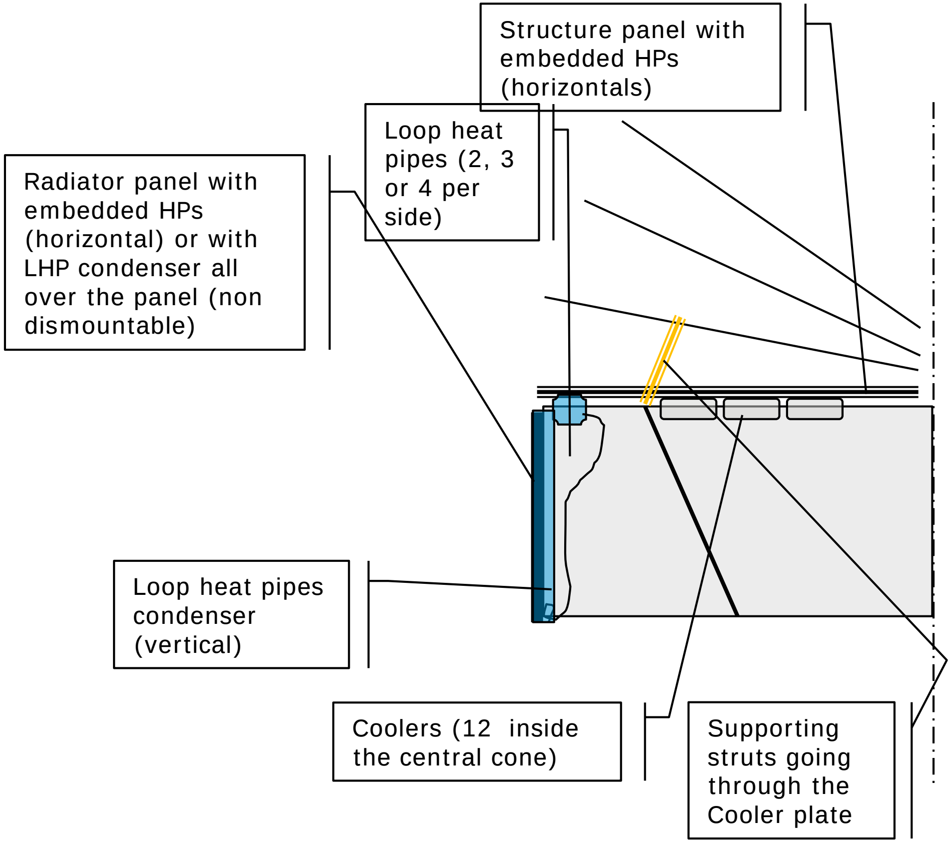
Item	Surface/Number	Mass per Unit/m2 (kg or kg/m2)	Total mass (kg)
Radiator coating (SG121FD)	1.93 m2	0.30	0.58
MLI	15.11 m2	0.40	6.04
Doublers (1mm Alu)	0.00 m2	0.00	0.00
Heat Pipes	19.30 m	0.35	6.75
Heaters	1.40 m2	0.80	1.12
Misc	1.00	1.00	1.00

Heating power necessary if no dissipation in the SVM: **480W**

  - Total: 58.1kg

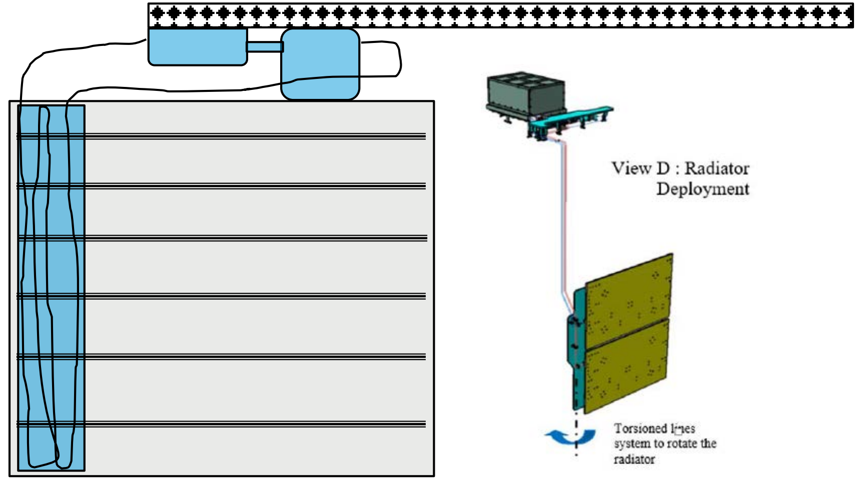
Hybrid PLM Option

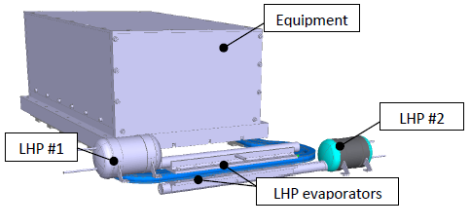
- General architecture:
  - Based on the 'Cooler Plate' Concept.
  - This plate, located on the top of the SVM will accommodate all the mechanical coolers (8x2ST, 2xJT1K, 2xJT4K)
  - Other electronics and units (CDE+Instrument Electronics + SVM equipment) are accommodated in the SVM.
  - Pros:
    - AIT/AIV easier (PLM and Coolers can be tested together without disconnection of the pipes).
    - Coolers are accommodated below the V-Grooves
    - LHP can be used to save heating power in cold case (heat switch)
    - LHP can permit the opening of the radiator panel for late access.
    - CMA are centralized for Microvibration insulation
  - Cons:
    - LHP adds a bit of operational and procurement complexity.

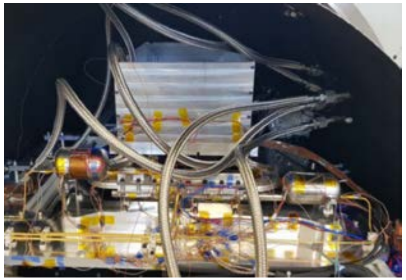


Elements of design of the Cooler plate

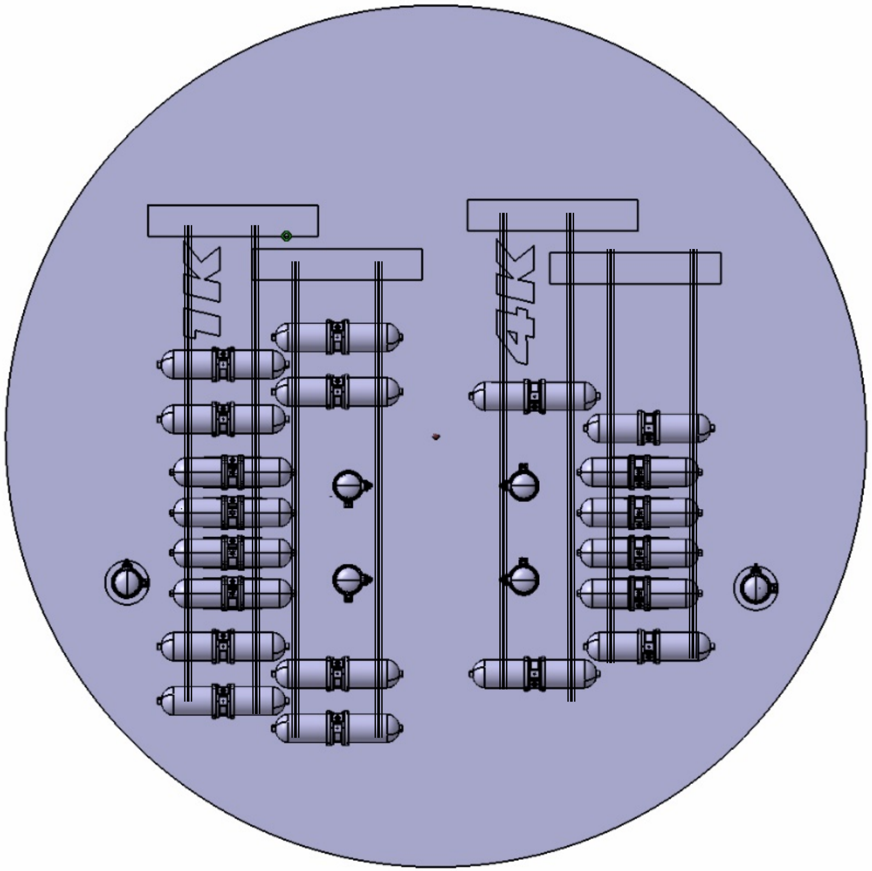
- Cooler Plate Design
  - 1 big plate with coolers accommodated on 2 halves.
  - Each Half will accommodate:
    - 3x2ST Precooler
    - 1x2ST Shield cooler
    - 2xJT (4K or 1K)
    - 4xLHP evaporator ~250mm size.
    - (400mm evaporator can be used to save mass)
    - Collecting embedded heatpipes
  - Such assembly has been qualified for Alphasat deployable radiator (3x400mm LHPs to manage 2kW of dissipation)
  - Is being developed in a 250mm LHP version (manages 250W) in the HESAS GSTP 6.2
  - Exemple from EHP (B) but an Iberespacio version exists.







Elements of design of the Cooler plate



- Rough conductivity estimation:
    - Coming from HESAS Thermal balance test: Gradient between the TRP of the equipment and radiator for 1LHP active, 250W transported: 20degC.
    - For 3 LHPs transporting 500W: ~13degC of gradient → 15degC is a sound assumption.

Hybrid PLM Option

- Sizing of the Radiators of the SVM:

Good radiator efficiency due to dense embedded heat pipes

Item	Location	Dissipation	Max Temperature (K)	Gradient (K)	Uncertainties (K)	Temperature Radiator (K)	Emissivity	Absorptivity	Sun Aspect angle (deg)	Sink Temp (K)	Radiator efficiency	Trimming Margin	Minimum Rad surface (m2)	Minimum Height (m)
Cooler Plate 1	-X/-Y	488	303	15	15	273	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	2.61	**1.31**
SAFARI SMI FAS	-X	233	323	10	15	298	0.9	0.3	10	194.02	0.9	0.9	0.87	0.87
Cooler Plate 2	-X/+Y	460	303	15	15	273	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	2.46	1.23
2(2x2ST) CDE + 2xJT1K CDE	+Y	258	323	10	15	298	0.9	0.3	2	129.91	0.9	0.9	0.82	0.82
POW+DHS	+X/+Y	221	303	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	1.08	0.54
AOCS	+X	133	323	10	15	298	0.9	0.3	10	194.02	0.9	0.9	0.50	0.50
COMMs PROP	-X/+Y	190	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.67	0.34
2(2x2ST) CDE + 2xJT4K CDE	-Y	268	323	10	15	298	0.9	0.3	2	129.91	0.9	0.9	0.85	0.85

The height of the SVM shall be 1.31m

H-PLM Options

- Mass Budget
  - SVM: 47.35kg
  - Cooler Plate: 20.56kg
  - Total: 71kg

	Item	Surface/Number	Mass per Unit/m2 (kg or kg/m2)	Total mass (kg)
	Radiator coating (SG121FD)	9.57	0.30	2.87
	MLI	9.04	0.40	3.62
	Doublers (1mm Alu)	0.00	0.00	0.00
	Heat Pipes	100.71	0.35	35.25
	Miscellanous	1.00	1.00	1.00
	Heaters	7.23	0.80	5.79
Part of the PLM	LHPs	4.02	4.00	16.08
	Cooler Plate HP	12.80	0.35	4.48
	Cooler Plate	2.56	4.14	10.61

Heating power necessary if no dissipation in the SVM: **1500W (helped by the LHPs)**

H-PLM Option

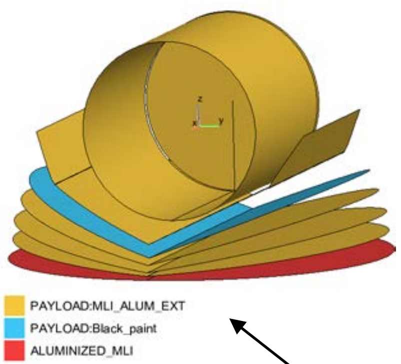
- Calculation of the Heating Power necessary between launch and SA deployment
  - Cooler Plates do not reach their minimum Non Operational temperature (-35degC with margin) within 3h30.
  - The driver for the heating is the POW panel, due to the high minimum temperature of the Batteries (~9degC).
    - Heating necessary after ~1h30 → **860Wh needed**

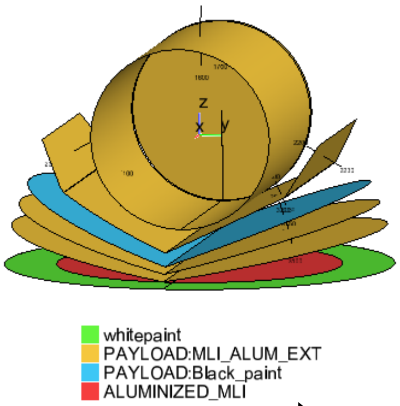
- **This can be reduced by accommodating the battery in a different thermal enclosure of the PCDU.**

Compact PLM Option

- Concept:
  - Use the fact that we can reject the Mechanical Cryocooler dissipation 'directly' (either with a white radiator on top of the SVM or with a dedicated V-Groove) to avoid using LHPs and having a smaller (~0.9m high) SVM.
  - Focus on the option with a Radiator Rim (Option 4), as it seems the most straightforward solution and it does not affect the design of the V-grooves.

→ Questions:
  - → Can we reject all the dissipation of the Coolers?
  - → How does it affect the efficiency of the V-Grooves, which translates into the requested heat lift to the Shield Coolers





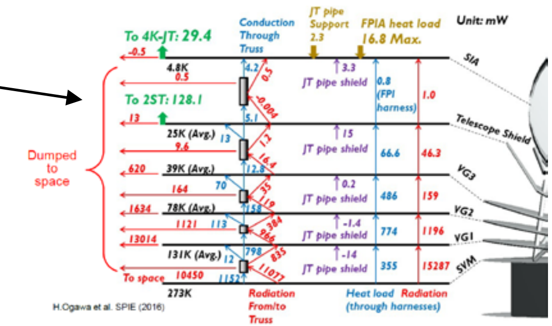
	Option 1 - Nominal	Option 3 – Extra V-Groove	Option 4 – Radiator Rim
V-grooves angles	5 - 10 - 15 - 25	5 - 10 - 15 - 20 -25	Radiator rim - 10 - 15 - 20 - 25
	3 V-grooves	4 V-grooves	3 V-grooves

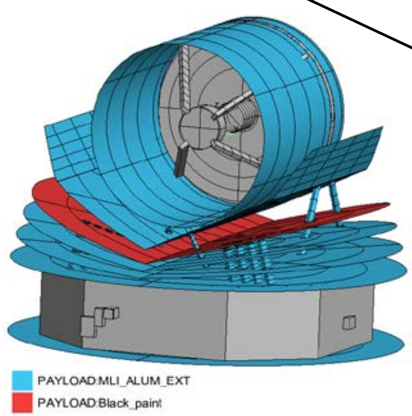
Compact PLM Option

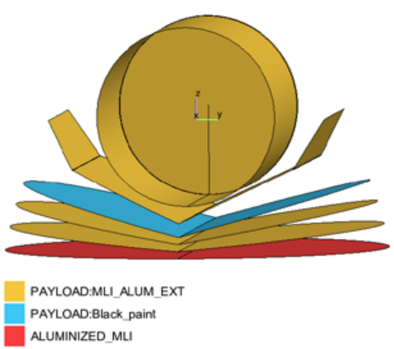
- First stage: Setting up a simplified model to reproduce JAXA results
  - Conductances coming from the Heat Flow Budget
  - Geometry simplified from NGCryo model
- Manage to reproduce the results only if we assume the MLI of the top plate of the SVM perfectly specular:

	Nominal Temperature [K]	JAXA Temperature [K]	Delta [K]
B - shield	25	25	0
VG3	39	39	0
VG2	80	78	2
VG1	134	131	3
VG0	//	//	//
B - SVM	273	273	0
Shield Heat load	131.41mW	128mW	3mW

- If we consider a diffusive external layer of the MLI (more realistic) the heat load increased from **131mW to 146mW**



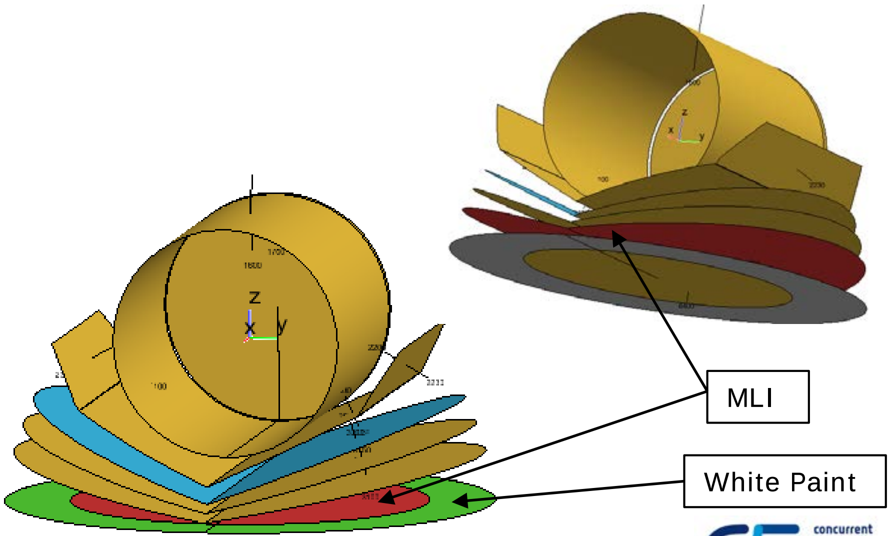




Compact PLM Option

- Feasibility of the Rim Design:
  - Objective: being able to reject ~1400W = 1000W/(0.8*0.9) to account for trimming margin and radiator efficiency. 1000W dissipation assumption is slightly larger than the nominal 948W to cover the fact that the shield coolers will need to be operated at higher power.
  - Works with a 60cm Rim Radiator + MLI on the back of the 1st V-Groove.
  - Effect on the V-Grooves?

	Nominal	Rim 60cm	JAXA
	Temperature [K]	Temperature [K]	Temperature [K]
B - shield	25	25	25
VG3	41	44	39
VG2	86	94	78
VG1	149	166	131
VG0	//	//	//
B - SVM	273	273	273
Shield Heat load	146.41mW	**195.9mW**	128mW
Rim heat rejection	N/A	**1414W**	N/A

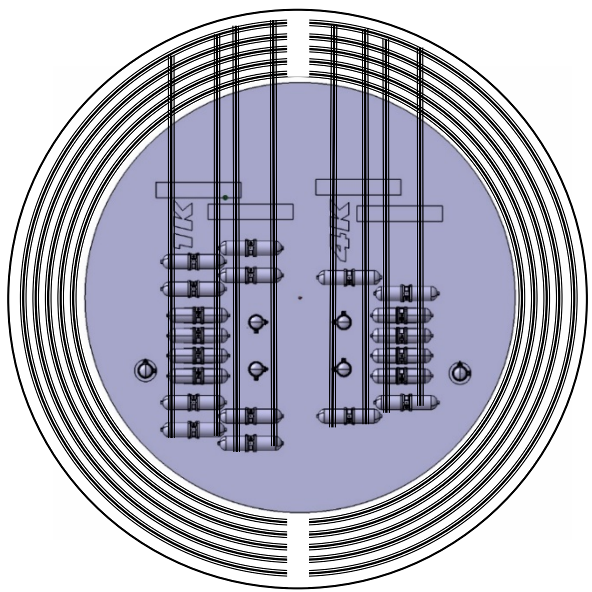


Compact PLM Option

- First Conclusion:
  - It seems feasible to radiate the dissipation of the Mechanical Cryocoolers with the rim radiator.
  - Can be considered if the Shield Cooler can lift ~200mW End of Life (with redundancy)
- Sensitivity:
  - MLI efficiency assumed in the calculation:
    - GL=0.0014W/m2K, GR=0.007
  - If MLI efficiency is multiplied by 2:
    - Heat load on the shield is reduced to ~175mW.

Compact PLM Option

- Elements of design of the Rim Radiator:
  - Thermal bus coming from the Coolers inside the come to the rim.
  - Semi-circular Heat pipes to ensure radiator efficiency of the rim



Compact PLM Option

- Sizing of the Radiators of the SVM:

Item	Location	Dissipation	Max Temperature (K)	Gradient (K)	Uncertainties (K)	Temperature Radiator (K)	Emissivity	Absorptivity	Sun Aspect angle (deg)	Sink Temp (K)	Radiator efficiency	Trimming Margin	Minimum Rad surface (m2)	Minimum Height (m)
2(2x2ST) CDE + 2xJT4K CDE	-X/-Y	268	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.95	0.47
SAFARI	-X	180	323	10	15	298	0.9	0.3	10	194.02	0.9	0.9	0.67	0.67
2(2x2ST) CDE + 2xJT1K CDE	-X/+Y	258	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.91	0.46
SMI FAS	+Y	53	323	10	15	298	0.9	0.3	2	129.91	0.9	0.9	0.17	0.17
POW	+X/+Y	180.00	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.64	0.32
DHS	+X	41.00	323	10	15	298	0.9	0.3	10	194.02	0.9	0.9	0.15	0.15
COMMs PROP	-X/+Y	190.00	323	10	15	298	0.9	0.3	2º around X, 10º around Y	179.42	0.9	0.9	0.67	0.34
AOCS	-Y	133	323	10	15	298	0.9	0.3	2	129.91	0.9	0.9	0.42	0.42

The height of the SVM can be 0.9m

Compact PLM Options

- Mass Budget
  - SVM: 25.2kg

Item	Surface/Number	Mass per Unit/m2 (kg or kg/m2)	Total mass (kg)
Radiator coating (SG121FD)	4.58	0.30	1.37
MLI	11.13	0.40	4.45
Doublers (1mm Alu)	0.00	0.00	0.00
Heat Pipes	45.83	0.35	16.04
Heaters	2.91	0.80	2.33
Misc	1.00	1.00	1.00

  - Cooler Plate: 42.52kg

Item	Surface/Number	Mass per Unit/m2 (kg or kg/m2)	Total mass (kg)
Radiator coating (SG121FD)	7.35	0.30	2.21
MLI	8.55	0.40	3.42
Doublers (2mm Alu)	0.00	5.40	0.00
Heat Pipes	93.40	0.35	32.69
Heaters	4.00	0.80	3.20
Misc	1.00	1.00	1.00

  - Total: 67.7kg

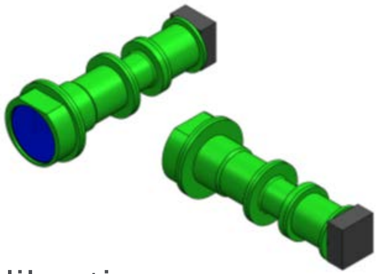
AOCS

AOCS Requirements

- Functional requirements
  - Sun acquisition and pointing (after separation & in safe mode)
  - 3 axes stabilization & scanning mode for Science operations (polarimeter)
  - Delta-V management (orbit & station keeping manoeuvres)
  - Angular momentum management (bias and offload)

- Performance requirements (3σ) covering all instruments
  - Absolute Knowledge Error (AKE) = 0.15" (TBC) for SAFARI, 0.17" (TBC) for SMI
    => we need to confirm the need is AKE and not RKE
    (otherwise possibly not achievable due to bias)
  - Mean Pointing Error (MPE) = 0.38" /600s for SMI
  - Relative Pointing Error (RPE) = 0.15" /200s for SAFARI
  - Relative Pointing Error (RPE) = 0.3" /3600s for POL

AOCS Trade-offs



- Fine Guidance Sensor (FGS) / Focal plane Attitude Sensor Vs conventional Star tracker based attitude estimation
  - FGS based AOCS is mandatory:
    Even without ThermoElastics Distortion (TED) stability & calibration accuracy, the next generation High accuracy Star Tracker will not enable to comply to the MPE (around 0.5” with FOV & pixel error and internal TED stability)
  - This may be revisited with cold temperature stabilization of the Optical Head if ThermoElastics Distortion (TED) stability is very good

- Conventional Reaction Wheels Vs Cold gas based attitude control
  - A Reaction Wheels based control enables to comply to the RPE:
    This implies obviously strong design constraints (see next slide Design drivers)

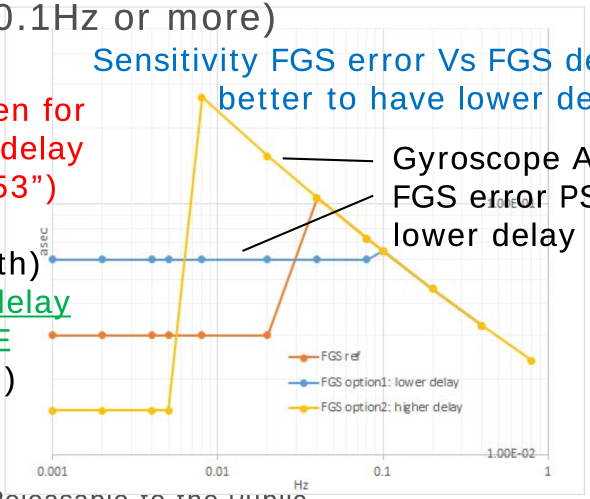
AOCS Design drivers - MPE

- Main design driver for the compliance to MPE:
  Fine Guidance Sensor (FGS) delay (integration time) and accuracy are critical
  - FGS requirements: MKE (star catalog+FOV error+pixel/centroid error) <0.38” with integration + processing duration < 35s
    => assuming AKE requirement are RKE requirement
  - Very low attitude control bandwidth (few mHz) and no gyroscope
  - Hence management of friction disturbance by wheel speed control loop with high bandwidth (around 0.1Hz or more)

Due the FGS delay:
- Gyroscope ARW error to be added: Not acceptable even for low delay: 0.08” for 2s minimum delay, 0.19” for 10s delay (FGS bias error alone not acceptable at 0.5Hz with 0.53”)

OR
- Very low attitude control bandwidth (at FGS bandwidth)
  => Degraded pointing stability: acceptable <u>if limited delay</u> 0.09” / 0.01” tachometer noise /friction impact on RPE
  (higher impact of tachometer noise and/or RW friction)

Sensitivity FGS error Vs FGS delay:
better to have lower delay and worst accuracy



Gyroscope ARW error PSD (sqrt)

FGS error PSD (sqrt): higher when lower delay

AOCS Design drivers - RPE

- Main design drivers for the compliance to the RPE:
  Microvibrations, tachometer noise and Reaction Wheel (RW) friction disturbance
  - Low RW speeds (2-3 Nms, 300-400 RPM) to avoid coupling with telescope flexible modes
    => unloading period = 2 days
  - High performance isolation and small RW for sufficient damping of the RW mechanical mode disturbance
  - High performance isolation of the Cryocooler
  - Wheel speed control loop with high bandwidth (around 0.1Hz or more) to optimize tachometer VS friction disturbance impact

AOCS Design drivers – Main assumptions

- Spacecraft inertia: [13240 13240 9810] kg.m2
  - based on Herschel and scaled based on the mass

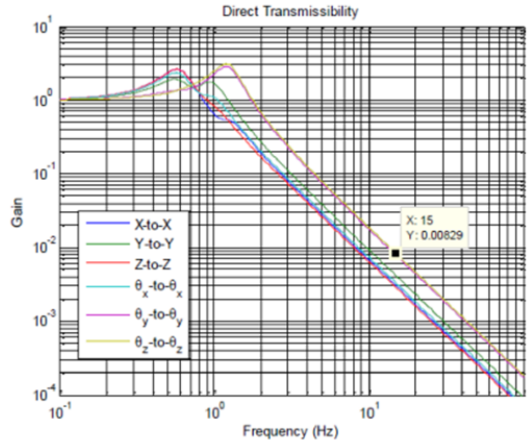
- The derivation of FGS requirements on accuracy and delay:
  - For the trade-off FGS error Vs FGS delay:
    Calculations using: integration time % (1/error)^2
    Not for budgeting but for optimization trend: the delay is the driver
  - JAXA FAS requirements:
    Random error (3s) 0.036”, Sampling 0.2Hz, FOV 7.5 arcmin
    Bias error (0-P) 0.53” with WISE star catalogue driving the bias

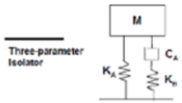
  ⇒ Assumptions considered as worst case for integration time and delay (35s =1/0.2 x7)

  ⇒ But still bias performance feasibility to be demonstrated (including star catalogue):
  Possibility of using VIS detector to be investigated

AOCS Design drivers – Main assumptions

- Cryocoolers isolation: based on JAXA inputs





- Reaction Wheels isolation: 0.01 damping at wheel mechanical mode frequency
  - Could be a slope of -40dB/decade starting at 20Hz
  - If isolator resonance (low damping to get high slope) is an issue, 3-parameters suspension, or active passive suspension maybe used

- Reaction Wheels tachometer: 0.03 rad/s error

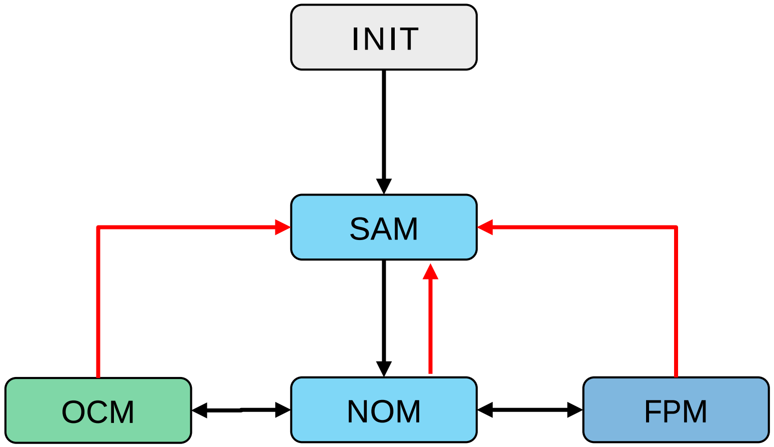
AOCS Baseline Design – AOCS equipment

Type	Units	Driving requirements	TRL
Sensors	2 Fine Guidance Sensors (FGS) / Focal plane Attitude Sensor	For Fine Pointing Mode Bias with pixel/centroid error & delay are critical for MPE	3
	2 Attitude Anomaly Detectors (AAD)	For FDIR	9
	2 Coarse Rate Sensors (CRS)	For detumbling in Safe mode	9
	2 Sun Acquisition Sensors (SAS)	For Sun acquisition in Safe mode	9
	3 Star trackers (STR) (3 Optical Heads + 2 Electronic Units)	For Nominal mode attitude estimation High performance off the shelf to relax TED stability and calibration accuracy, and for high accuracy slews and easy transition to FPM, 3OH for redundancy	9
	1 Fine Gyroscope (GYR) (internally redundant)		9
Actuators	4 Reaction Wheels (RW)	For attitude control during Nominal mode High performance tachometer are required for RPE	9
	6+6 1N Thrusters (THR-A)	For small delta-V (& attitude control during them), Safe mode attitude control & angular momentum offloading	9
	6+6 20N Thrusters (THR-B)	For large delta-V (& attitude control during them)	9

Cold redundancy foreseen except for RW & fine Gyroscope

AOCS Baseline Design – AOCS modes

- Safe & initial acquisition Mode (SAM)
- Nominal Mode (NOM)
- Orbit Control Mode (OCM)
- Fine Pointing Mode (FPM)



Units	SAM	OCM	NOM	FPM
FGS			(X)	X
AAD	X	X	X	X
CRS	X			
SAS	X			
STR	(X)	X	X	(X)
GYR	(X)	X	X	(X)
RW		(X)	X	X
THR-A	X	(X)	X	
THR-B		(X)		

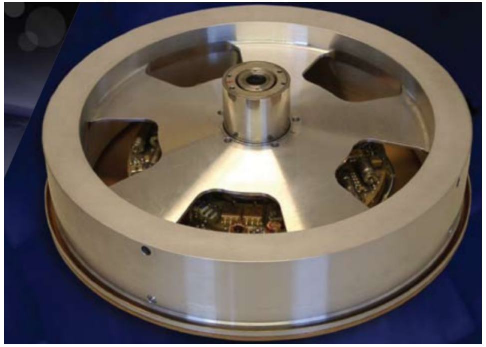
FGS in NOM for FPM initialization
STR and GYR in SAM & FPM for fall back to NOM
RW at constant speed in OCM
THR1 for continuous momentum offloading in NOM
THR1 or THR6 in OCM depending on delta-V

AOCS Baseline Design – Actuators sizing

- 6+6 x 1N Thrusters:
  - tilted by 35deg, Minimum Impulse Bit= 0.05 Ns, Specific impulse= 215s
  - Max torque = [3 3 2.6] Nm
    with accommodation coef = [1.1 1.1 1.3] Nm/N

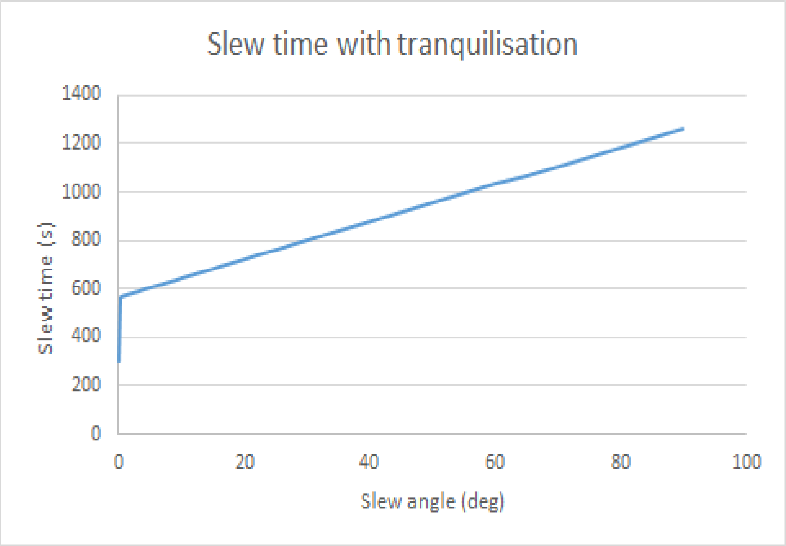
- 6+6 x 20N Thrusters:
  - a priori not tilted (spin control by the 1N THR)
  - with accommodation coef = [2 2 0] Nm/N

- 4 x 15Nms - 0.2Nm Reaction Wheels:
  - Small size / angular momentum preferred
    for low mechanical mode disturbance
  - Imbalances: static 1.5 gcm / 20 gcm2



AOCS Performances - Agility

- Driving parameters:
  - Slew rate: 0.84 deg/s
  - Tranquilization time: 300s
    for both NOM & FPM control loops:
    driven by the AOCS bandwidth at FGS bandwidth frequency
    => Tranquilization time strongly reduced if remaining in NOM



- Performances:
  - 2" slew angle: 302s
  - 8x60" slew angle: 570s
  - 1 deg slew angle: 577s
  - 90 deg slew angle: 1262s

AOCS Performances - Pointing

- MPE marginally Compliant: 0.37”   (Spec 0.38”)
  Main contributors:
  - FGS Centroid/Pixel error (including catalogue) = 0.280”
  - FGS FOV error = 0.093
- RPE 200s marginally compliant: 0.144” (Spec = 0.15”)
  Main contributors:
  - RW tachometer noise = 0.104"
  - RW microvibrations (with 50% margin) = 0.083"
  - Cryocooloer microvibrations (with 100% margin) = 0.048"
  - RW friction jump = 0.006"

Contributors		Pointing metrics (asec)		
Type	PES	MPE	RPE 200s	RPE 3600s
System	TED stability error (between instruments LOS and FGS LOS)	0.000		
	Cryocoolers microvibrations	0.000	0.048	0.048
AOCS sensing	FGS FOV error	0.093		
	FGS pixel & NEA error	0.280	0.002	0.002
AOCS control	RW torque noise & friction jump	0.000	0.006	0.006
	RW tachometer noise	0.000	0.104	0.104
	RW microvibrations	0.000	0.083	0.083
	Total	0.373	0.143	0.143
	Spec	0.380	0.150	0.300
	Margin (%)	1.8	4.5	52.3

Propulsion

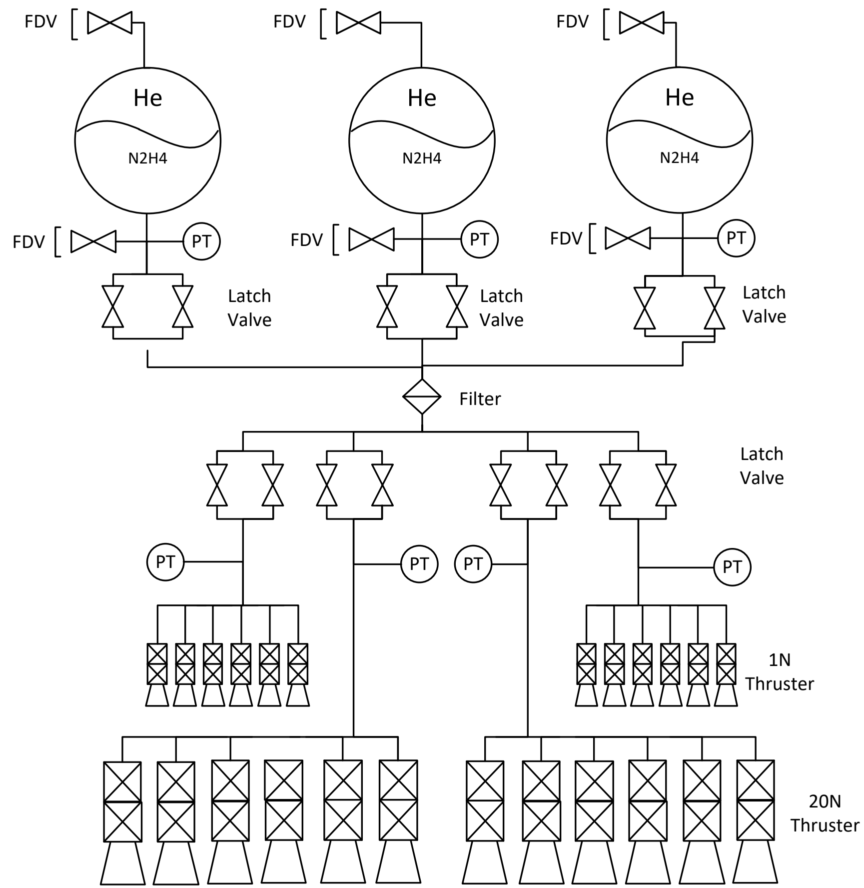
Assumptions & Requirements

- Design driver, deliver required Δv with minimum contamination by exhaust plume
- Spacecraft dry mass (w/o propulsion): 3335 kg
- Spacecraft maximum wet mass: 3700 kg
- Baseline: hydrazine (monoprop) propulsion system
- 2% propellant residuals
- Large thrusters (20N) are assumed to be aligned with required thrust vector
- Small thrusters (1N) are tilted by 35°

Propellants Trade-off

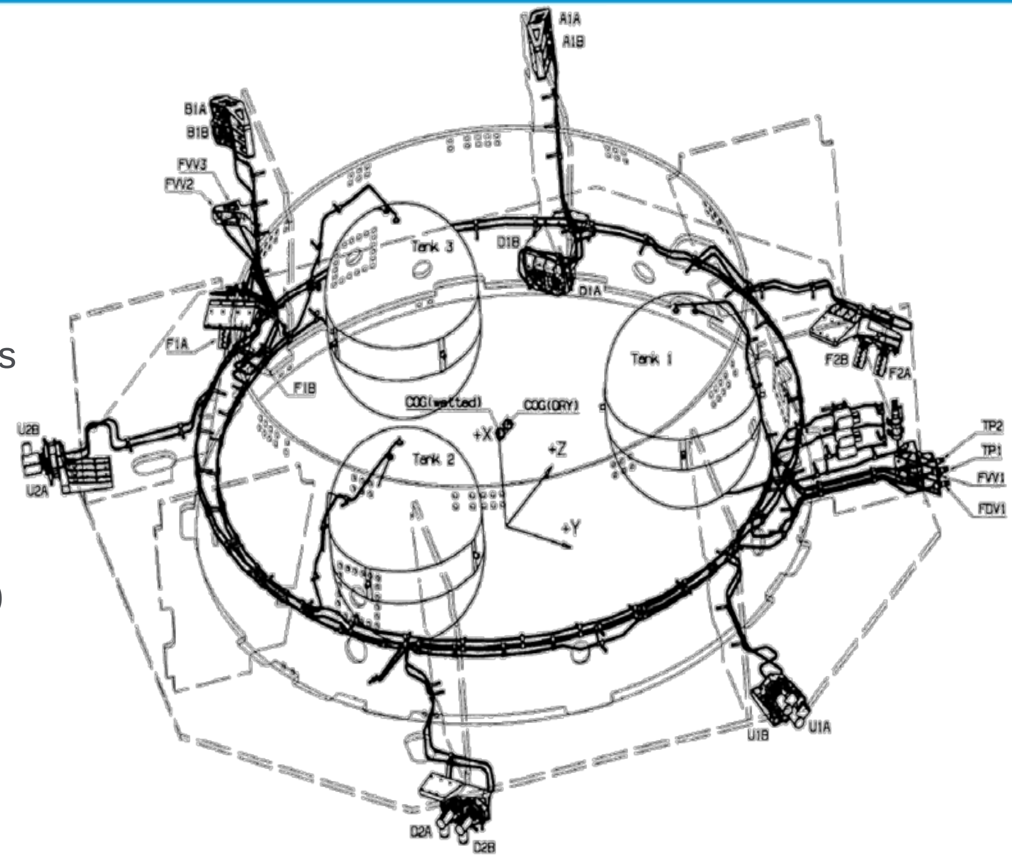
	Hydrazine	LMP-103S	MMH / NTO	Hydrazine / NTO
Specific impulse	200 - 220s	240 - 255s	290 – 300 s	295s
European Supplier	Yes	Yes	Yes	No (but Japanese)
TRL	9	6	9	9
system complexity	simple monoprop blowdown	simple monoprop blowdown	biprop blowdown	biprop pressure fed & monoprop blowdown
Reaction products in science mode	NH_3, H_2, N_2	H_2O, N_2, H_2, CO, CO_2, (as well as acidic droplets)	H_2O, N_2, H_2, CO, CO_2, (as well as acidic droplets)	NH_3, H_2, N_2

Proposed System Architecture

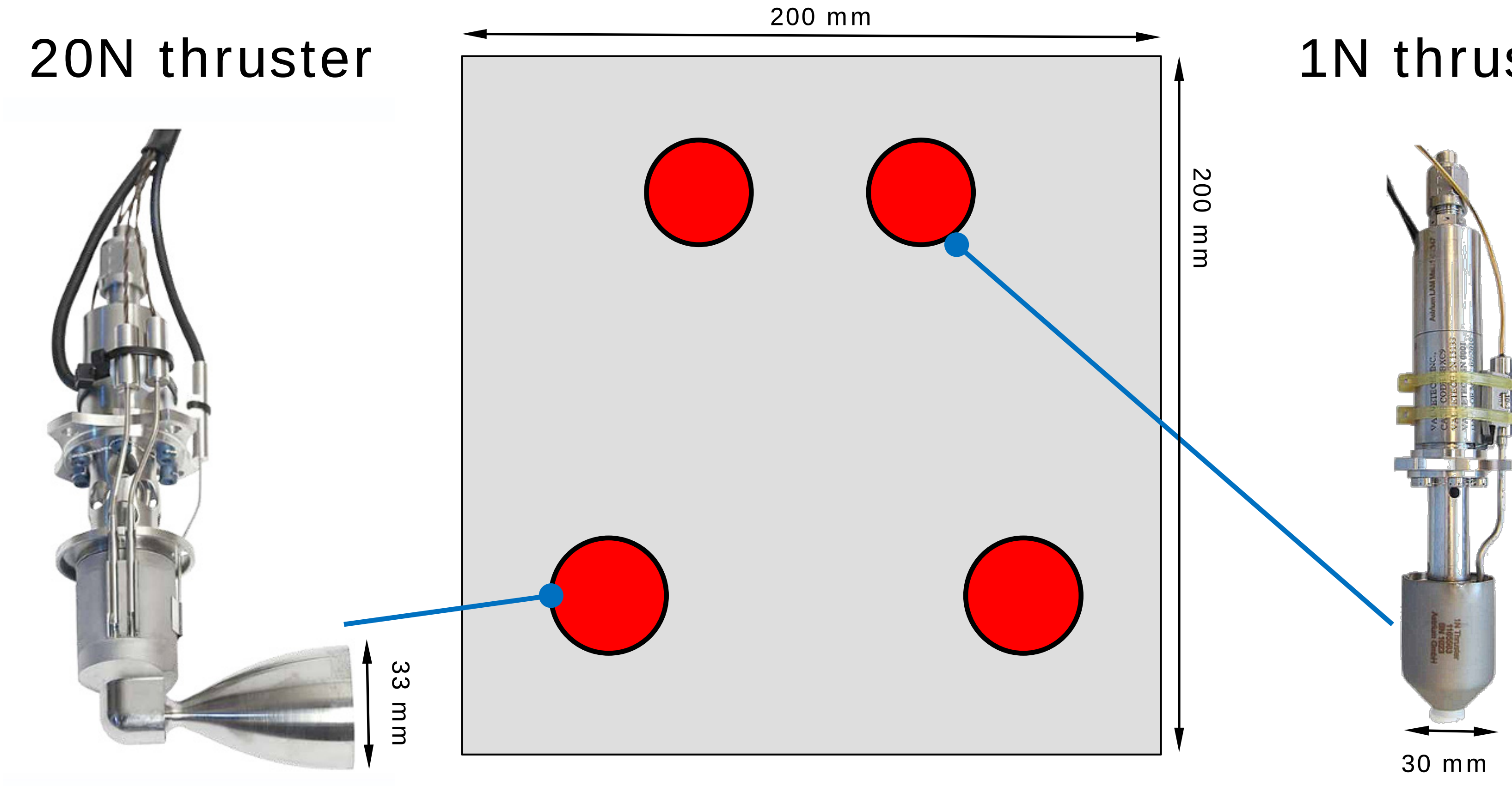


System Design

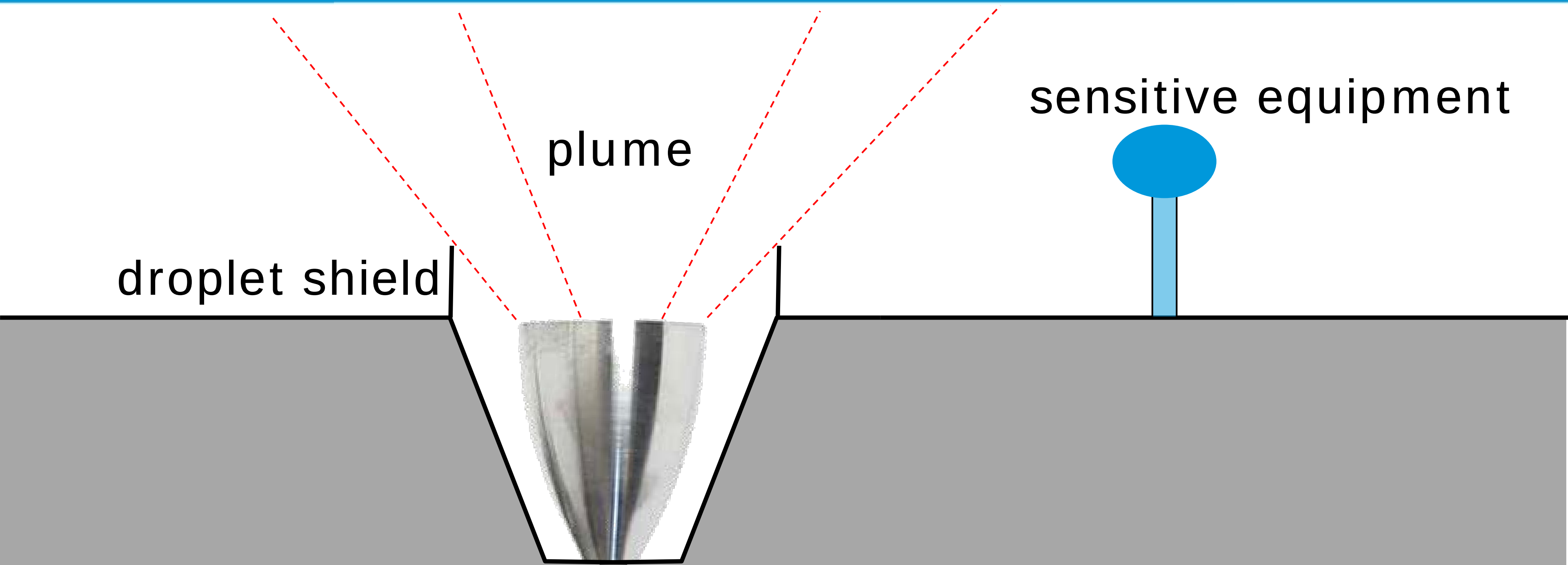
- Similar to Herschel/Planck
- 3 Tanks (currently ca. 50% oversized)
- 6 thruster brackets and one or two similar sized panels for service valves
- Each Thruster bracket could accommodate:
  - 2 x 1N thruster (redundant)
  - 2 x 20N thruster (redundant)



Thruster Bracket



Droplet Shield

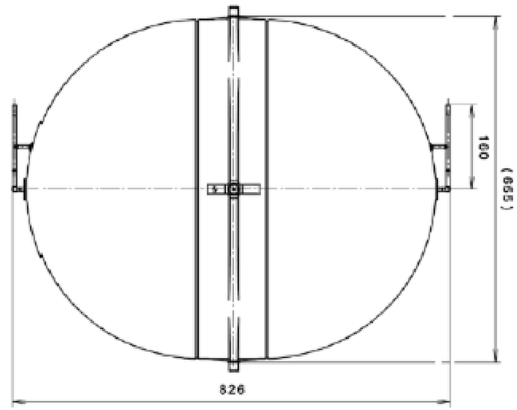


Hydrazine Tanks: 3 x PTD-177

- 3 tanks
- maximum hydrazine loading: 415 kg
- current loading: 297 kg
- resulting blowdown ratio: 2.2 : 1

PTD-177

Monopropellant Diaphragm Tank - COTS



Heritage			Herschel Planck, Sentinel 3
Fluids			N_2H_4 (Hydrazine)
Pressurant Gas			He, N_2
Propellant Management			Diaphragm
Materials	Shell		Ti-6Al-4V
	Tube		Ti-3Al-2.5V
	Diaphragm		EPDM
Mounting interface			equatorial trunnions
Total Volume		177 l	10.801 in³
Propellant Volume		135 l	8.238 in³
Temperature Range		0 / +50 °C	+32 / +122 °F
Tank Dry Mass		15,5 kg	34,2 lbs
Diameter		654,6 mm	25,77 in
Length		827,0 mm	32,56 in
MEOP*		24,0 bar	348 psi
Proof pressure (x 1,50)		36,0 bar	522 psi
Burst pressure (x 2,00)		48,0 bar	696 psi
Burst pressure tested		55,5 bar	805 psi

* Maximum Expected Operating Pressure

Δv + Propellant Assumptions

- All Δv are doubled due to alignment of thrust vector, sun, and payload

  → Thrust can only be provided into the anti-sun direction
- Thruster are pointing directly into thrust direction
- 100 % Margin on AOCS
- 1 N Thruster: 35 degrees tilted

Simplified DeltaV Budget (Mission Analysis Slides)

Lissajous orbit DV is optional – Quasi Halo is baseline

	Example values – Ariane 5/6, Large amplitude Quasi Halo, noisy S/C	Suggested margin	Double on biased trajectory
• Flight program correction			
– 1.5 m/s * 9	13.5 m/s	10%	Yes
• Launcher dispersion correction			
– 3-4.5 m/s * 9 (JAXA 5.28 m/s)	40.5 m/s (JAXA 47.56 m/s)	0%	Yes
• Correction of TCM#1			
– 0.1 * TCM#1	5.4 m/s (JAXA 6.1 m/s)	10%	Yes
• Lissajous orbit insertion			
– 12 m/s/(DEC SSCE)	168 m/s (28->14 Deg)	10%	NO
• Station-Keeping			
– 0.7-7 m/s/year	35 m/s	50%	Yes
• Disposal			
– 10 m/s	10 m/s	10%	Yes
• Eclipse avoidance			
– 15 m/s	15 m/s	10%	Yes

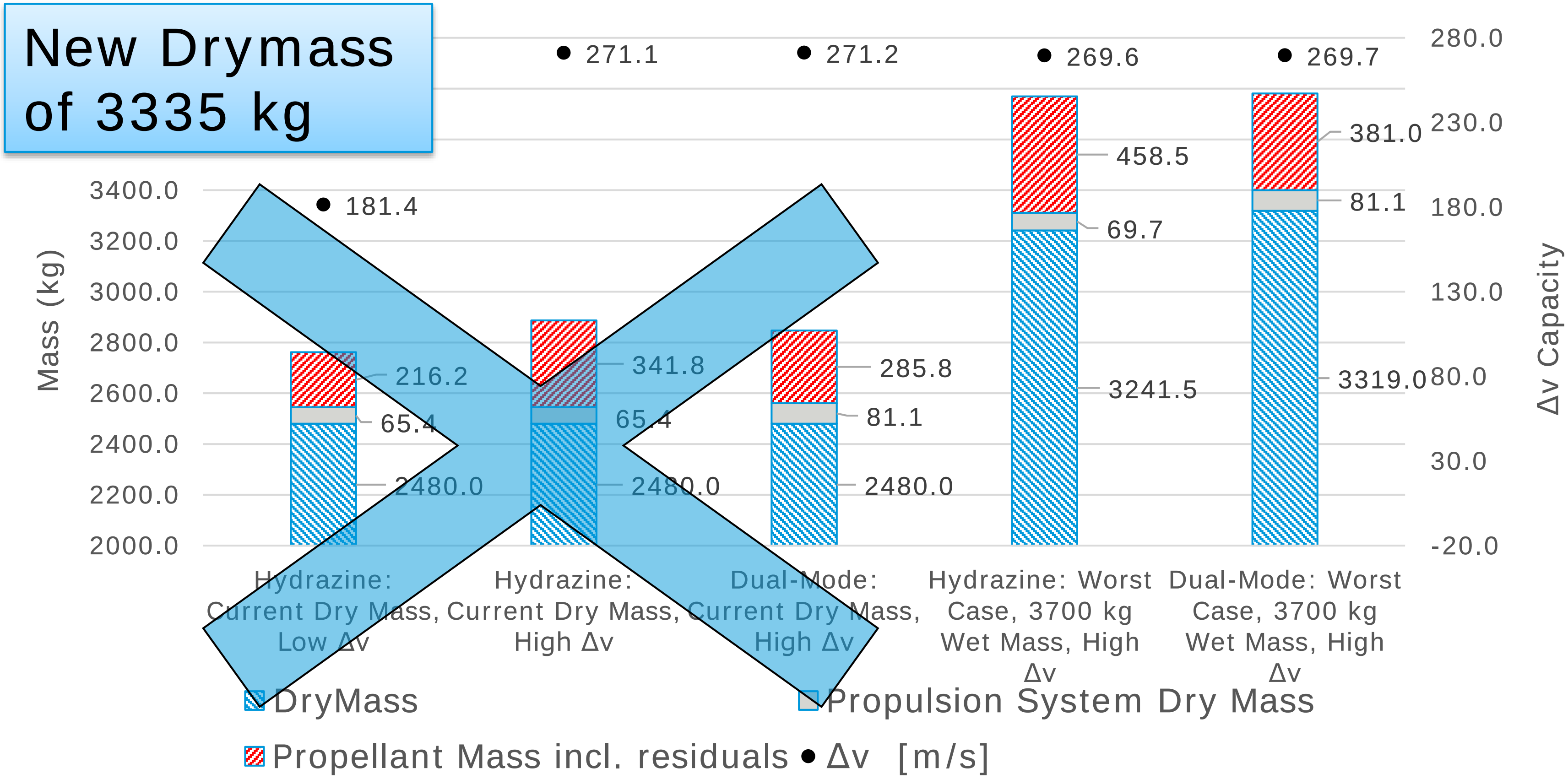
Δv Assumption + Inputs for Propulsion System Calculations

Manoeuvre	Δv [m/s]	propellant mass [kg]
Flight Prog Corr	29.7	
Launcher Dispersion Correction	95.1	
Correction of #TCM1	13.4	
AOCS Budget		3.6
Station Keeping	15.0 – 105	
Disposal	22	
AOCS Budget		3.4

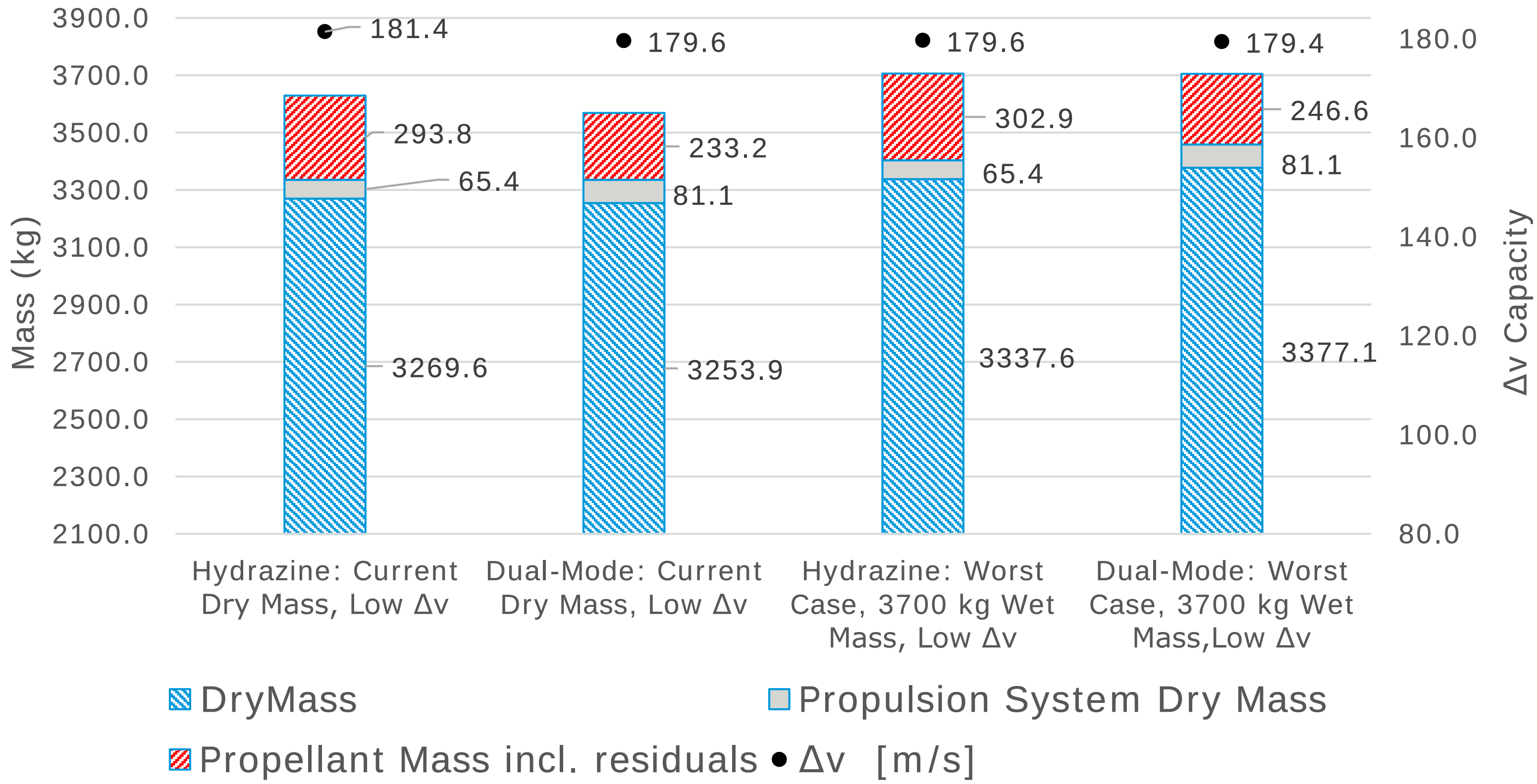
Low Δv → Station Keeping = 15 m/s

High Δv → Station Keeping = 105 m/s

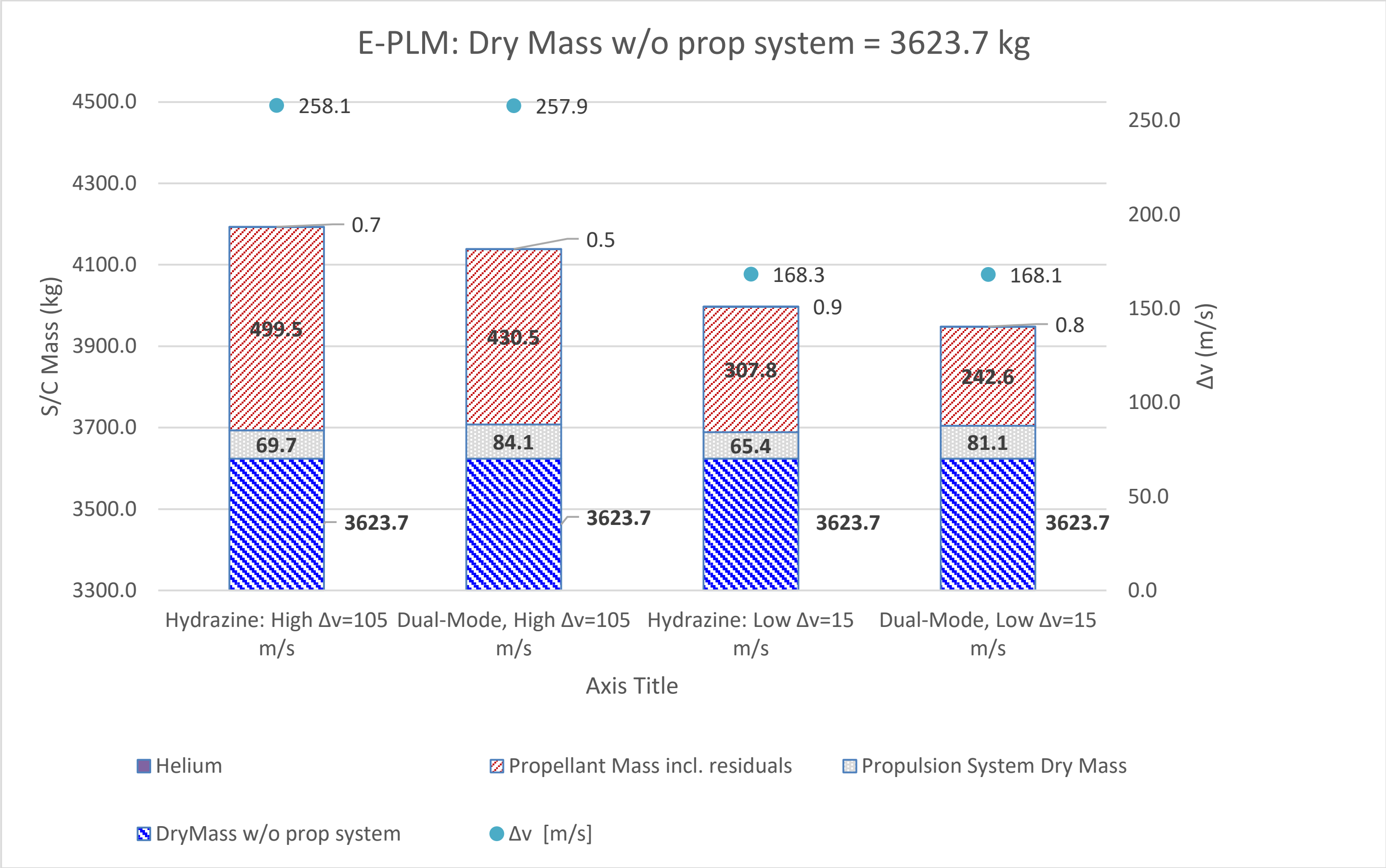
Comparison: Different combinations
Dry Mass: 2480.02 kg



Comparison: Different combinations
Dry Mass: 3335 kg, Low Δv



E-PLM: Comparison



Dry Mass: 3335 kg, low Δv

Hydrazine System

Manoeuvre	mass begin [kg]	mass end [kg]	velocity incre	Thruster	propellant mass [kg]	Fuel mass	Calc. Tank s	tank pressure [bar]	Firing time	Isp Value
Flight Prog Corr	3623.1	3575.0	29.7	CHT-20N	48.1	48.1	47.6	24.0	13.7	225.4
Launcher Dispersion Correction	3575.0	3422.4	95.1	CHT-20N	152.6	152.6	151.0	21.3	54.9	220.0
Correction of #TCM1	3422.4	3401.2	13.4	CHT-20N	21.2	21.2	21.0	15.8	7.9	219.5
AOCS Budget	3401.2	3397.6	2.2	CHT-1N	3.6	3.6	3.6	15.2		213.4
Station Keeping	3397.6	3373.3	15.0	CHT-1N	24.3	24.3	24.1	15.1		212.6
Disposal	3373.3	3338.8	22.0	CHT-20N	34.5	34.5	34.1	14.5		218.1
AOCS Budget	3338.8	3335.0	2.4	CHT-1N	3.8	3.8	3.8	13.8		211.5
Summation	3335.0		179.8		288.1	288.1	285.2	13.7		

		Residuals	New Drymass
Residuals	3335.0	5.8	3340.8
Helium	1.5		

Dual-Mode System

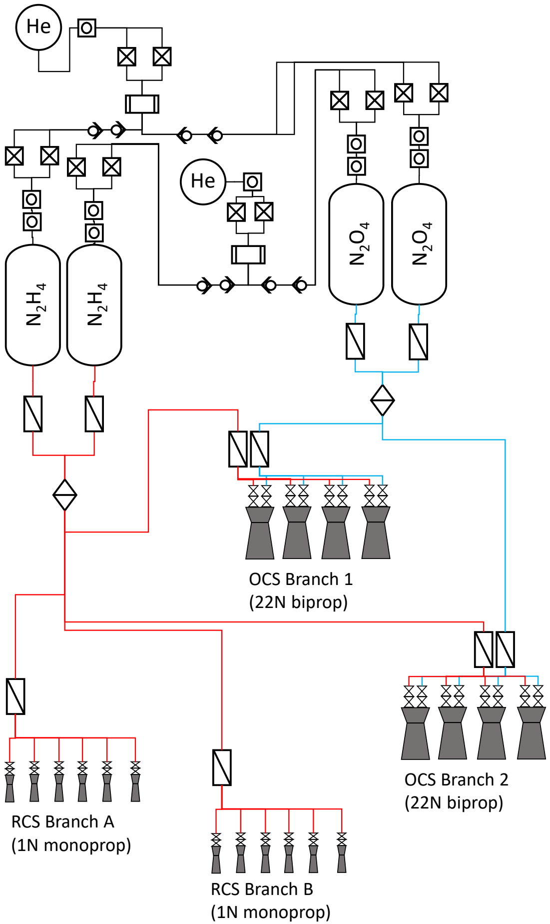
Method	Manoeuvre	mass begin [kg]	mass end [kg]	Δv [m/s]	Thruster	propellant mass [kg]	Fuel mass	Oxid mass	Firing time	Isp Value
1	Flight Prog Corr	3568.2	3531.8	29.7	IHI 22N Dual	36.4	19.7	16.7	13.3	295.0
1	Launcher Dispersion Correction	3531.8	3417.6	95.1	IHI 22N Dual	114.2	61.7	52.5	41.7	295.0
1	Correction of #TCM1	3417.6	3401.7	13.4	IHI 22N Dual	15.8	8.5	7.3	5.8	295.0
2	AOCS Budget	3401.7	3398.1	2.2	CHT-1N	3.6	3.6	0.0		214.8
1	Station Keeping	3398.1	3373.9	15.0	CHT-1N	24.2	24.2	0.0		213.0
1	Disposal	3373.9	3338.4	22.0	CHT-1N	35.5	35.5	0.0		210.9
2	AOCS Budget	3338.4	3335.0	2.1	CHT-1N	3.4	3.4	0.0		210.7
	Summation	3335.0		179.6		233.2	156.7			

Option: Dual Mode Propulsion System

- high specific impulse (295 s vs. 225 s)
- less contamination than MMH/NTO
- simple hydrazine blow down operation for station keeping

break even point – tbd

- for larger delta v:
  - propellant mass saving ca. 70 kg
  - dry mass penalty ~20 kg



Power

Power system Requirements

Requirements	
Orbit	L2 (not eclipses during operation)
Lifetime	5 years
Power consumption with 20% margin	Launch mode:165.7W during 2h launch + 971.9W during 1.5h sun acquisition (heaters are ON, 860Wh +20% are needed for the battery) Science + communications mode: 2409.8W (max average)
Solar Angle (SAS)	0 deg (sun-pointing) with +/-10 deg off-pointing considering 2 deg of error
Solar Array	Body mounted (1 panel)

Power system Assumptions

Assumptions	
Radiation degradation	Data extracted from Lisa Pathfinder for the solar array degradation Cover-glass 150 µm
Power bus	28V (based on heritage units for science missions)
Factor degradations for the solar array	Data extracted from Lisa Pathfinder
Maximum temperature of the solar array	140^{0}C (based on other missions in Lagrange orbits and with body mounted solar array)
Redundancy	For the solar array 5 string loss For the PCDU: cold redundant N+1 For the battery 1 parallel cells

Trade-off / options

Three options preferred for Deep missions and high power:

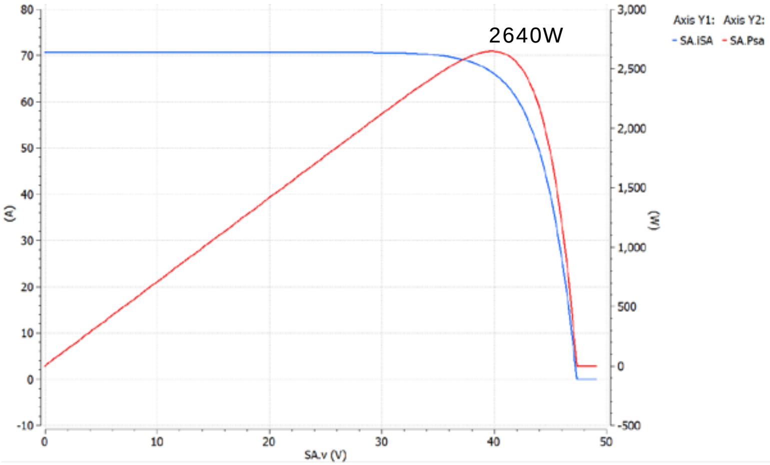
- MPPT + unregulated bus
- S3R + regulated bus
- S3R + unregulated bus

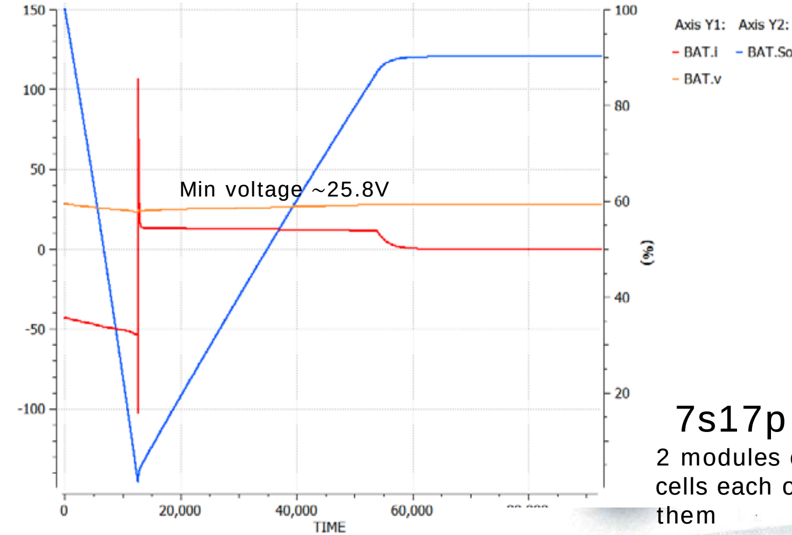
	MPPT + unregulated bus	S3R + regulated bus	S3R + regulated bus
Advantages	- Marginal better behavior in EMC - Reduction of the thermal gradient - No BCR and BDR needed - Permit extract the maximum power of the SA	- More efficient overall for power bus 50V - Simplicity of the PCDU design: mass, dimensions	- More efficient overall for power bus 50V - Simplicity of the PCDU design: mass, dimensions - No BCR and BDR needed
Disadvantages	- PCDU heavier - PCDU more expensive	- Needed to oversize the SA but SA works to fix voltage - Battery higher due to the loss in the BCR and BDR	- Bus no regulated

Current Baseline Design

- Baseline Design:
  - Solar Array cells: 3G30 from Azur Space
    - Triple junction solar cell
    - Efficiency ~30% (BOL), 30.18 cm^2
    - Max temperature 140 ⁰C
    - 1 string lost
  - Battery cells: VES16 Li-Ion cells from SAFT:
    - 33 mm diameter by 60 mm high
    - Nominal mass: 40.5g
    - 4.5Ah total capacity
    - 4.1V EoC and 2.7V EoD
  - PCDU unit
    - Case 1: Architecture MPPT and unregulated bus of 28V
    - Case 2: Architecture S3R and regulated bus of 28V
    - Case 3: Architecture S3R and unregulated bus of 28V

Design MPPT + unregulated bus

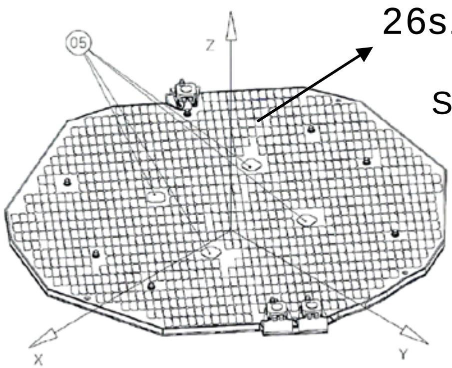




7s17p

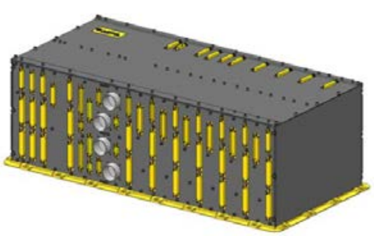
2 modules of 60 cells each one of them

26s156p



Surface PVA 14.2 m^2

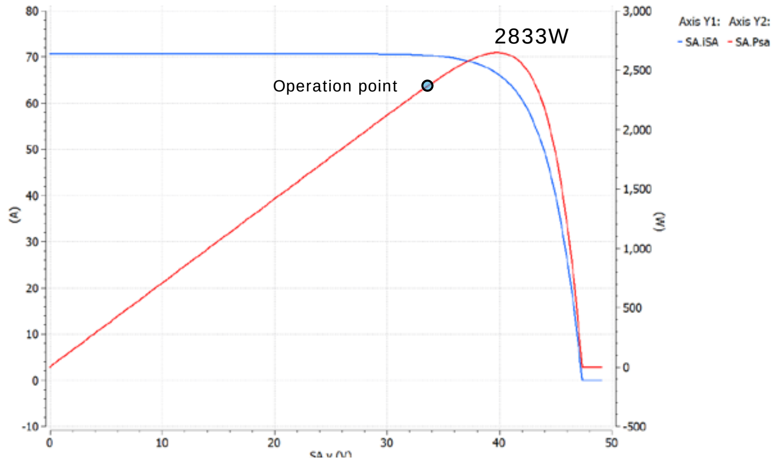
Mass PVA + harnes
29.78 kg ± 20%
Mass substrate
34kg ± 20%

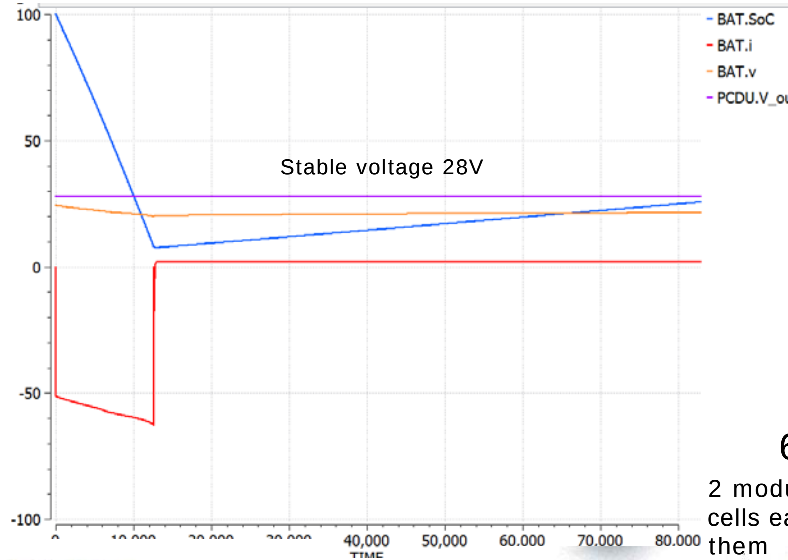


PCDU: Pout configurable

Mass 20.7 kg ± 20%

Design S3R + regulated bus

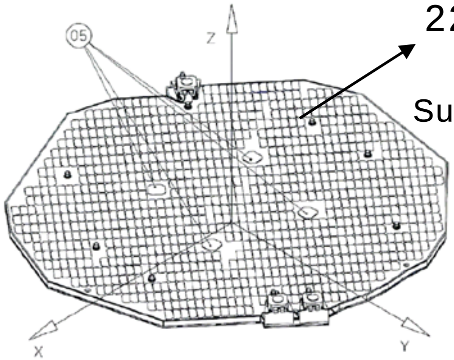




6s21p

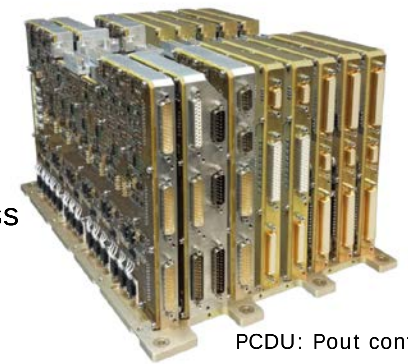
2 modules of 63 cells each one of them

22s193p

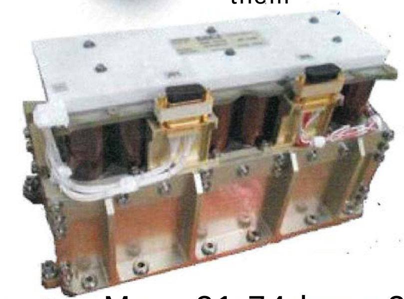


Surface PVA 14.86 m^2

Mass PVA + harness
32 kg ± 20%
Mass substrate
34kg ± 20%



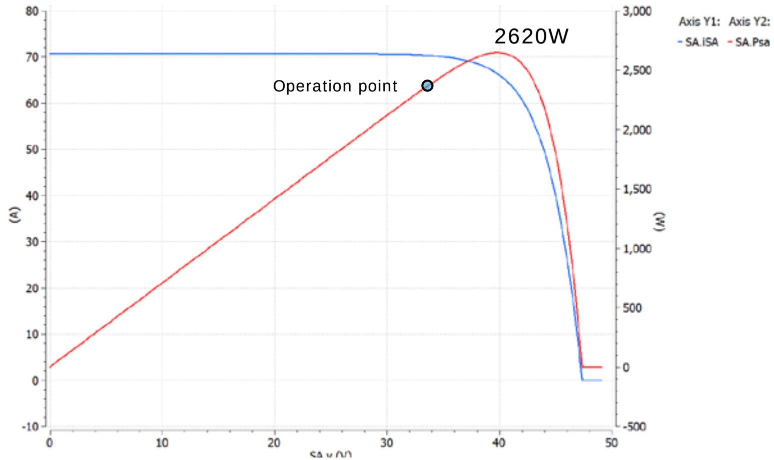
PCDU: Pout configurable with 3kW (max)

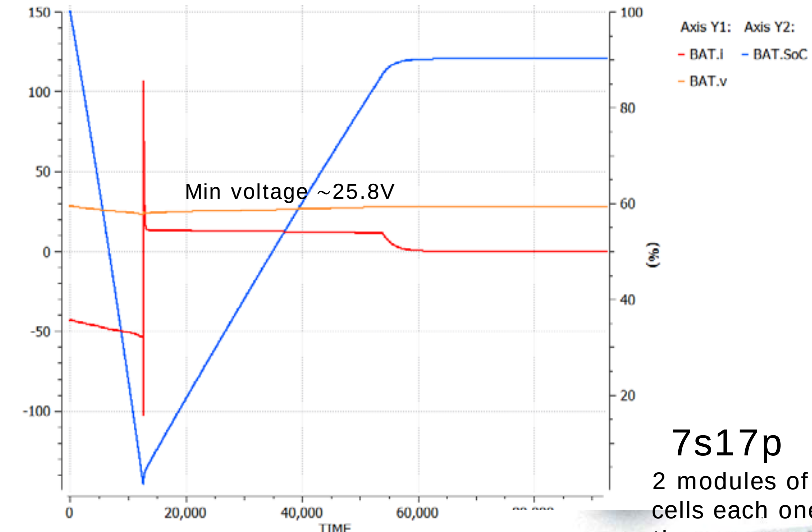


Mass 21.74 kg ± 20%

concurrent design facility

Design S3R + unregulated bus

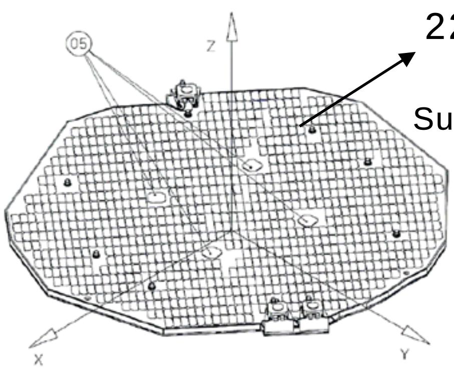




7s17p

2 modules of 60 cells each one of them

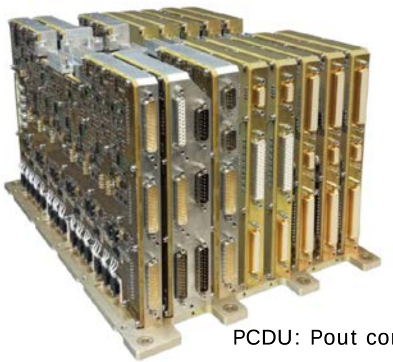
22s193p



Surface PVA 14.86 m^2

Mass PVA + harness 32 kg ± 20%

Mass substrate 34kg ± 20%



PCDU: Pout configurable with 3kW (max)

Mass 43.05 kg ± 20%

Conclusion

	MPPT + unreg bus	S3R + reg bus	S3R + unreg bus
Mass	SA: 63.78 kg BAT: 20.7 kg PCDU: 31 kg TOTAL: 115.5 kg	SA: 66 kg BAT: 21.74 kg PCDU: 22 kg TOTAL: 109.74 kg	SA: 66 kg BAT: 20.7 kg PCDU: ~16.5 kg TOTAL: 103.2 kg
Surface SA	14.2 m^2	14.86 m^2	14.86 m^2
Complexity	-	+	++
Cost	-	+	++

Preferred solution

S3R + unregulated bus

Elements of the Power System

Element	Characteristics	TRL	Heritage
Battery	Configuration 7s17p → 2 x modules of 60 cells each on Mass 20.7 kg ± 20% Surface 2 modules of 305 x 196 x 165 mm^3	7	MTG Cheops Euclid
Solar Array	Configuration 22s193p Mass PVA + harness 32 kg ± 20% Mass substrate 34 kg ± 20% Surface PVA 14.86 m^2	7	Proba 3 Euclid Cheops EDRS-C MTG
PCDU	Mass < 16kg ± 5% (TBC) Volume 292 x 350 x 210 mm^3 Fix power dissipated ~ 70W	7	Juice (S3R regulated) Sentinel 3 Sentinel 5P Seosat

On the time of the project development solar cells 4G32 with high efficiency could be used reducing the mass and dimensions of the solar array in around 10%

Mechanisms

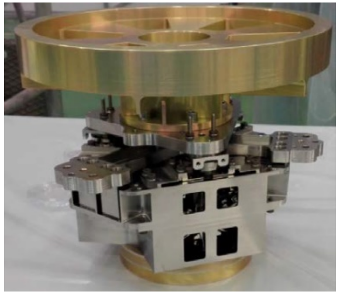
M2 MIRROR MECHANISM

Main functional requirements

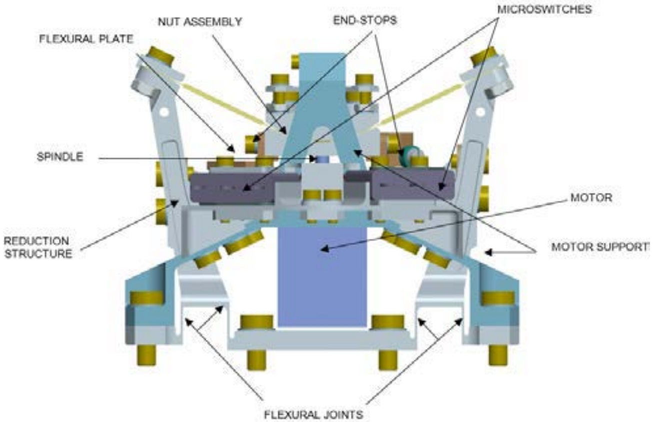
- Perform M2 position adjustments along M2 axis direction, and angular tip/tilt rotations;
- Support secondary mirror with 9 kg mass, 600 mm diameter;
- Axial translation range: 600 µm =>
  - mounting the actuators at 200 mm radius, the tilt range will be 2 mrad
- Parasitic motion / cross-talk in lateral directions (decentering)< 5 µm;

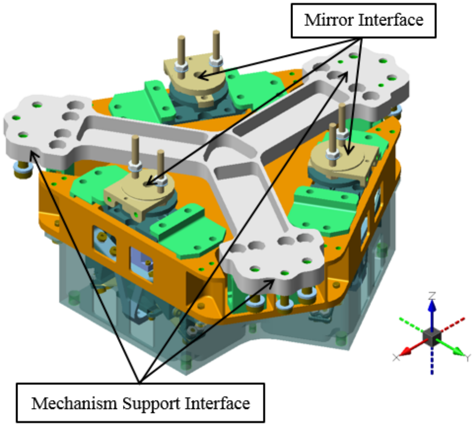
Configuration

- Tripod full symmetrical arrangement the 3 linear actuators;
- Compatible with cryogenic environment 100 K;
- Linear actuator based on Sener Gaia / Euclid heritage:
  - Stepper Motor
  - Planetary Gearbox
  - Plain Screw-nut
  - Flex joint with structural reduction



- 1x HDRM needed due to the higher mass and size of the M2
  - Located in the centre of the M2;



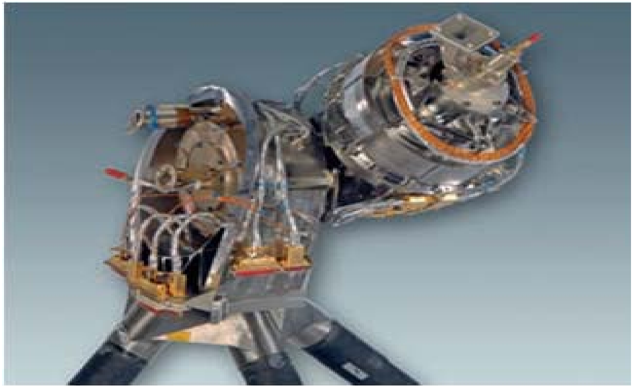


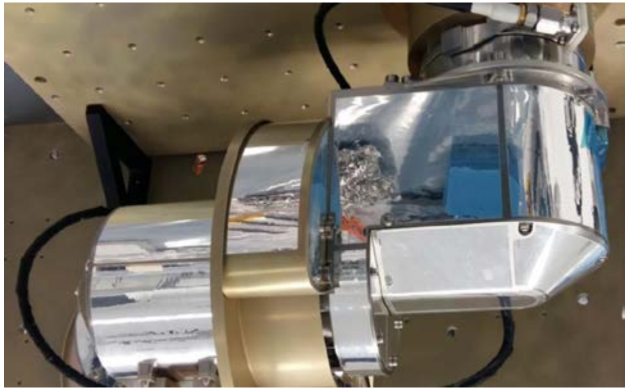
Antenna Pointing Mechanism

Characteristics

- X-Band Antenna: 430 mm diameter;
- Elevation motion range ±38°;
- Pointing accuracy of 0.5 deg and 2 Degrees of Freedom;
- Motors: 2x stepper motors;
- Power consumption, peak <12 W;
- APM Mass: 6 kg (excluding Antenna, HDRM and electronics);
- Heritage: Bepi-Colombo, Euclid;

- 1x HDRM: launch locking at 0° elevation angle;





Mass budget

Agency	Component	S/S	No. of Units	Unit mass (kg)	Mar-gin (%)	Tot. mass (kg)	Power (W)	Notes
ESA	M2 Focus	SIA	1	8	20	9.6	4	-
ESA	M2 Focus HDRM	SIA	1	2	20	2.4	-	-
ESA	APM	SVM	1	6	10	6.6	12	-
ESA	HDRM APM	SVM	1	1	10	1.1	-	-
JAXA	Launch lock for Cryocoolers Isol.	CRYO	6	0.1	5	0.63	-	1 panel, 6 units per panel
JAXA	MINT	CRYO	6	0.2	5	1.26	-	1 panel, 6 units per panel
JAXA	Cryocooler Isolators	CRYO	6	2	5	12.6	-	1 panel, 6 units per panel
JAXA	Separation mechanism with Launch Lock	CM	6	4	5	25.2	-	-
-	**Total**	**-**	**28**	**-**	**-**	**59.39**	**16**	-

Data Handling

Requirements

- The DHS shall manage Spacecraft modes
- The DHS shall manage the SVM and the PLM
- The DHS shall provide the needed interfaces to the PLM
- The DHS shall be dual chain
- The DHS shall support autonomous operations according

to a mission timeline up-loaded from the ground

- The DHS shall provide the I/F to the Thermal System
- The DHS shall be able to interface to sensors/actuators needed for AOCS/GNC and propulsion

Main Drivers

- Within allocated budget (mass, power, volume)
- Reuse as much as possible from similar mission (L2 orbit: Herschel and Euclid)
- Mature and proven technology

Constraints

Geo return may have an impact on the design

Assumptions & Trade-off

- Cold dual redundancy, no need for warm or hot redundancy (impact on power budget)
- Autonomy of 72 hours for storage
- The PLM is using standard I/F

Note: detailed information regarding the I/F of the PLM to the DHS is not available

Baseline Design 1

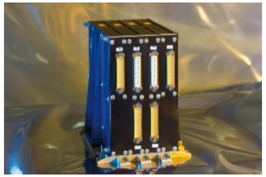
Three units will constitute the Data Handling System

- The On Board Computer (OBC)
- The Remote Interface Unit (RIU)
- The Solid State Mass Memory for Science Data (SSMM)

Baseline Design 2

Starting from two preselected OBC

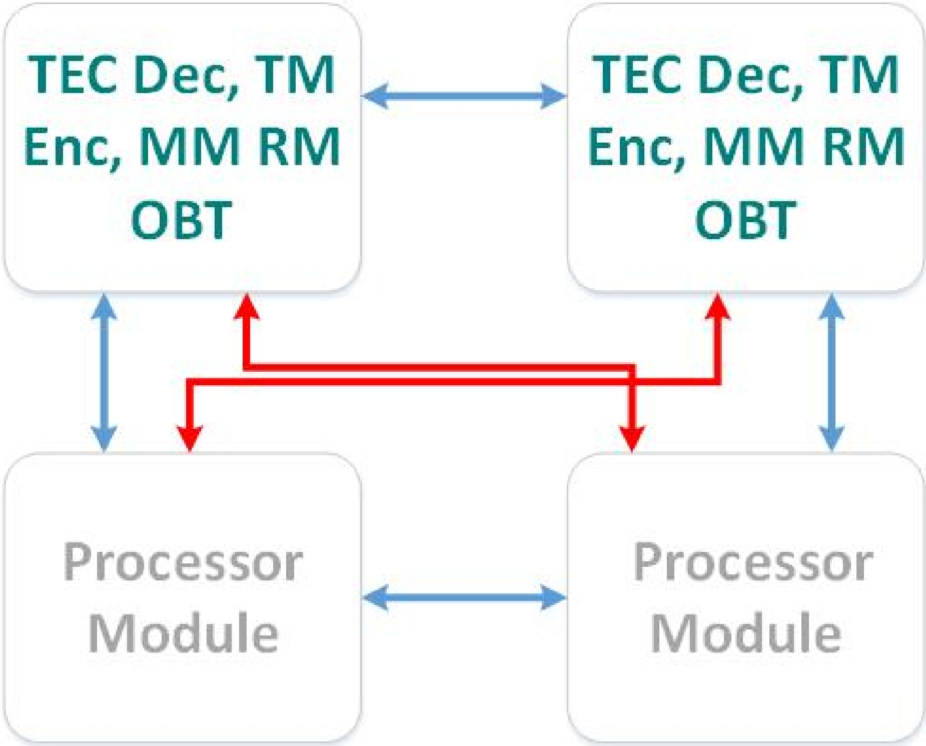
- OSCAR from ADS (SCOC3, Leon based SoC)



- Cole based OBC from RUAG (COLE . Leon based SoC)

- The Selected baseline will be based on Cole OBC

OBC



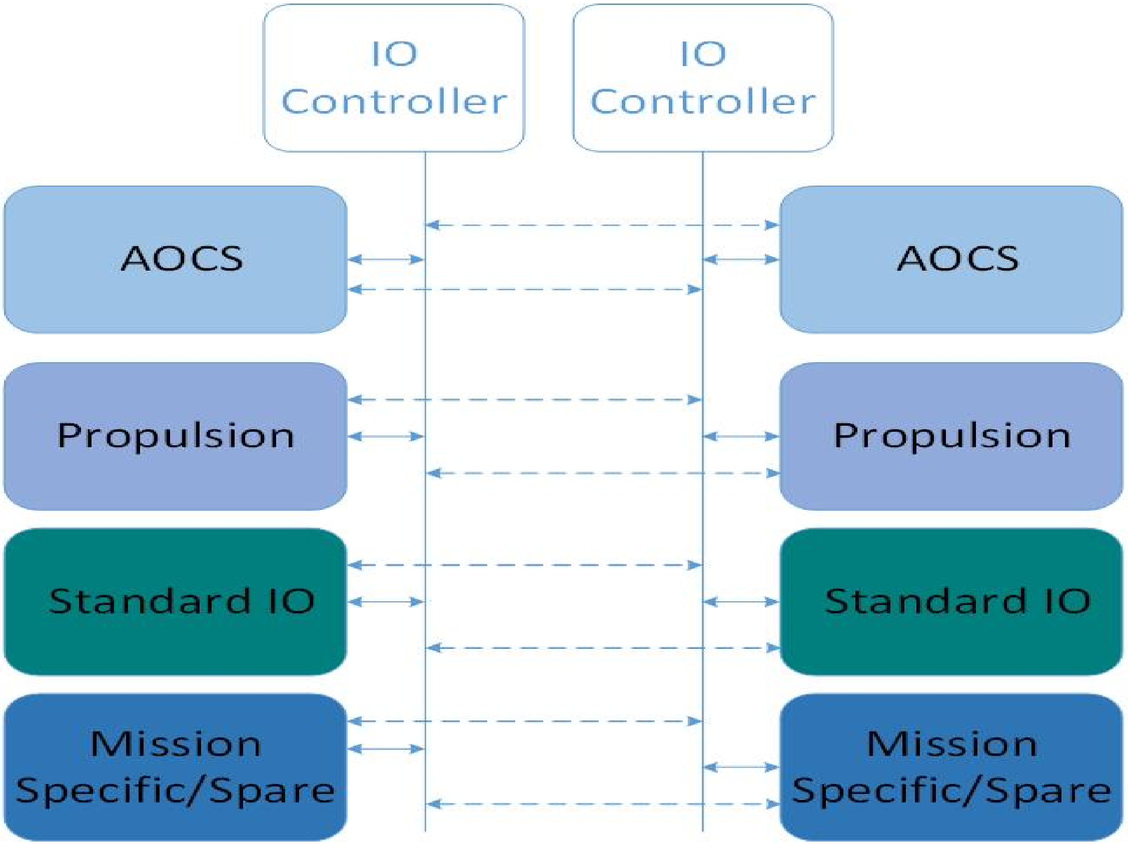
TEC Dec, TM Enc, MM RM OBT
TEC Dec, TM Enc, MM RM OBT
Processor Module
Processor Module

RIU - 1

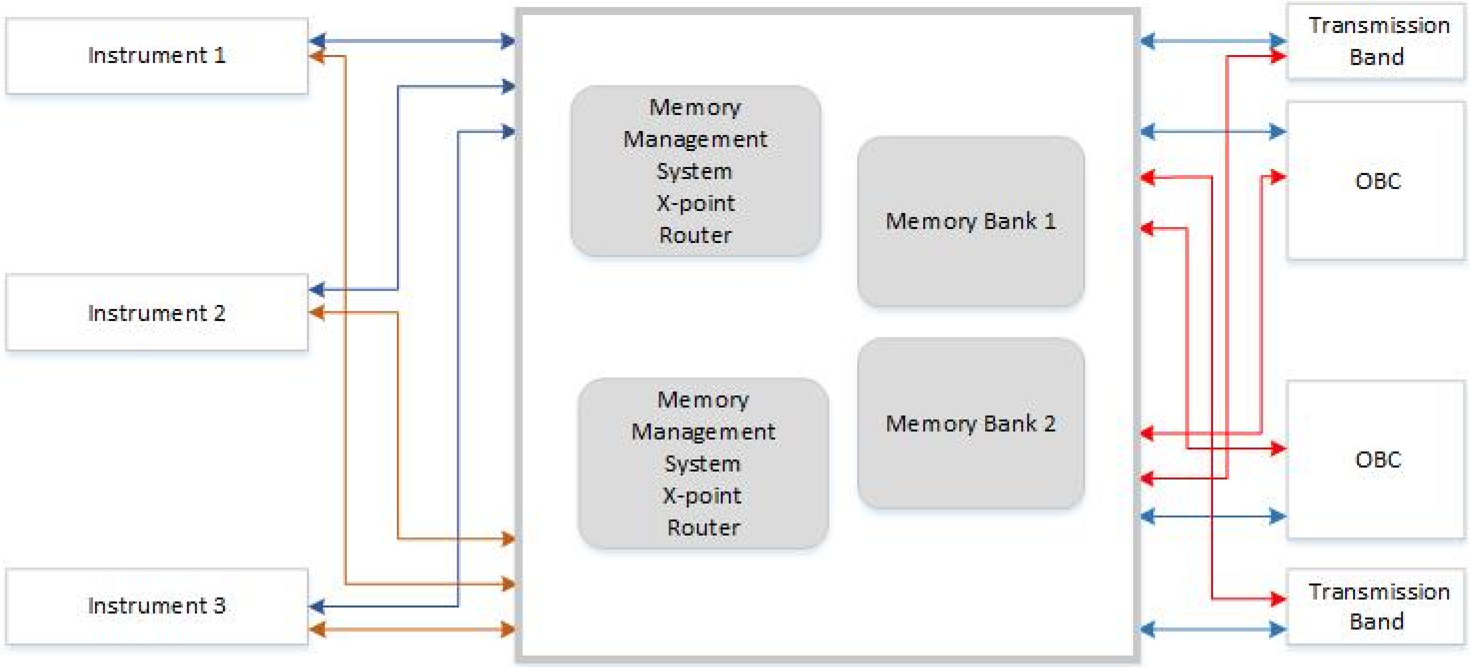
- Many suppliers, the main one: CRISA and RUAG provide RIU compatible with the mission requirements
- Dual redundant unit composed of controller/Interface to OBC and Standard I/F AOCS I/F Propulsion I/F. Many reuse from previous mission, new I/Fs, extension or adaption is expected

- Accommodate all the I/F (sensors, actuators, voltage, current ...) which are not Mil-Std-1553B or SpW
- Interface to Thermal Control Subsystem (Heat pipe, cryo coolers compressors etc...)

RIU 2


IO Controller
IO Controller
AOCS
AOCS
Propulsion
Propulsion
Standard IO
Standard IO
Mission Specific/Spare
Mission Specific/Spare

SSMM - 1


Instrument 1
Instrument 2
Instrument 3
Memory
Management
System
X-point
Router
Memory Bank 1
Memory
Management
System
X-point
Router
Memory Bank 2
Transmission
Band
OBC
OBC
Transmission
Band

SSMM - 2

- The Controller which includes the MM management, the SpW I/F, the cross switches and the routers can be reused from other projects
- The memory bank need to be developed
- Use of CFDP

Mass Memory Budget -1

	Platform	SAFARI	POL	SMI
Data Generation: HK	30 Kb/s	128 Kb/s	15Kb/s	15Kb/s
Total/day	2.592 Gbit/day	11.0592 Gbit/day	1.296 Gbit/day	1.296Gbit/day
Mission Share		65.45 %	4.55 %	30%
Science Data: Declared Effective		4 Mb/s 2.8 Mb/s	1 Mb/s 0.833 Mb/s	5.67 Mb/s 3.969 Mb/s
RECYCLING/ANNEALING CALIBRATION + OBSERVATION (hours)		7.2 16.8	4 20	4 20
Total/day		241.9 Gbit/day	72 Gbit/day	342.9 Gbit/day

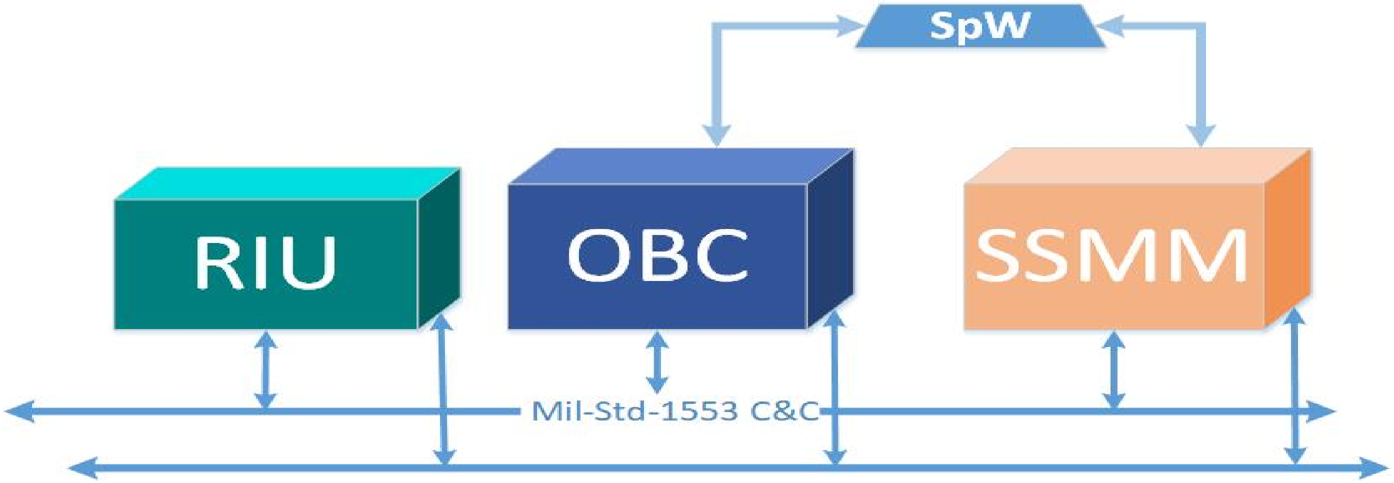
Mass Memory Budget -2

- Total HK stored in OBC MM 16.25 Gbit/day, 25 % EoL -> 20.3 Gbit size
- 72 autonomy -> 61 Gbit, HK Mass Memory EoL size

- Total Science data
- 342.9 Gbit/day + 50 % EOL -> 514.5 Gbit size
- 72 hours autonomy -> 1.544 Tbit, Science Data memory EoL size

Communication Network

- Mil-Std-1553B used for the Command & Control bus: Platform & Payload
- SpW Network used for Science Data



List of Equipments

	Mass (kg)	Margin	Total (kg)	Power (W)	Duty Cycle
OBC	5.5	5%	5.77	14	100%
RIU	15.5	10%	17	34	100%
SSMM	8	15%	9.2	24.5	83%

Options

Communications:

Mil-Std-1553B for Platform and use the SpW Network as a C&C bus for payload and to carry the science data (Metop-SG)

Mechanical Layout:

OBC + RIU in the same box and SSMM in separate Box (S3)

OBC + SSMM in the same box and RIU in separate Box (JUICE)

Conclusion

- The baseline presented here is mostly based on existing equipment, components and technology. Further improvement/change will be possible by the time of the mission preliminary design

Communications

Requirements and Design Drivers

Requirements

- Provide telemetry, telecommand and tracking (ranging) functionalities (at any attitude and mode).
- Provide payload (science + instrument HK) data downlink.

Design drivers

- Payload Data Volume (HK + Science)
  - 278 Gbit/day (mission average)
  - 357 Gbit/day (cycle average)

  Drives S/S design
- Large amplitude quasi Halo orbit around SE-L2
  - 1.77e6 [km] (maximum distance)
- Compression of payload data already taken into account

Assumptions and Trade-Offs

Assumptions

- Ground station
  - ESA DSA (X-band, 3 stations), 35 [m] dish
  - Assume contact times well below 8h (DSA servicing several missions by 2032)
- Modulation and coding schemes
  - The following is considered as the starting point:

  a) Current state-of-art modulation and coding capabilities (for X-band & K-band)

  b) Use of higher order modulation and SCCC coding schemes (acc. CCSDS 131.2) to go beyond 10 [Msps] (for X-band only)
- Payload (science + HK) bit rates
  - The *gross* bit rates must be converted to actual payload bit rates
  - MODCOD rates (they take between ~10% & ~50% of the total transmitted bits)
  - 18% overhead considered (CCSDS CADU as per ECSS-E-ST-50-03C)

Assumptions and Trade-Offs

Trade-Offs

Frequency Bands

- Option 1: X-Band
  - Bandwidth limitation: 10 MHz
  - Can accommodate the required data volumes with the use of higher order modulation (QPSK, 8PSK, 16APSK) and improved coding (SCCC)
  - CCSDS 131.2 (High Data Rate Telemetry) already in place
  - 3/3 DSA with X-band capabilities ; longer contact times required
- Option 2: K-Band
  - No bandwidth limitation
  - Lower component efficiencies (TWTA, …): higher power consumption
  - Increased subsystem cost, mass and volume (X-Band always required)
  - Tighter pointing requirement
  - 2/3 DSA with K-band capabilities (on-going) ; shorter contact times required

Assumptions and Trade-Offs

Trade-Offs

Antennas

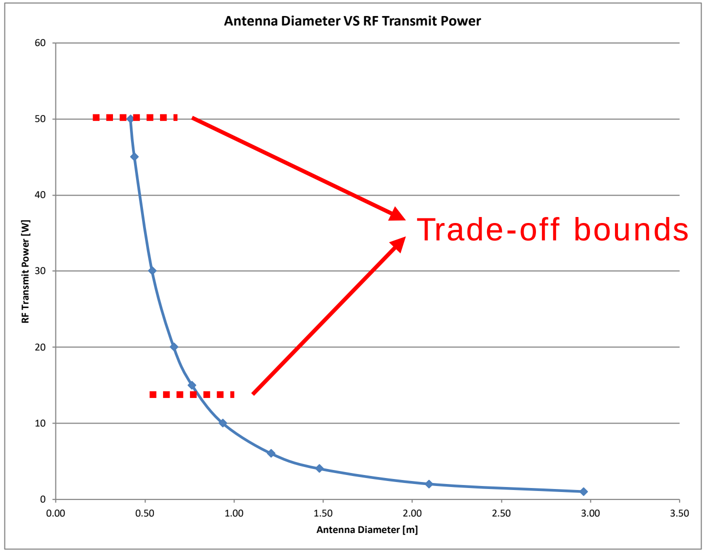
- HGA
  - APM required to ensure pointing for downlink
    - APM-induced vibrations not a driver for science observations
  - Dish size must not compromise the solar array surface (minimum shadows)
- LGA
  - Required for omni coverage (LEOP, Emergency)
  - Must be placed such that there are no disruptions on P/L electronics
  - Accommodation: on SVM, opposite sides (+Y , -Y) (2 LGA is the typical approach)
    - However: bottom plate of PLM adds constraints on omni coverage
      - 3rd LGA added (on the bottom plate of SVM , -Z axis)
      - Similar approach as for Planck

Assumptions and Trade-Offs

Trade-Offs

RF output power vs antenna diameter/gain

- Data rates and link quality (req. Eb/No) drive EIRP, which needs proper split between:
  - RF output power ➡ drives power consumption of amplifiers (affects s/c EPS, TCS)
  - Antenna dish gain + diameter ➡ affects s/c configuration, pointing acc.



Assumptions and Trade-Offs

Baseline (→ Option 4)

Parameter	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
Frequency band	X-Band	X-Band	X-Band	X-Band	X-Band	K-Band
Modulation Coding	GMSK CC+RS	GMSK Turbo	QPSK SCCC	8PSK SCCC	16APSK SCCC	GMSK Turbo
EIRP	36.2 dBW	32.3 dBW	38.1 dBW	44.6 dBW	49.8 dBW	45.1 dBW
Bandwidth (99%, occ.)	8.6 MHz	8.6 MHz	10 MHz	9.6 MHz	9.6 MHz	51.7 MHz
Science + HK data rate	5.5 Mb/s	4.2 Mb/s	8.6 Mb/s	14.9 Mb/s	19.6 Mb/s	25.4 Mb/s
G/S pass	8 h (max)	8 h (max)	8 h (max)	6 h	4 h	4 h
Science + HK data volume	160 Gb/d	122 Gb/d	247 Gb/d	321 Gb/d	282 Gb/d	365 Gb/d
Target volume (mission avg)	278 Gb/d	278 Gb/d	278 Gb/d	278 Gb/d	278 Gb/d	278 Gb/d

Assumptions and Trade-Offs

Baseline

Parameter	Option 4
Frequency band	X-Band
Modulation Coding	8PSK SCCC
EIRP	44.6 dBW
Bandwidth (99%, occ.)	9.6 MHz
Science + HK data rate	14.9 Mb/s
G/S pass	6 h
Science + HK data volume	321 Gb/d
Target volume (mission avg)	278 Gb/d

Assumptions and Trade-Offs

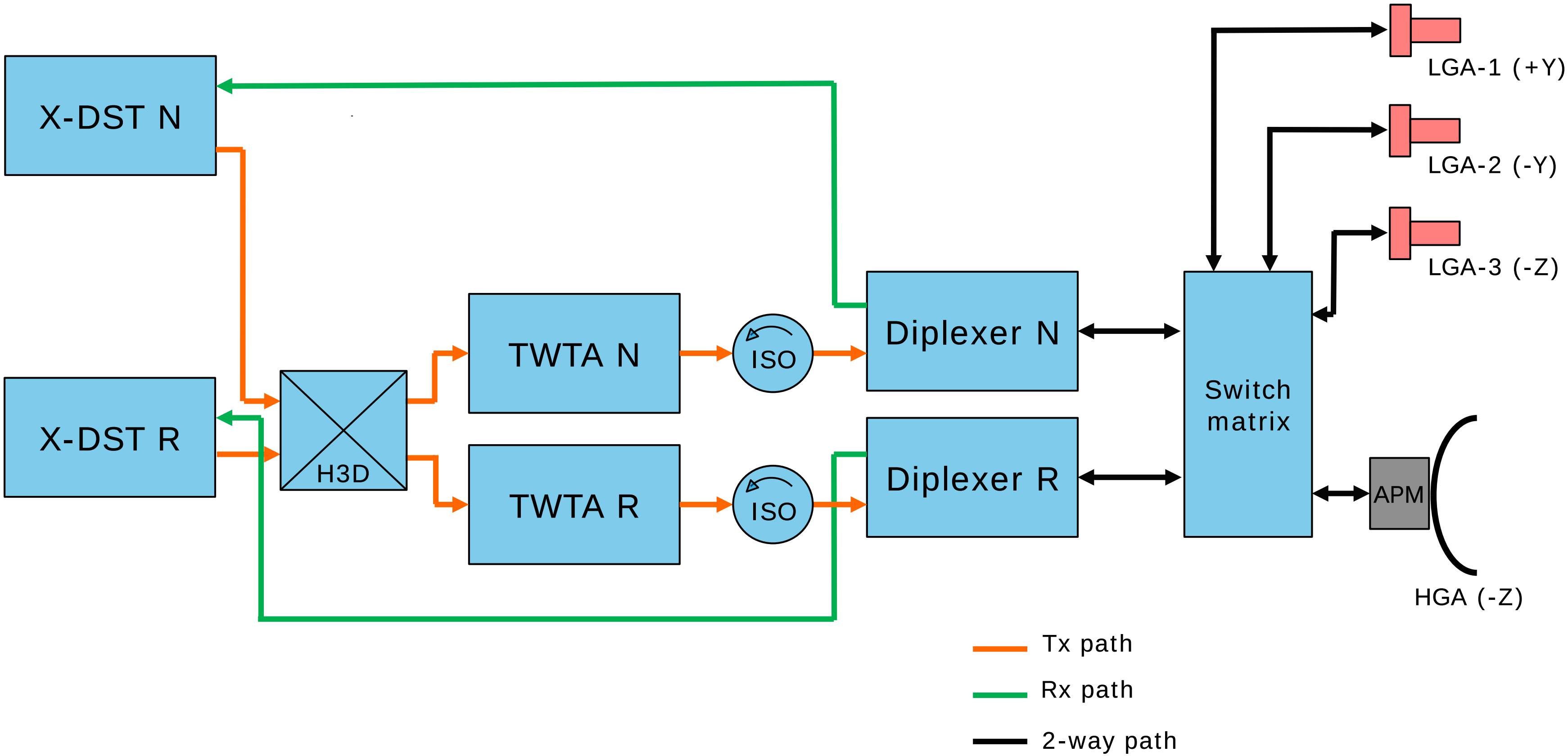
Baseline

Parameter	Option 4
Frequency band	X-Band
Modulation Coding	8PSK SCCC
EIRP	44.6 dBW
Bandwidth (99%, occ.)	9.6 MHz
Science + HK data rate	14.9 Mb/s
G/S pass	6 h
Science + HK data volume	321 Gb/d
Target volume (mission avg)	278 Gb/d

A) Reserving 10 m for RNG
&
B) Including 2.6 Gb/d of platform HK TM

G/S pass	5 h 50 m
Science + HK data volume	310 Gb/d
Target volume (mission avg)	278 Gb/d ✓

Baseline Design



Baseline Design

Mass & Power

22.85 [kg] ; 26.3 [kg] (incl. margin)	
~137 [W] peak power consumption (one TX ON ; both RX ON)	

Baseline Design

Mass & Power

	22.85 [kg] ; 26.3 [kg] (incl. margin)
	~137 [W] peak power consumption (one TX ON ; both RX ON)

Hardware

3 LGAs for omni coverage (LEOP, emergency)
1 HGA for P/L data downlink (high rate)
1 RF front-end (X-band only), redundant, cross-strapping (hot red. for Rx) (cold red. for Tx)
External RF signal amplification required (via TWTA)
Overall, high TRL (technologies are flight proven) However, transponder needs additional development (TRL-6 by 2024 feasible)

Baseline Design

Mass & Power

22.85 [kg] ; 26.3 [kg] (incl. margin)
~137 [W] peak power consumption (one TX ON ; both RX ON)

Hardware

3 LGAs for omni coverage (LEOP, emergency)
1 HGA for P/L data downlink (high rate)
1 RF front-end (X-band only), redundant, cross-strapping (hot red. for Rx) (cold red. for Tx)
External RF signal amplification required (via TWTA)
Overall, high TRL (technologies are flight proven) However, transponder needs additional development (TRL-6 by 2024 feasible)

Features

X-band, 8PSK modulation + SCCC coding
Ranging (RNG) and data downlink possible at ~1.1 [Mbps] (P/L bit rate) (10m link for RNG) (GMSK + PN-ranging) (to-be-used in SolO)
LGAs can be used as back-up for nominal downlink (at lower rates); and also for RNG

Baseline Design

Mass & Power

22.85 [kg] ; 26.3 [kg] (incl. margin)
~137 [W] peak power consumption (one TX ON ; both RX ON)

Hardware

3 LGAs for omni coverage (LEOP, emergency)
1 HGA for P/L data downlink (high rate)
1 RF front-end (X-band only), redundant, cross-strapping (hot red. for Rx) (cold red. for Tx)
External RF signal amplification required (via TWTA)
Overall, high TRL (technologies are flight proven) However, transponder needs additional development (TRL-6 by 2024 feasible)

Features

X-band, 8PSK modulation + SCCC coding
Ranging (RNG) and data downlink possible at ~1.1 [Mbps] (P/L bit rate) (10m link for RNG) (GMSK + PN-ranging) (to-be-used in SolO)
LGAs can be used as back-up for nominal downlink (at lower rates); and also for RNG

Data Rates

Data rates for HK TM & TC (from platform): • HK TC: 4 [kbps] • HK TM: 32 [kbps]
High data rates: • Up to 20 [Msps] (gross) using 8PSK + SCCC (14.9 [Mbps] P/L data rate) • Up to 2 [Msps] (gross) for combined Data (GMSK) + RNG (~1.1 [Mbps] P/L data rate)

Baseline Design

Mass & Power

22.85 [kg] ; 26.3 [kg] (incl. margin)
~137 [W] peak power consumption (one TX ON ; both RX ON)

Hardware

3 LGAs for omni coverage (LEOP, emergency)
1 HGA for P/L data downlink (high rate)
1 RF front-end (X-band only), redundant, cross-strapping (hot red. for Rx) (cold red. for Tx)
External RF signal amplification required (via TWTA)
Overall, high TRL (technologies are flight proven) However, transponder needs additional development (TRL-6 by 2024 feasible)

Features

X-band, 8PSK modulation + SCCC coding
Ranging (RNG) and data downlink possible at ~1.1 [Mbps] (P/L bit rate) (10m link for RNG) (GMSK + PN-ranging) (to-be-used in SolO)
LGAs can be used as back-up for nominal downlink (at lower rates); and also for RNG

Data Rates

Data rates for HK TM & TC (from platform): • HK TC: 4 [kbps] • HK TM: 32 [kbps]
High data rates: • Up to 20 [Msps] (gross) using 8PSK + SCCC (14.9 [Mbps] P/L data rate) • Up to 2 [Msps] (gross) for combined Data (GMSK) + RNG (~1.1 [Mbps] P/L data rate)

Driving Link Budgets
(at farthest distance)

P/L (science + HK) data downlink (high rate) (HGA)	✓
P/L (science + HK) data downlink (low rate) (LGA) **(*)**	✓
Platform HK TM downlink (nominal) (LGA) **(*)**	✓
Platform HK TM downlink (emergency) (LGA)	✓ (orange)

✓ ⇨ ➢ **5 [dB] margin**

✓ (orange) ⇨ ➢ **3 [dB] margin**

*** These links are a "nice to have"**

Baseline Design

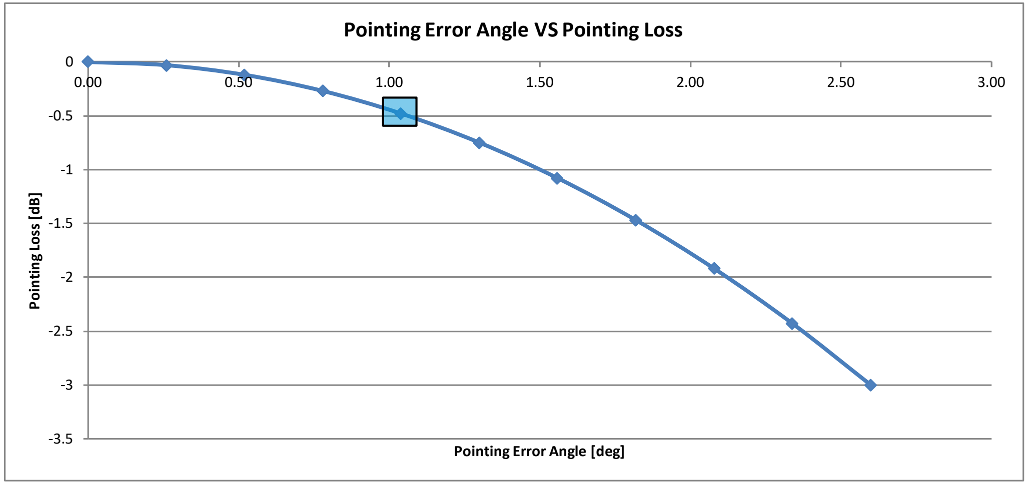
Data Volume (achieved) (assuming 6h pass)
Gross data volume -> **432 Gbit / pass** (actual data volume sent to ground)
Payload (science + HK) data volume -> **321 Gbit / pass**

Data Volume (required)	Feasible with baseline design?
Payload (science + HK) data volume (mission average) -> **278 Gbit / day**	**YES**
Payload (science + HK) data volume (cycle average) -> **357 Gbit / day**	**NO**

As a result, specific management of instrument cycles shall be needed at some points during the mission in order to fulfill communications needs

Baseline Design

- Baseline: **X-Band, 8PSK + SCCC**
  - 45 [W] RF output power (TWTA) (16.5 [dBW])
  - 0.44 [m] ø HGA ; boresight gain of 30 [dBi]
    - 3dB beam-width @ ±2.60 [deg] ➡ drives pointing accuracy
      - 0.5 [dB] pointing loss <--> 1.05 [deg] pointing error

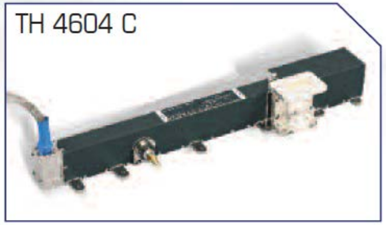


Equipment List

- **X-band DST** (TAS-I): needs modifications (CCSDS 131.2-B-1 for high rate TM downlink)
- **TWTA (TWT + EPC)** (Thales): TRL-9
- **LGA** (Rymsa, RUAG): choked horn, TRL-9
- **HGA** (Rymsa, RUAG): technologies are TRL-9
- **RFDN** (several): TRL-9, waveguide (passive) equipment

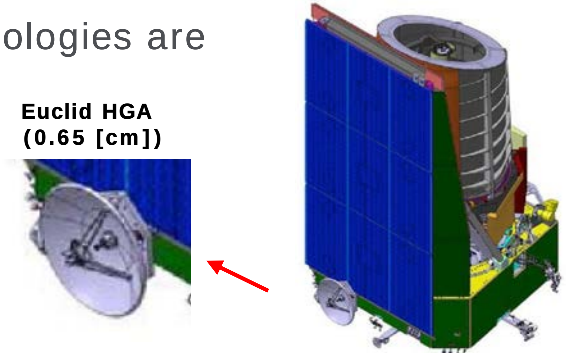
X-DST

X-band TWT + EPC



X-band TWT

Euclid HGA (0.65 [cm])



X-Band LGA

Options

- Option 1: [X-Band, 16PSK + SCCC]
  - Can be used in case data volume requirements increase
  - TRL is the same as baseline equipment; same delta-development on the DST required (with a bit more complexity/risk)

- Option 2: [K-Band, GMSK]
  - Can be used in case data volume requirements dramatically increase
  - Overall high TRL, but with the caveats of K-band outlined earlier in the presentation

Technology Readiness

- CCSDS 131.2 (Higher order modulation + SCCC)
  - Transmitter implemented in activity for EOP
  - IP core for SCCC in place
  - Implemented K+X-Band Transmitter, demonstrated up to 2.7 Gbit/s
  - EQM (TRL 6) available, end of activity Q4/2018
  - Analyzed full scope of standard (up to 64APSK), including TWTA non-linearity and RF output filtering
- Transponder
  - Currently no Deep Space Transponder with CCSDS 131.2 available
  - Requires delta development on TAS-I Deep Space Transponder
  - **High confidence of maturity until mission adoption**

Structures

Payload Interface (mechanical)

- PAF937C
- PAF1194C
- PAF1666C
  - Interface diameter : 1,666 mm
  - Height : 450 mm
  - Attached system : Clamp bands
  - Separation springs : 4 - 8 springs

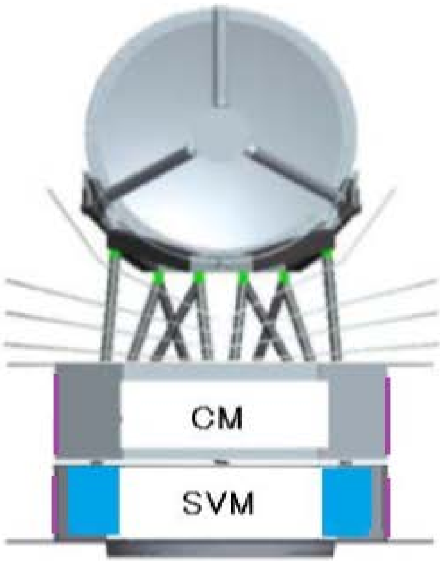
Stiffness Requirement

- Fundamental Frequency **Stiffness of the primary structure**
  - Longitudinal : > 30Hz
  - Lateral : > 10Hz
- Center of Gravity Location **Stiffness, Configuration**
  - Horizontal: preferably within 35 mm of the center axis (up to 100 mm acceptable).
  - Height from Separation Plane : depends on PAF type
    - PAF1666C: S/C CoG Height : < 4m for S/C Mass < 4000 kg

Configuration Concepts

1st

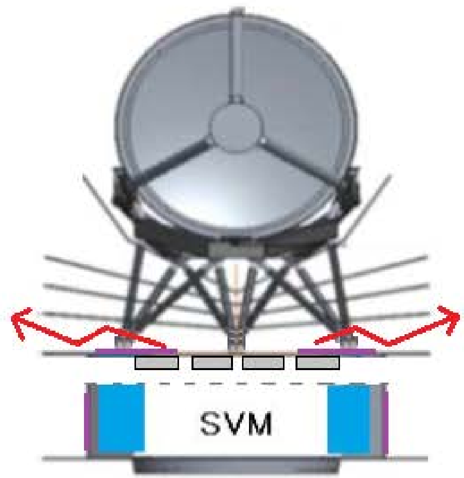
M5 Proposal



Extended PLM

Cryo-coolers and Instrument warm units in CM (PLM radiators in PLM)

4th

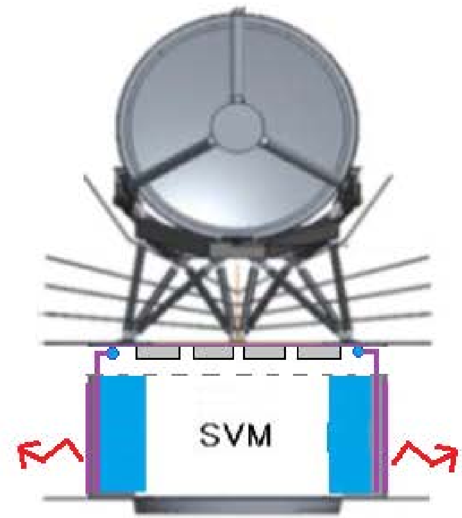


Compact PLM

Cryo-coolers in PLM and Instrument warm units in SVM (PLM radiators in PLM)

3rd

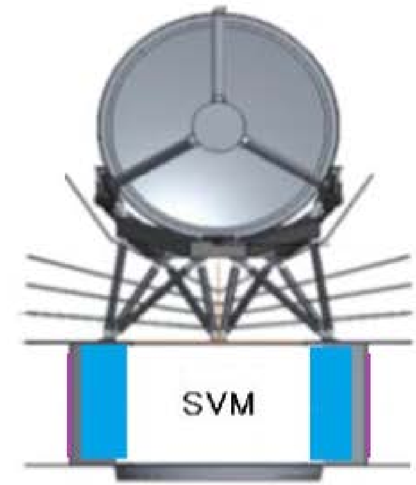
CDF Baseline



Hybrid PLM

Cryo-coolers underneath* PLM bottom panel and Instrument warm units in SVM (PLM radiators in SVM with LHP I/F)

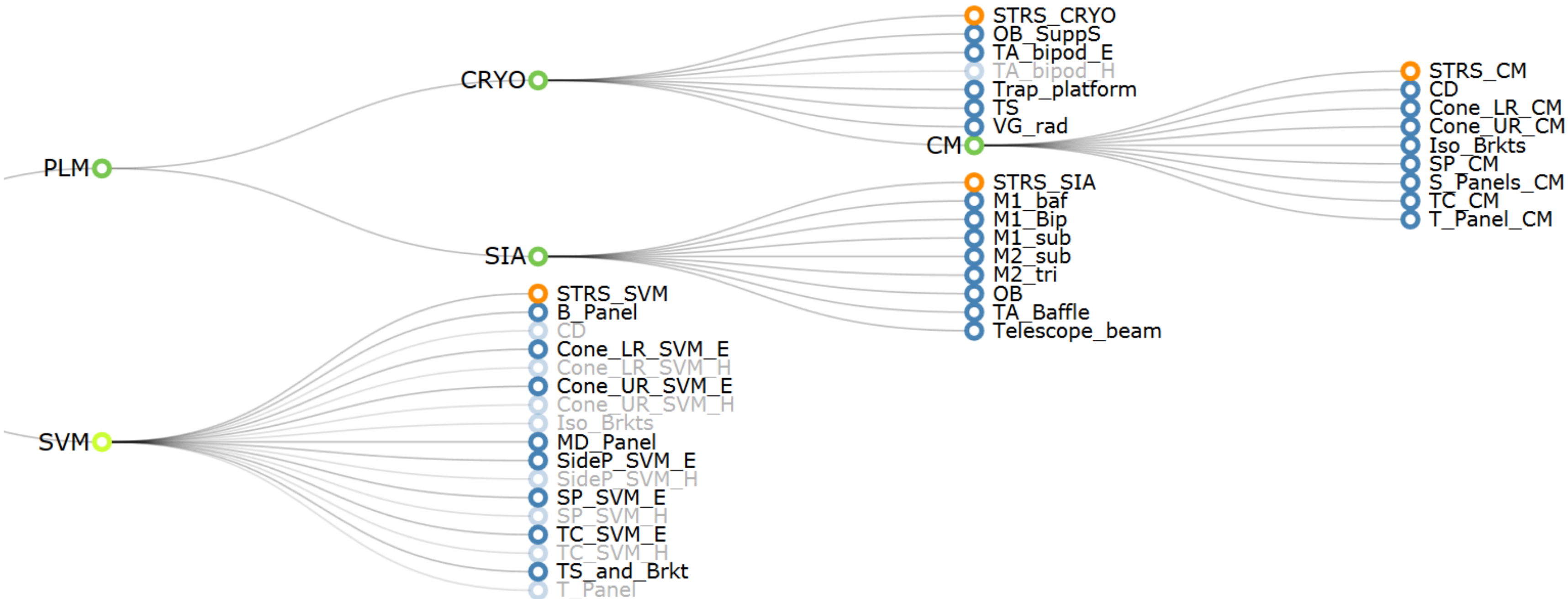
2nd



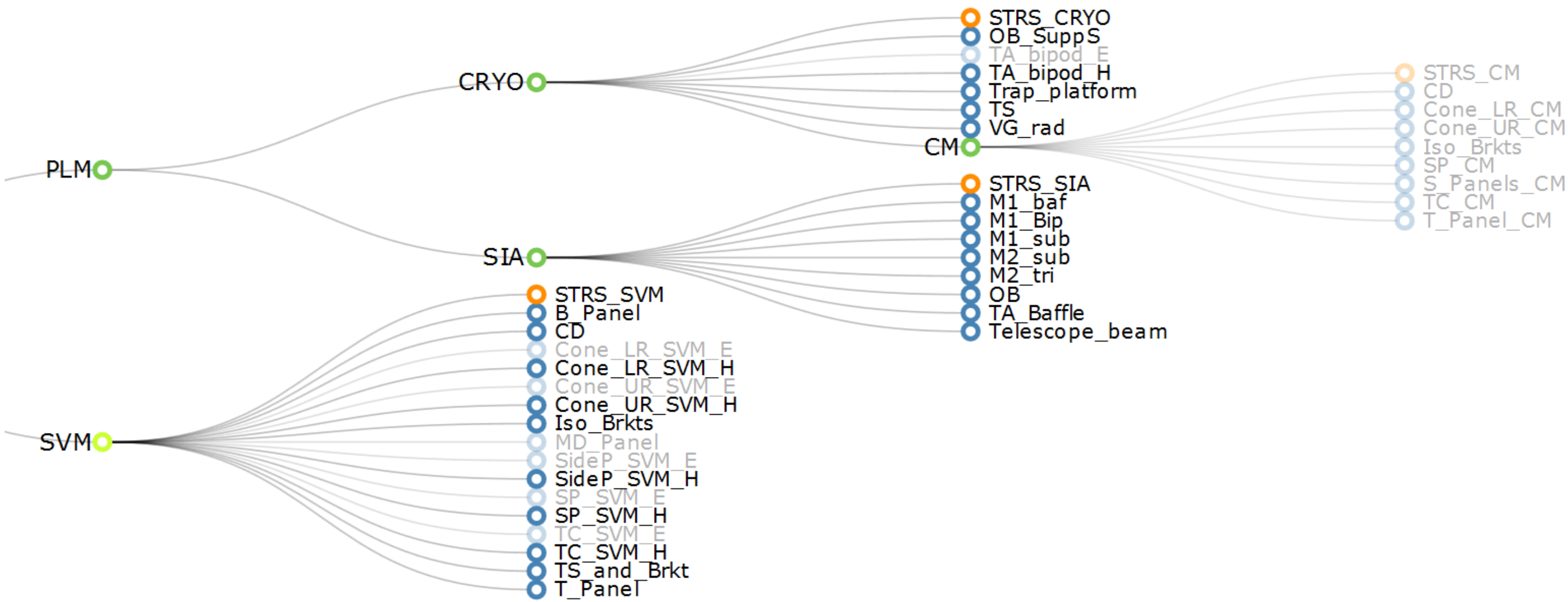
Modified PLM

Cryo-coolers and Instrument warm units fully integrated in SVM (all radiators in SVM)

E-PLM Structure in SPICA Sinoptics

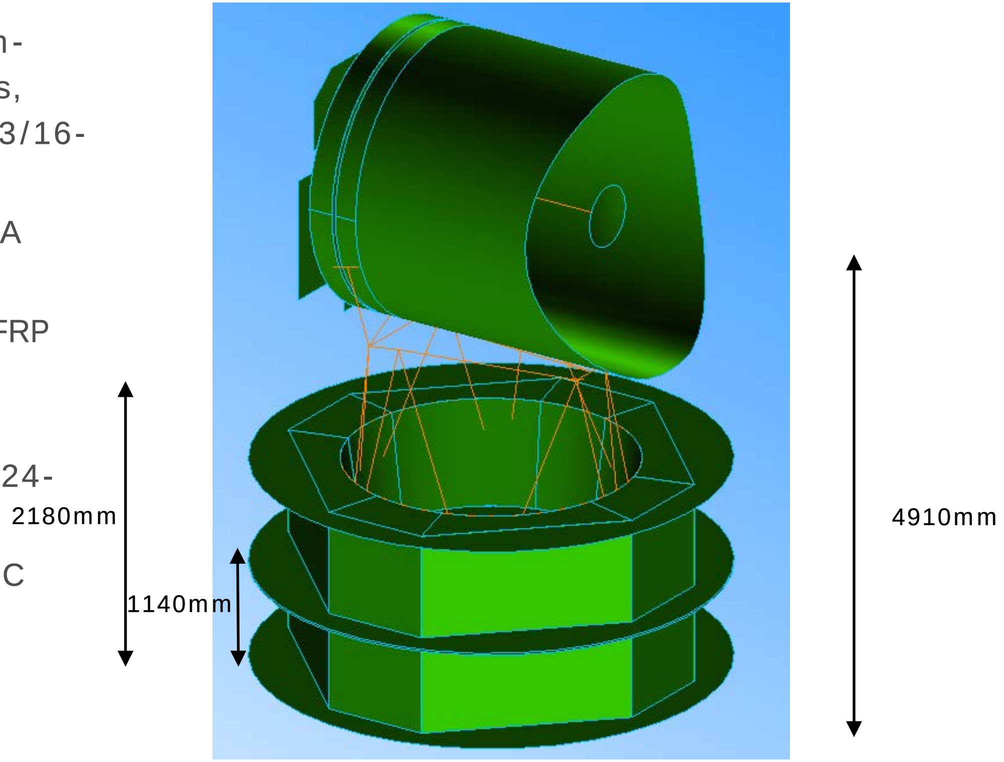


H-PLM Structure in SPICA Sinoptics



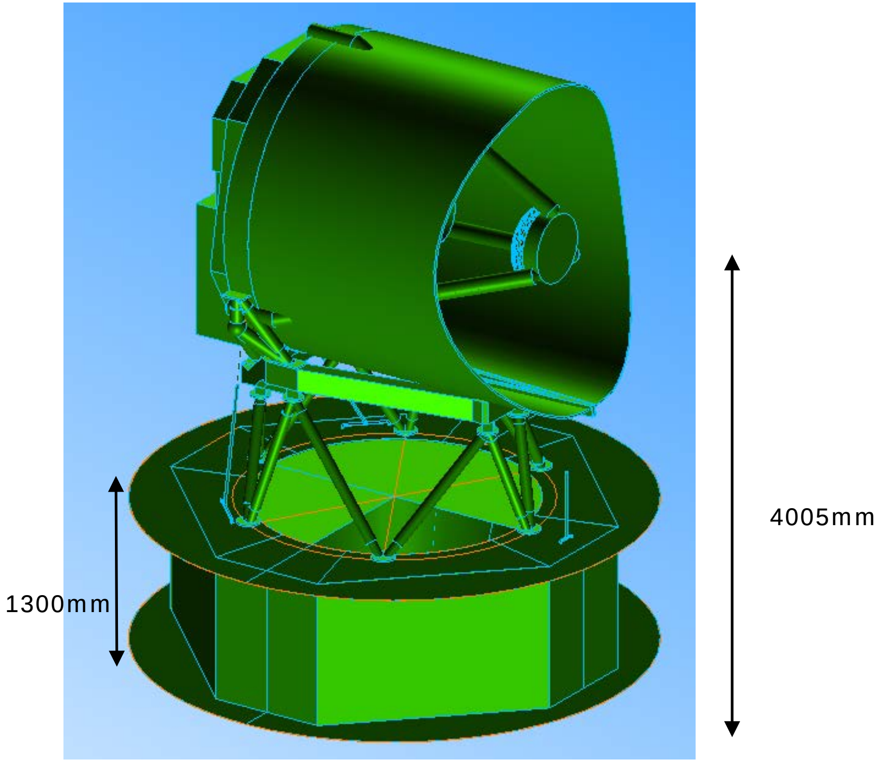
Extended PLM - Layout

- **Main features:**
- 2 trust cones, 16 shear panels, bottom-middle- and top-panels, 16 side panels, composite sandwich (honeycomb: AA 3/16-5056) with CFRP skins
- Cone rings (in SVM and CM): forged AA 7075-T73
- long P/L supporting truss structure, CFRP tubes with Al fittings
- TA baffle: composite sandwich (Al honeycomb AA 3/16-5056, skin AA 2024-T81)
- Mirror’s substrates and OB support: SiC (Herschel’s heritage)



Hybrid PLM - Layout

- **Main features:**
- 1 trust cones, 8 shear panels, bottom- and top-panels, 8 side panels, composite sandwich (honeycomb: AA 3/16-5056) with CFRP skins
- Cone rings (lower/upper): forged AA 7075-T73
- Shorter P/L supporting truss structure, CFRP tubes with Al fittings



Structural Mass Breakdown – CM / E-PLM

Element	Material	Density, kg/m^3, kg/m^2 , kg/m	Volume, Area , Length m^3 , m^2 , m	Mass, kg	Margin, %
Thrust Cone	CFRP, AA1/8-5056	49.7, 6.35	8.6	54.6	20
Shear Panels	CFRP, AA 3/16-5056	32.036 , 3.66	5.4	19.8	20
Side Panels	CFRP, AA 3/16-5056	32.036 , 3.66	12.3	45.0	20
Top Panel	CFRP, AA 3/16-5056	32.036 , 3.66	9.74	35.6	20
Cone Ring - lower	AA 7075-T73	2800.	23.56E-03	64.8	20
Cone Ring - upper	AA 7075-T73	2800.	26.34E-03	72.6	20
Isolator brackets	AA7075-T73	JAXA ref.	14.4	14.4	20
Cryo-dampers		JAXA ref.	-	9.2	20
STRS_CM				316.0	379.20

Structural Mass Breakdown – CRYO / E-PLM

Element	Material	Density, kg/m^3, kg/m^2 , kg/m	Volume, Area , Length m^3 , m^2 , m	Mass, kg	Margin, %
Telescope Frame (trapezoid)	CFRP, 150x200	JAXA ref.	-	72	20
TAMain Struts + fitt.	CFRP Tube Φ100x4mm	1.885 kg/m	28.4m	51.5	20
OB Supp. Struts +fitt.	CFRP Tube Φ120x6mm	3.396 kg/m	4.27m	37.2	20
Thermal Shell	CFRP Sandw. (Al core:AA3/16-5056)	2.06 kg.m^2	16.4m^2	36.8	20
V-groove 1 radiators	CFRP Sandw. (Al core:AA3/16-5056)	2.06 kg.m^2	56.4m^2	117.3	20
STRS_CRYO				314.8	377.6

Structural Mass Breakdown – SIA

Element	Material	Density, kg/m^3, kg/m^2 , kg/m	Volume, Area , Length m^3 , m^2 , m	Mass, kg	Margin, %
M1 Substrate	SiC	3140 kg/m^3	Φ2500mm	136.5	20
M2 Tripods +fitt.	Ti	4440 kg/m^3	ref. Herschel	16.3	20
M1 Bi-pods+I/F to substrate	Ti	4440 kg/m^3	Ref. Herschel	10.7	20
M2 substrate	SiC	3140 kg/m^3	Φ595mm	9.2	20
Telescope beam	CFRP		Ref. JAXA	6.9	20
Telescope Baffle	Skin:AA 2024-T81 Core: AA 3/16-5056	32.036 kg/m^3	18.7m^2	71.1	20
Optical Bench	SiC	3140 kg/m^3	Ref. NG	185	20
M1 Baffle	Skin:AA 2024-T81 Core: AA 3/16-5056	32.036 kg/m^3		8.8	20
SIA TOTAL:				444.5	533.4

Structural Mass Breakdown – SVM / E-PLM

Element	Material	Density, kg/m^3, kg/m^2 , kg/m	Volume, Area , Length m^3 , m^2 , m	Mass, kg	Margin, %
Thrust Cone	Skin: M55/EX1515 Core: AA1/8-5056	49.7 kg/m^3 / 6.35kg/m^2	7.33 m^2	46.5	20
Bott. Panel	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	15.9 m^2	58.2	20
Shear Panels	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	7.2 m^2	26.4	20
Side Panels	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	11.6 m^2	42.5	20
Mid. Deck	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	11 m^2	40.3	20
Thrust cone - LR	AA 7075-T73	2800 kg/m^3	15.7E-03 m^3	43.2	20
Thrust cone - UR	AA 7075-T73	2800 kg/m^3	23.56E-03 m^3	64.8	20
Tank struts	Ti	4440 kg/m^3	Ref. NG	40	20
SVM TOTAL:				361.9	434.3

Structural Mass Breakdown – SVM / H-PLM

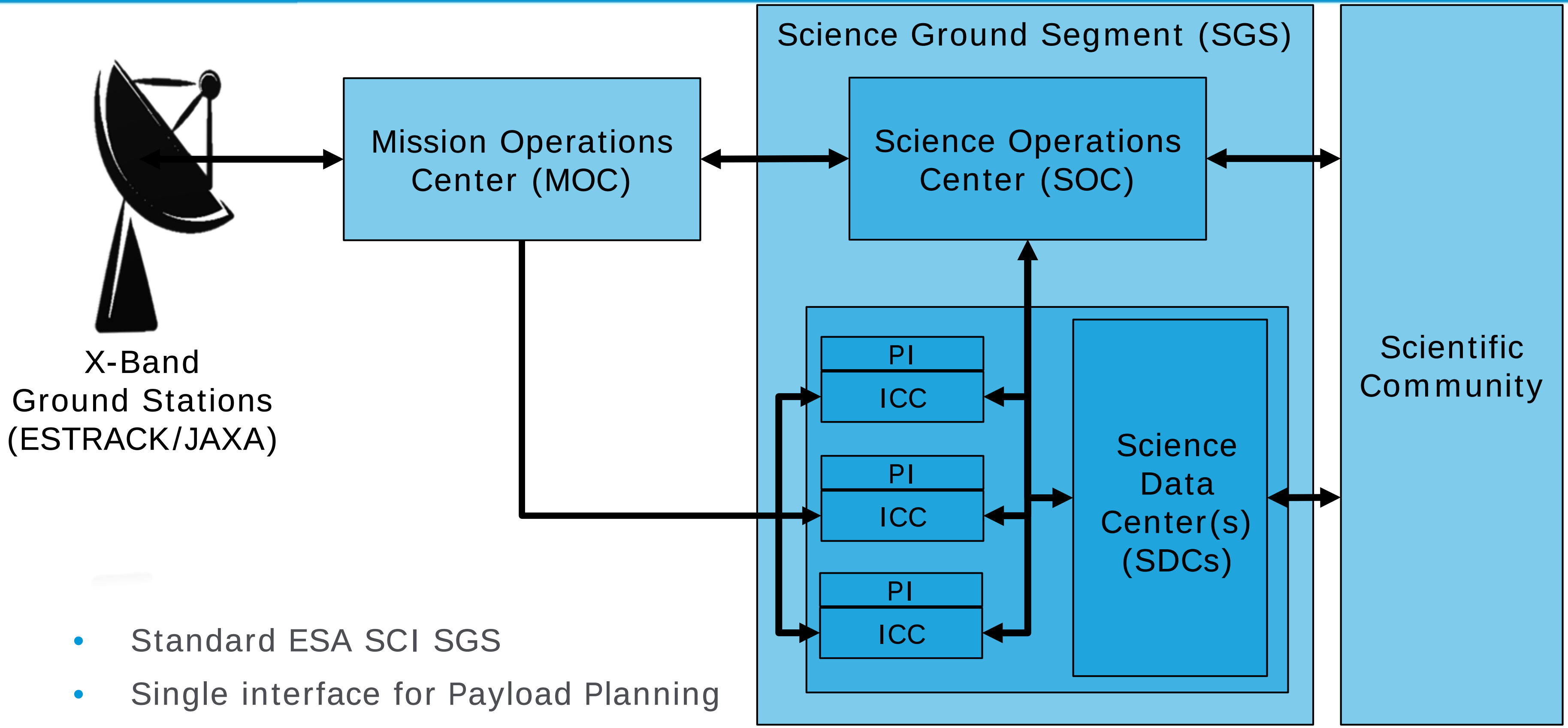
Element	Material	Density, kg/m^3, kg/m^2 , kg/m	Volume, Area , Length m^3 , m^2 , m	Mass, kg	Margin, %
Thrust Cone	Skin: M55/EX1515 Core: AA1/8-5056	49.7 kg/m^3 / 6.35kg/m^2	10.191 m^2	64.7	20
Bott. Panel	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	15.9 m^2	58.2	20
Shear Panels	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	9.7 m^2	35.4	20
Side Panels	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	15.8 m^2	57.8	20
Top Panel	Skin: M55/EX1515 Core: AA3/16-5056	32.036 kg/m^3 / 3.66 kg/m^2	16.2 m^2	59.4	20
Thrust cone - LR	AA 7075-T73	2800 kg/m^3	15,74E-03 m^3	43.3	20
Thrust cone - UR	AA 7075-T73	2800 kg/m^3	23.56E-03 m^3	65.9	20
Tank struts	Ti	4440 kg/m^3	Ref. NG	40	20
Isolator brackets	AA7075-T73	JAXA ref.	14.4	14.4	20
Cryo-dampers		JAXA ref.	-	9.2	20
SVM TOTAL:				448.3	538.0

Conclusions / Status

- Hybrid configuration offers significant advantage w.r.t. structural simplicity, efficiency and mass (e.g. E-PLM mass 1320 kg vs. H-PLM mass: 912 kg).
- Spacecraft stiffness (lateral/axial) shall be assessed by means of FEM, on dedicated structural model
- The subsystem (other than structural) mass budgets will be modelled as a rigid, lumped mass and/or NSM distributed over panel structures as practicable
- System CoG lateral excursion shall be assessed against launcher requirement
- Thermo-elastic assessment will be done on adapted structural FEM

Ground Segment and Operations

SPICA CDF Ground Segment



- Standard ESA SCI SGS
- Single interface for Payload Planning
- *ESA/ESOC infrastructure, requiring no operational interfaces to non European space agencies*

SPICA MOC assumptions

MOC Assumptions

- **Single** Mission Operations Centre (**MOC**). For the purpose of the CDF, assumed at **ESOC**.
- MOC responsibilities, among others:
  - **Spacecraft operations** after launch, spacecraft **monitoring** and **control**, **mission planning** for deferred operations, **orbit and attitude determination and control** – OD accuracy necessary to perform all OCM throughout all the missions phases -.
  - Perform all **communications** with the S/C through the Ground Stations.
  - **Mission data distribution**, MOC shall provide all telemetry (HKTM and Science) to the SOC.

SPICA SOC assumptions

SOC Assumptions

- **Single** Science Operations Centre (**SOC**), standard approach SCI missions. For the purpose of the CDF, assumed at **ESAC**.
- SOC responsibilities (To be Iterated during Phase A):
  - **Interface** with **Science Data Centre**, in order to ensure overall coordination of the Spica payload operations as well as support to the Spica scientific community.
  - **Interface** with the **MOC** for reception of spacecraft data.
  - **Scientific mission planning** requests to MOC, 3 months in advance.
  - Analysis of **calibration data** from s/c HK and Science TM.
  - **Update**, and **provide** to MOC, **calibrations parameters** for uplink.
  - Analysis of **Instruments health** and **performance** (PI *TBC*).

SPICA Ground Stations Options

Use of the **ESTRACK 35 m** antennas for **LEOP** and **Routine:**

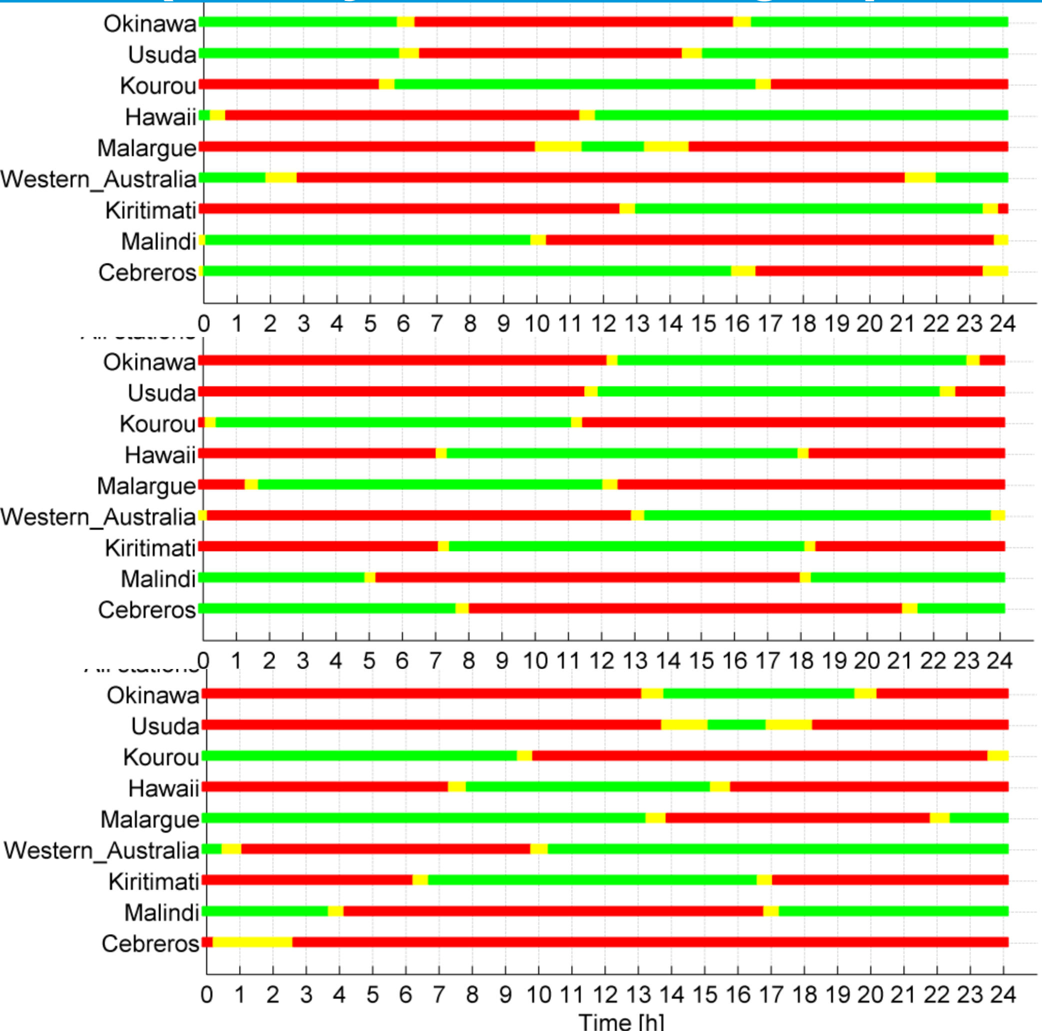
X-Band uplink (7145-7235 MHz range) and downlink capability (8400-8500 MHz) (Upgrade to implement QPSK/8PSK + SCCC)

- **Cebreros**
- **Malargüe**
- **New Norcia-1**

Use of additional antennas to support **LEOP** and **Routine:**

- **New Norcia-2** (4.5m) (**LEOP** Only)
- **MAL-X** (2m) (**LEOP** Only)
- **Kourou** (15m) (**LEOP** Only)
- ***Jaxa: GREAT*** *(54m)*, **Uchinoura** (34m) (**Routine**) – *Mod: BPSK & QPSK Cod:RS+CC. Currently not compatible with QPSK/8-16PSK+SCCC.*

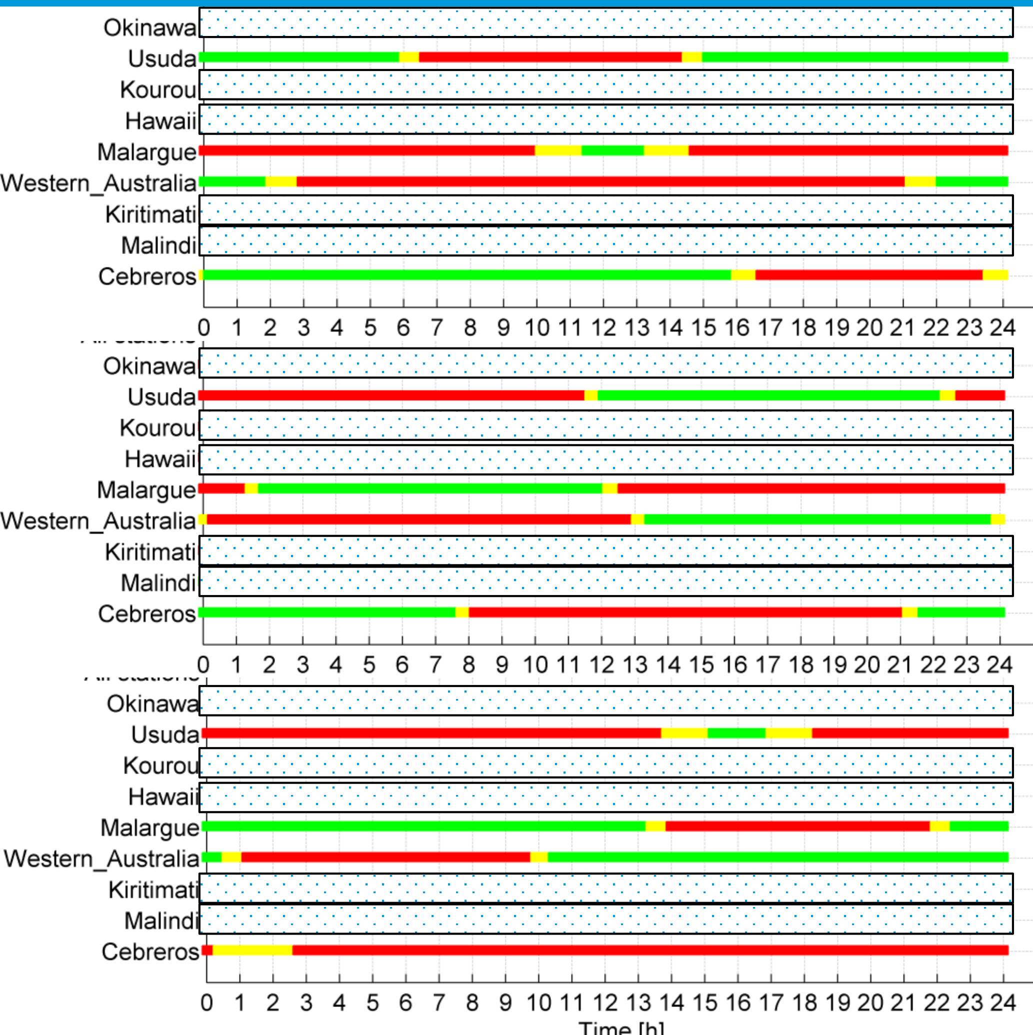
Ground Station Options (NGCryoIRTel – large quasi-Halo orbit)



Max (top), zero (middle) and minimum declination (bottom).

- >=35m Malargue, New-Norcia, Cebreros, Usuda, Uchinoura (not in the figure)
- Okinawa (10/18m), Kourou (15m) Hawaii (15m), Kiritimati, Malindi (10/15m)

Ground Station Routine – Size >=35 m



Max declination (top) –> 1+1 DS GS:

- **~~MLG~~ < 2hrs, NNO1 ~4hrs, CEB ~15hrs**
- (Usuda ~15hrs) GREAT & Uchinoura

Zero (middle) –> 3+1 DS GS:

- **MLG,NNO1 & CEB ~ 10 hrs**
- (Usuda ~10hrs),GREAT & Uchinoura

Minimum declination (bottom) –> 2 DS GS:

- **MLG & NNO ~15hrs, ~~CEB~~**
- ~~Usuda~~, ~~Uchinoura~~

Booking of ESA DSA

ESA L2 missions (Apr. 2018)

Mars oppositions will occur Jun 2033, Sep 2035

Lisa (2034) & SSA SWM Lagrange L5 (2026): Overlap, conflict possible at start or end of SPICA pass.

External support

Missions within **lifetime** have **higher** station **scheduling priority** than mission in the extension phase.

2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
						Spica				
WFIRST (GS support)										
Plato (6 hours/day, Ka-Band)										
		Ariel (15 hours/week, X-Band)								
					Athena (4 h/day X-Band+1x8 h/month)					

SPICA Ground Station Assumptions

- All aspects of the mission shall be **compatible** with the **network** of **ESA** and **JAXA** ground stations.

  Note: JAXA is currently incompatible with QPSK, 8(or16)PSK + SCCC.
- **Baseline** of an AVERAGE **6 hours/day** in routine (**incl**. 5+5 min. **ranging**). Further reduction of ground station contact shall be envisaged.
- **X-Band** deep space. **Baseline**: 8PSK+SCCC. ~~**Backup**: QPSK+SCCC~~

TRP High Rate Flexible Order SCCC Comms for Science X-band:

- **Study** start in **2019**, the complete system to support Variable Coding and Modulation VCM up to Adaptive Coding and Modulation ACM 17, **up to** 16APSK for X-band.
- The additional cost for integrating in the **ESTRACK TTCP** depends a lot on who is the company that makes the study, in the order 200-300 K.

Mission Phases Assumptions - LEOP

LEOP – Launch and Early Orbit Phase:

- Operations executed on **LGAs**
- ~ **2 days** -> LPF LEOP-like durations should be avoided.
- No critical LEOP operations foreseen: attitude acquisition, functional **platform** checkouts, start telescope decontamination heating.
- **Correction manoeuvre** (MA) **L+24 hours** (or 48hrs).

Ground Response time:

- *LEOP critical operations: up to 2 hours,*
- *LEOP outside critical operations: up to 12 hours*

***Questions**: is there a telescope cover to avoid illumination/contamination during launch?* – Answer NO: this should be taken into account in next phase.

Mission Phases Assumptions – CP & PV

Commissioning / Performance Verification Phase

- Completion of telescope decontamination, functional spacecraft checkouts, science data acquisition, first light on instruments and orbit correction manoeuvres.
- HGA deployment.

- **Instrument** performance **determination** and **calibration**
- **Platform** and **Payload** performance **verification** and **optimisation.**
- Use of routine operations instruments.

Ground Response time transfer and Commissioning up to 48 hours

Mission Phases Assumptions – Routine & Disposal

Routine Phase

- **Monthly orbit correction / maintenance manoeuvres**.
- **WoL**, frequency TBC. Coinciding with SKMAN when possible.
- **Science observation plan** loaded on-board **7 days** in advance. No ToOs are assumed.
- **Communications** windows scheduled outside **Safari** Science mode. Like Herschel DSA scheduling together with the Science Community and the safari Science mode will be operated accordingly outside communication windows.
- ***Latency***:
  - *Instrument **Science**: 4 days.*
  - *Instrument **HK**: 1 day.*

Disposal Phase

*Details TBD, **one month** operational efforts assumed for **disposal manoeuvre** and spacecraft **passivation**.*

GS&Ops Remarks

Operational remarks:

- CCSDS and ECSS PUS-C interfaces space to ground. (MO services to transfer files within the Ground Segment)
- High preference for use of **file based operations** to enable use of the **CFDP** protocol to ensure consistency and completeness of data uplink and downlink. The protocol allows for automatic retransmission request for acquiring missed data.

Programmatics

SPICA

Requirements

- Launch in 2032
- Mission Selection Review September 2021
- Phase B1 K.O. December 2021
- Mission Adoption Review March 2024 (SPC June ‘24)
- Phase B2/C/D K.O. March 2025
- SRR Q3 25, PDR Q3 26, CDR Q3 28, QR Q3 30, FAR Q2 31
- Satellite responsibility: ESA
- PLM responsibility: JAXA
- Telescope/SIA responsibility: ESA
- Cryo-chain responsibility: JAXA

Assumptions

- Shipping scheme ESA/JAPAN is the optimised one, after preliminary meetings and JAXA's SPICA-PP-18002 dated June 25, 2018.
- It is assumed that SIA can be assembled and tested in EU
- STM SVM refurbishment to FM is optional
- Cryo test can be done at CSL F6.5 (with modification) while vibration, ambient EMC and integration will have to be planned in one of the main EU space test facilities (ESTEC NL, IABG D, Intespace – ADS F). Other possibilities depend on the Prime Contractor of choice.

Model Philosophy (study final)

	Structural Thermal Model STM (SM for the SVM)	Development Model DM	Cryogenic Qualification Model CQM	Flight Model
Instrument	Structural dummies Mass, CoG (*or CQM, not agreed yet*)	BB, Functional and cryo tests	**CQM units** for SIA and PLM level cryogenic test *(BB refurbished TBD)*	FM Functional and cryo tests
Telescope, SIA	Flight std structure and thermal control, flight std (TBC) Mirrors "CQM" Instruments	No	deleted	full FM, STA optical performance **SIA level test**
PLM	CQM Cryo-chain, **CQM Instruments TBD** BB warm units on SVM dummy, Cryo PLM level test, Flight std. PLM structure	Cryo-chain limited performance, warm units	deleted	Full cryo performance, Warm units on dummy SVM, Microvibration check, EMC test
SVM	FM quality structure, dummy units	BB, EBB equipment, ATB	None	Flight Structure Flight units
S/C	Sine, acoustic, shock, microvibr.	Avionics test bench ATB	deleted	Functional Cryo test, acoustic, microvibration

HW Matrix and test facilities

- Hardware matrix:
  - Telescope structure: 1 FM, 1 dummy
  - Mirrors: 1 set dummy, 1 set FM (2 sets as option)
  - Instruments: 1 dummy, 1 BB, 1 CQM (option: upgraded from BB), 1 FM
  - PLM Structure: 2 FM (option: 1 FM refurbished from STM)
  - PLM thermal control and cryo-chain: 2 flight std (1 on PLM STM, 1 FM)
  - SVM Structure: 1 dummy, 2 FM (option: 1 FM refurbished from STM)
- Test Facilities
  - Accessibility to Focal 6.5 at CSL to be verified, in theory suitable for cryo testing, EMC suitability to be assessed
  - Feasibility of testing: test attitude, heat pipes and 1-g related features
  - Microvibration environment to be controlled during cryo test, CSL did that before
  - Vibration testing at ESTEC, IABG (D) or ADS Intespace (F)

STM PLM

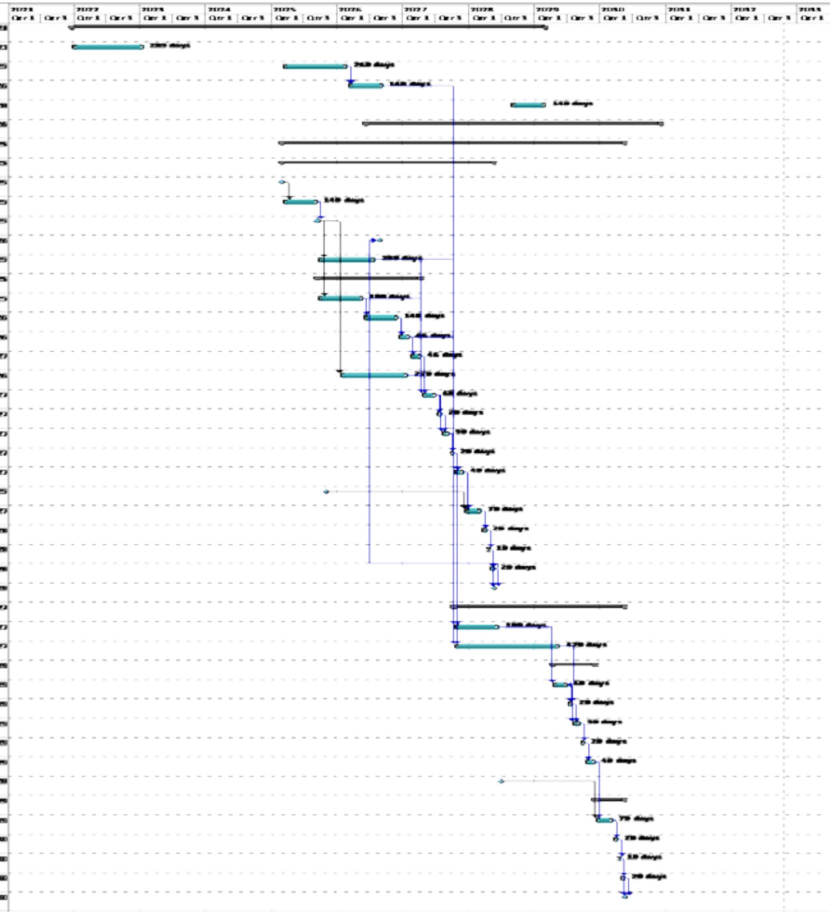
- The need for active instruments on the STM PLM for JAXA testing has been remarked by JAXA
- The JAXA STM PLM is in ESA terms a CQM equivalent, thermally, structurally and functionally representative
- Testing the Instruments with the STM PLM as JAXA request means that a representative telescope needs to be present as well, in ESA view that is in practical terms a QM telescope
- It is not for granted that Instrument “CQM equivalent” can be made available for JAXA STM PLM test campaign. Assessment needed (next phase)

Telescope

- The proposed “protoflight telescope” is from Herschel heritage
  - On the other hand it is deemed risky
  - An added “enhanced STM” would be desirable to qualify its design
  - “Enhanced” because test of the instruments in a SIA configuration would be possible in cryogenic conditions
  - Reduced technical risk, increased cost, schedule seems OK
- An additional “enhanced STM” SIA is added to the schedule
  - Recalculated based on now available Herschel telescope real schedule
  - Remains compatible with a Mission Adoption Review in mid 2024
  - Mirror procurement is the closest activity to critical, and needs consolidation of the design by the SRR: together with the Telescope, this represents a necessary anticipation of procurement
  - SIA FM: 6 months available for AIT with FM PLM

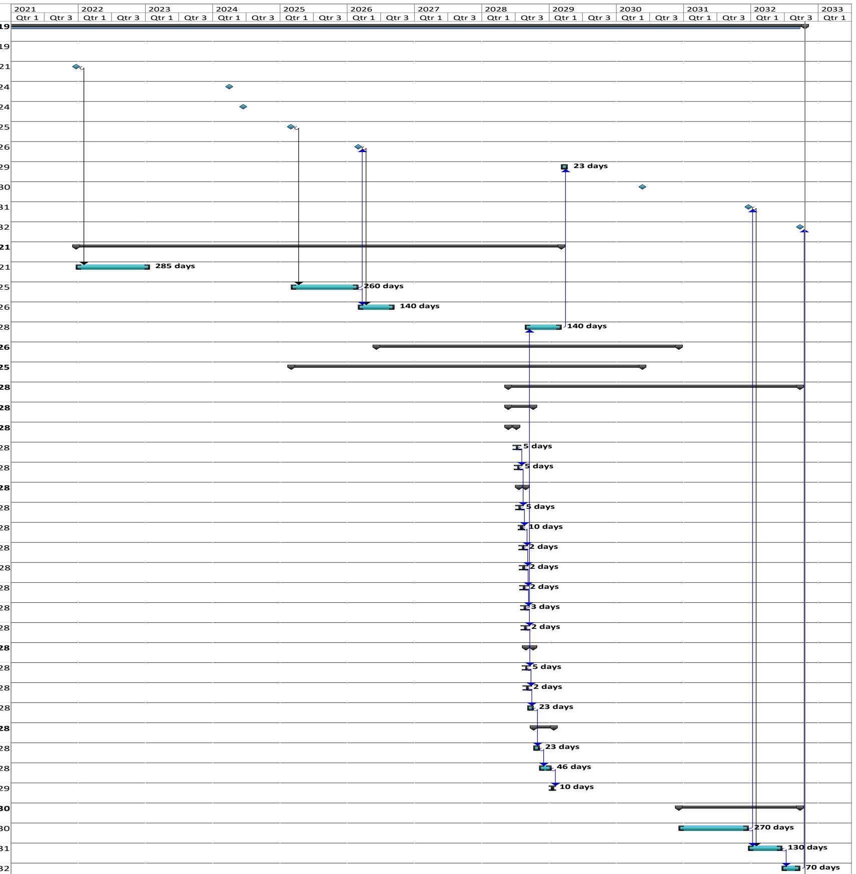
SIA with STM and FM

ID		Task Name	Duration	Start
53		System	1882 days	Tue 21/12/21
54		Early design phase and req. definiti	285 days	Tue 21/12/21
55		Preliminary design	260 days	Mon 03/03/25
56		Lower level PDR's	140 days	Mon 02/03/26
57		Lower level CDR's	140 days	Thu 24/08/28
58		SVM	1174 days	Mon 08/06/26
55		Telescope/SIA	1362 days	Mon 03/03/25
56		STM Telescope/SIA	842 days	Mon 03/03/25
57		SIA Req. Review	0 days	Mon 03/03/25
58		Phase B2 SIA Preliminary Design	140 days	Mon 03/03/25
59		SIA PDR	0 days	Mon 15/09/25
60		SIA CDR	0 days	Wed 26/08/26
61		STM Telescope Structure mfg and assembly	230 days	Mon 15/09/25
62		STM Mirrors	412 days	Mon 15/09/25
63		STM Telescope M1 mfg	180 days	Mon 15/09/25
64		STM Telescope M1 polishing	140 days	Mon 25/05/26
65		STM Telescope M1 coating	46 days	Mon 07/12/26
66		STM Telescope M1 Test	46 days	Tue 09/02/27
67		STM Telescope M2 mfg, polishing, coating and test	270 days	Mon 19/01/26
68		STM Telescope AIT ambient	60 days	Wed 14/04/27
69		STM Telescope vibration test	20 days	Wed 07/07/27
70		STM Telescope cryo test prep.	30 days	Wed 04/08/27
71		STM Telescope cryo performance	20 days	Wed 15/09/27
72		STM Telescope reconfig and check	40 days	Wed 13/10/27
73		GQM Instruments available	0 days	Thu 30/10/25
74		STM SIA Telescope and Instruments AIT (ambient)	70 days	Wed 08/12/27
75		STM SIA Thermal Balance	20 days	Wed 15/03/28
76		STM SIA cryo functional test	10 days	Wed 12/04/28
77		STM SIA final activities	20 days	Wed 26/04/28
78		STM SIA available to STM PLM	0 days	Wed 24/05/28
79		FM Telescope/SIA	680 days	Wed 13/10/27
80		FM Telescope Structure Procurement	180 days	Wed 13/10/27
81		FM Telescope Mirrors mfg and test	420 days	Wed 13/10/27
82		FM Telescope AIT	170 days	Wed 11/04/29
83		FM Telescope AIT ambient	60 days	Wed 11/04/29
84		FM Telescope vibration test	20 days	Wed 04/07/29
85		FM Telescope cryo test prep.	30 days	Wed 01/08/29
86		FM Telescope cryo performance	20 days	Wed 12/09/29
87		FM Telescope reconfig and check	40 days	Wed 10/10/29
88		FM Instruments available	0 days	Thu 29/06/28
89		FM SIA AIT	120 days	Wed 05/12/29
90		FM SIA Telescope and Instruments AIT (ambient)	70 days	Wed 05/12/29
91		FM SIA Thermal Balance	20 days	Wed 13/03/30
92		FM SIA cryo functional test	10 days	Wed 10/04/30
93		FM SIA final activities	20 days	Wed 24/04/30
94		FM SIA available to FM PLM	0 days	Wed 22/05/30



ESA overall schedule (SIA STM + FM)

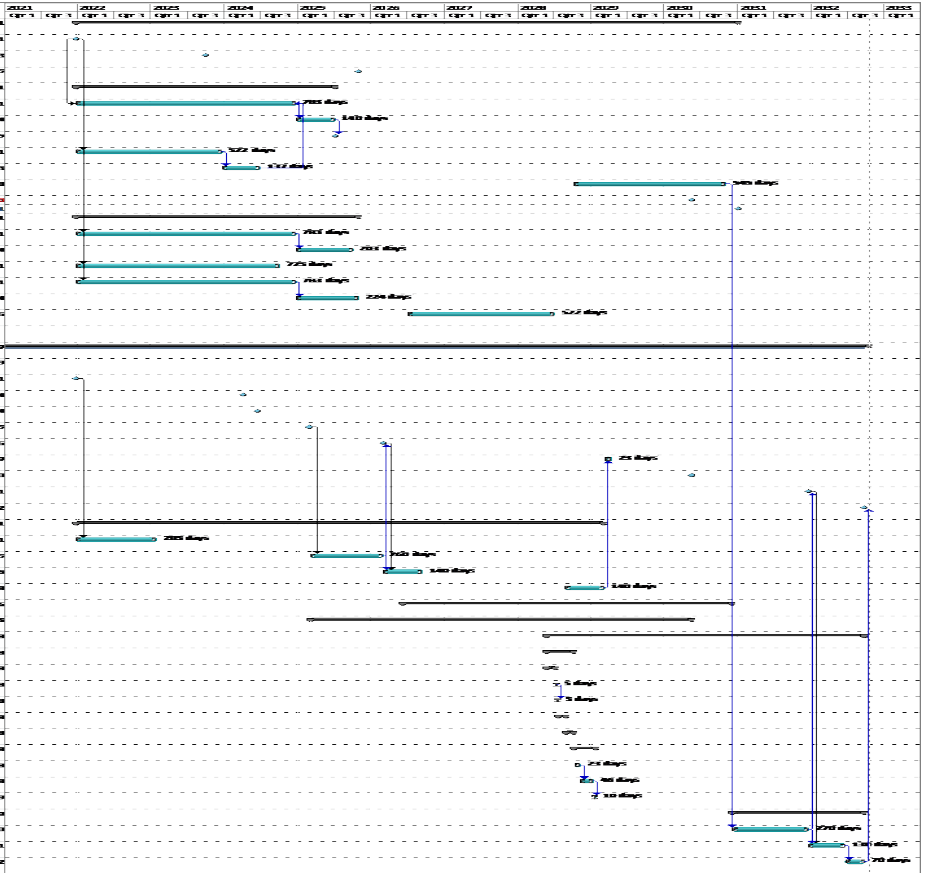
ID		Task Name	Duration	Start
22		**ESA**	**3474 days**	**Sun 30/06/19**
23		Phase A kick off	0 days	Sun 30/06/19
24		Phae B1 kick off and PRR	0 days	Tue 21/12/21
25		Mission Adoption Review	0 days	Sun 31/03/24
26		SPC	0 days	Sat 15/06/24
27		SRR -> Phase B2	0 days	Sat 01/03/25
28		PDR -> Phase C	0 days	Mon 02/03/26
29		CDR -> Phase D	23 days	Thu 08/03/29
30		QR	0 days	Wed 22/05/30
31		FAR -> Phase E1	0 days	Fri 19/12/31
32		Launch	0 days	Fri 24/09/32
33		**System**	**1882 days**	**Tue 21/12/21**
34		Early design phase and req. definit	285 days	Tue 21/12/21
35		Preliminary design	260 days	Mon 03/03/25
36		Lower level PDR's	140 days	Mon 02/03/26
37		Lower level CDR's	140 days	Thu 24/08/28
38		**SVM**	**1174 days**	**Mon 08/06/26**
55		**Telescope/SIA**	**1362 days**	**Mon 03/03/25**
95		**S/C**	**1132 days**	**Wed 24/05/28**
96		**STM S/C**	**98 days**	**Wed 24/05/28**
97		**JAXA activities on STM**	**32 days**	**Wed 24/05/28**
102		STM S/C Telescope Baffle AIT	5 days	Fri 07/07/28
103		STM S/C SVM to PLM mating and check	5 days	Fri 14/07/28
104		**STM S/C Mechanical test campaign**	**26 days**	**Fri 21/07/28**
105		STM S/C Alignment check	5 days	Fri 21/07/28
106		STM S/C Sine Vibration test	10 days	Fri 28/07/28
107		STM S/C Acoustic test	2 days	Fri 11/08/28
108		STM S/C Shock test	2 days	Tue 15/08/28
109		STM S/C Leakage check	2 days	Thu 17/08/28
110		STM S/C Alignment check	3 days	Mon 21/08/28
111		STM S/C PLM health check	2 days	Thu 24/08/28
112		**STM Disassembly**	**30 days**	**Mon 28/08/28**
113		STM S/C PLM removal from S	5 days	Mon 28/08/28
114		STM S/C SIA Removal from PL	2 days	Mon 04/09/28
115		STM PLM at ESA health check	23 days	Wed 06/09/28
116		**AVM S/C**	**79 days**	**Mon 09/10/28**
117		AVM SVM to PLM STM Integrati	23 days	Mon 09/10/28
118		AVM S/C PLM Functional test	46 days	Thu 09/11/28
119		AVM S/C Conducted EMC	10 days	Fri 12/01/29
120		**FM S/C**	**470 days**	**Fri 06/12/30**
121		Integration and AIT	270 days	Fri 06/12/30
122		ESA Contingency	130 days	Fri 19/12/31
123		Launch campaign	70 days	Fri 18/06/32



concurrent design facility

ESA – JAXA overview (SIA STM + FM), with JAXA schedule integrally moved to the right

ID	Task Name	Duration	Start
1	JAXA	2357 days	Tue 21/12/21
2	P-SDR	0 days	Tue 21/12/21
3	P-PDR	0 days	Sat 30/09/23
4	P-CDR	0 days	Sat 01/11/25
5	STM PLM	923 days	Tue 21/12/21
6	STM PLM Design, procurement and Integration	783 days	Tue 21/12/21
7	STM PLM Cryo-chain test	140 days	Fri 20/12/24
8	STM PLM available to ESA	0 days	Fri 04/07/25
9	STM MCS-PM Design and Mfg	522 days	Tue 21/12/21
10	STM MCS-PM AIT + Cryo – test	137 days	Thu 21/12/23
11	FM PLM	545 days	Sun 01/10/28
12	FM SIA available to FM PLM	0 days	Wed 22/05/30
13	FM PLM Need date for S/C	0 days	Thu 02/01/31
14	CQM Instruments	1007 days	Tue 21/12/21
15	SMI CQM Design and mfg	783 days	Tue 21/12/21
16	SMI CQM AIT and Cryo test	203 days	Fri 20/12/24
17	SMI E-EM Design, mfg and test	725 days	Tue 21/12/21
18	SAFARI CQM Design and mfg	783 days	Tue 21/12/21
19	SAFARI CQM AIT and cryo-test	224 days	Fri 20/12/24
20	FM Instruments	522 days	Tue 30/06/26
21			
22	ESA	3474 days	Sun 30/06/19
23	Phase A kick off	0 days	Sun 30/06/19
24	Phae B1 kick off and PRR	0 days	Tue 21/12/21
25	Mission Adoption Review	0 days	Sun 31/03/24
26	SPC	0 days	Sat 15/06/24
27	SRR -> Phase B2	0 days	Sat 01/03/25
28	PDR -> Phase C	0 days	Mon 02/03/26
29	CDR -> Phase D	23 days	Thu 08/03/29
30	QR	0 days	Wed 22/05/30
31	FAR -> Phase E1	0 days	Fri 19/12/31
32	Launch	0 days	Fri 24/09/32
33	System	1882 days	Tue 21/12/21
34	Early design phase and req. definiti	285 days	Tue 21/12/21
35	Preliminary design	260 days	Mon 03/03/25
36	Lower level PDR's	140 days	Mon 02/03/26
37	Lower level CDR's	140 days	Thu 24/08/28
38	SVM	1174 days	Mon 08/06/26
55	Telescope/SIA	1362 days	Mon 03/03/25
95	S/C	1132 days	Wed 24/05/28
96	STM S/C	98 days	Wed 24/05/28
97	JAXA activities on STM	32 days	Wed 24/05/28
102	STM S/C Telescope Baffle AIT	5 days	Fri 07/07/28
103	STM S/C SVM to PLM mating and check	5 days	Fri 14/07/28
104	STM S/C Mechanical test campaign	26 days	Fri 21/07/28
112	STM Disassembly	30 days	Mon 28/08/28
116	AVM S/C	79 days	Mon 09/10/28
117	AVM SVM to PLM STM Integrati	23 days	Mon 09/10/28
118	AVM S/C PLM Functional test	46 days	Thu 09/11/28
119	AVM S/C Conducted EMC	10 days	Fri 12/01/29
120	FM S/C	470 days	Fri 06/12/30
121	Integration and AIT	270 days	Fri 06/12/30
122	ESA Contingency	130 days	Fri 19/12/31
123	Launch campaign	70 days	Fri 18/06/32



Conclusions

- Based on Herschel S/C schedule data, the recalculated schedule shows a feasible insertion of a SIA “enhanced” STM in the planning
- The Telescope schedule is anyway close to critical
- In particular the manufacturing and test of the mirrors is a key element
- A combined test of the SIA including the instruments on the STM is a matter of evaluation, not possible in the frame of this study:
  - Availability of instrument CQM-like models not agreed yet
  - Depth of testing at this level not investigated
- The cost of the STM telescope is an important impact, though such a model is technically recommended
- Overall schedule: with the assumed milestones incl. Mission Adoption Review by mid 2024, launch is possible in late 2032 with a standard ESA contingency.

Revised Conclusions (cont'd)

- Open issues for AIV:
  - Microgravity control – specifically the knowledge and control of the environment at cryo temperatures. Readiness of the test facilities. Heritage available from Planck at CSL.
  - EMC verification – how to test in cryo condition or to what extent. Any analytical escape combined with testing?
  - Modification of the CSL Focal 6.5, envisaged tests are SIA STM and FM, PLM STM and FM, with the S/C FM being an option (not recommended)
  - Balancing the test activities between Telescope, SIA and PLM
- Open issues for Programmatic:
  - SIA Contract/Telescope Contract
  - Anticipation of Mission Adoption Review to help the schedule
  - Harmonisation of JAXA, ESA and Instruments planning

Conclusions

Study Objectives

In the Beginning, there was The Plan:

Sess.	Date	Activities	Who
1 - KO	June 15	*See KO agenda*	
2	June 20	Telescope architecture trades Freeze launcher I/F's and performance assumptions Establish prelim. delta-V budget, parameters of L2 transfer orbit injection, solar aspect angle constraints. Freeze Payload Instrument budgets (mass, power, data, volume) PLM design review & establish related inputs for CDF study (thermal: radiator sizing, thermal shielding) Detector characterisation & environmental sensitivity Initial SVM S/S trades (Comms, DHS, Prop. Power, Therm., Struc.), spec. AOCS: wheels vs. cold gas	Optics JAXA Mission Analysis JAXA, SRON JAXA, thermal, other Detectors S/S, AOCS
3	June 22	Instrument Optical Bench definition Freeze Telescope concept (incl. baffle) & size Freeze PLM budgets (mass, power, data, volume) Preliminary System budgets + identification of main issues & drivers L2 transfer and halo orbit sizing, delta-V budget update Cryo mechanisms trades Discuss AIV/T logic & Programmatics Initiate trade FAS vs. Star Tracker	Optics, Detectors Optics Systems with JAXA Systems Mission Analysis Mechanisms AIV & Prog. & JAXA AOCS
4	June 27	S/C configuration trades covering Telescope, PLM, SVM ROM cost estimate & identification of main cost drivers Prelim. Risk overview SVM S/S trades (Comms, DHS, Prop. Power, Therm., Struc.; AOCS not available)	Config. & Struc. Cost Risk Subsystems
5	June 29	(semi-)Finalise AIV/T logic Discuss Operations logic Trade FAS vs. Star Tracker First iteration incl. all S/S -> System budgets update	AIV & Prog. & JAXA GS & Ops. AOCS S/S & Systems
6	July 4	Preliminary configuration of complete S/C on launcher Overview of all subsystem designs iteration incl. all S/S -> System budgets update Cost estimate update Risks updated with TRL evaluation	Config. & Struc. S/S Systems Cost Risk
7	July 6	Finalise all S/S trades iteration incl. all disciplines -> System budgets update	S/S Systems
8 - IFP	July 11	Complete CDF design, final presentations by all disciplines – hand-out acts as CDF output document until issue of Final Report.	All, incl. JAXA

... which we followed (surprisingly) well.

Study Objectives

1. Accommodation of the Japanese payload module with its 3 instruments (SAFARI, POL and SMI) and the European provided telescope. ☑
2. Review and incorporation of Japanese PLM design ☑ + definition of alternatives
3. Design of the telescope ☑ + exploration of alternatives
4. Preliminary design of the required S/C ☑ and provide the associated mission cost (in prep.)
5. AIV approach and work share between JAXA, ESA and the Instrument Consortia ☑
6. Requirements consolidation, as input to subsequent industrial phase A study. (in prep.)

Study Critical Areas

- ESA cost needs to fit Cosmic Vision M-class mission budget, ≤ 550 M€[2017] / (TBC)
- Launch Mass may be an issue – 3.7 ton to L2
- Radiators sizing
- PLM cryo-coolers: physically in PLM or in SVM? – Hybrid solution proposed
- AOCS: FAS in Telescope, or Star Tracker outside Telescope sufficient? /
  TBD, pending ongoing thermo-elastic & AOCS analysis
- AIV/T: logic and sharing between JAXA and ESA – workable logic & schedule

Study Output

- CDF Integrated Design Model – most coherent, complete and detailed equipment and mass breakdown for SPICA up to date, in line with latest ESA, JAXA, CEA and SRON parameters. 👍
- Final Presentation Hand-out (to be updated by Friday) 👍
- Technical Report (in two weeks; before or right after your holiday, please!)
- Cost Report (internal only)