CMB Polarisation Mission

Introduction

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

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Study Background

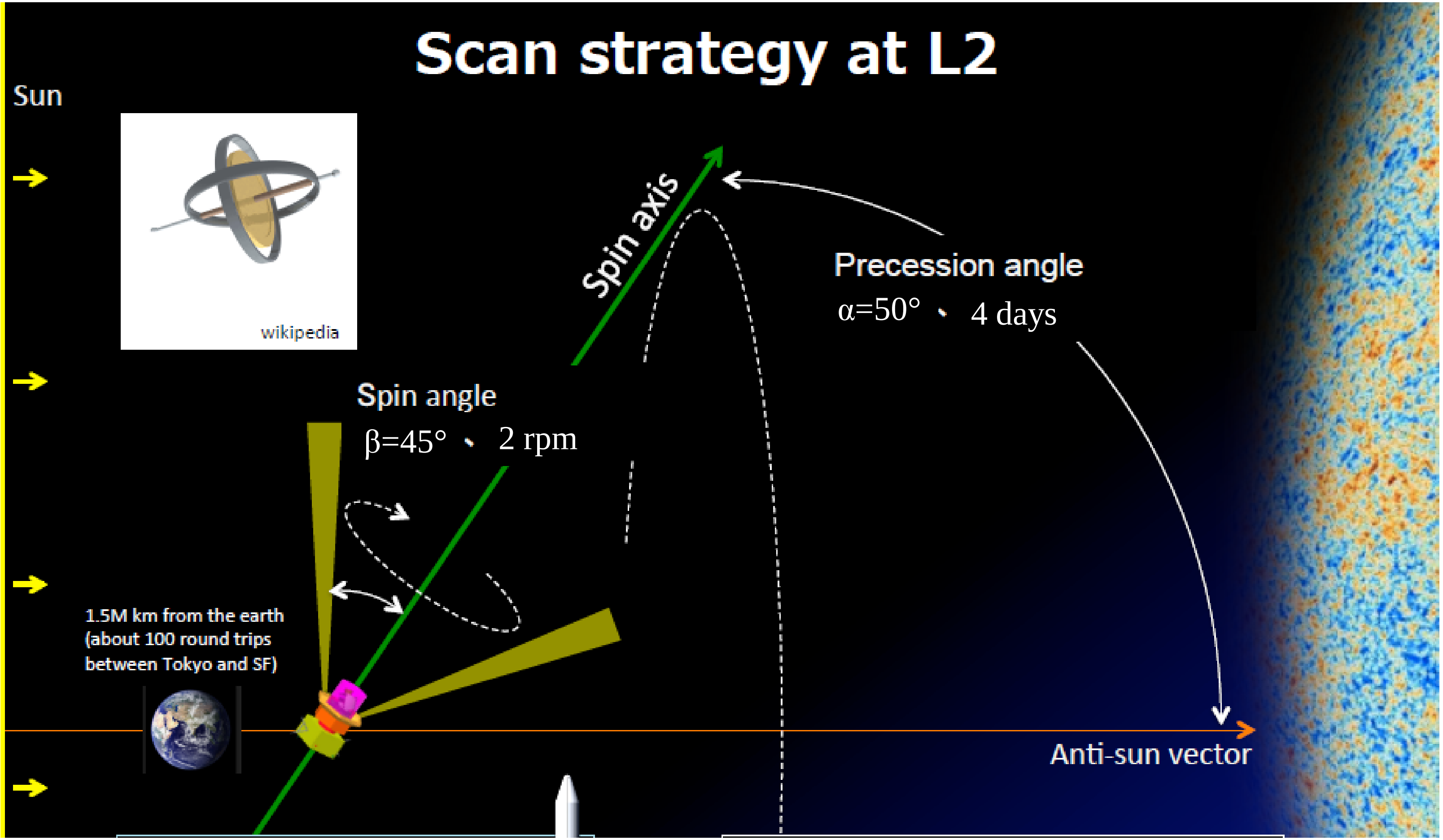
CMB Polarisation Mission

- 5.5 session CDF study
- Requested by SCI-FM to support European and Japanese Science community in preparation of M5 call
- Post-Planck mission building on the European led Core+ M4 proposal and JAXA Litebird mission concept
- High sensitive survey of the microwave polarisation of the entire sky for probing cosmic origins
- The objective of the CDF study is to explore potential configurations of a combined European-Japanese CMB mission which could be proposed for the M5 call

Mission description

- The mission will be launched either on a Japanese H-II/H-III launcher or an European Ariane 6.2 into an orbit around L2 .
- The operational mission is 3 years observation.
- The telescope shall provide astronomical background limited observation between 50-500GHz (tbc), using either TES or KID detectors operating at 100mK. The Focal Plane will include any additional cold stops, horn couplings etc. and is treated as a black box

Scan strategy



Scan strategy for study

Starting point for CDF:

- α = 50° β = 45°, spin rate (1 rpm) → 2 rpm, precision: 4 days

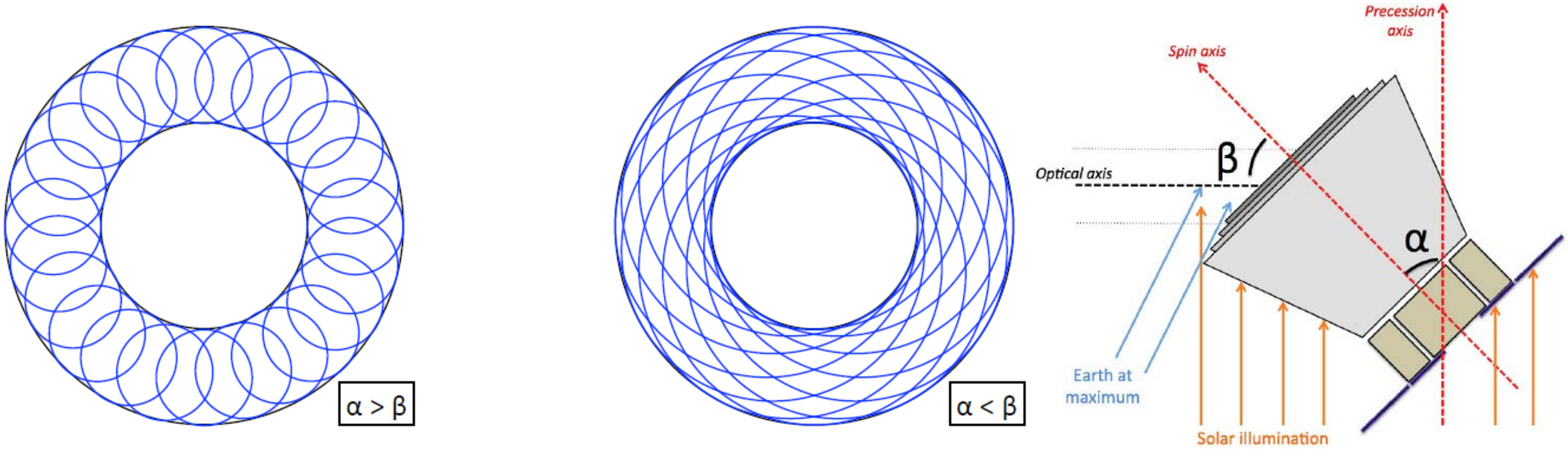


Figure 2: For one complete precession, the FOV observes a ring of width $|\alpha + \beta| - |\alpha - \beta|$. Left: case where $\alpha > \beta$. Small rings cross at large angles, for a good coverage of angles over time scales of order β days, and good distribution of scanning directions for most pixels of the sky over the course of the mission. Right: case where $\alpha < \beta$. Large rings cross at small angles, but connect of short periods very distant pixels.

Areas of focus

- Definition of a 1.2 m projected aperture telescope configuration compatible with the defined envelope and its accommodation
- The accommodation of the instruments and the available resources (e.g. dissipation at cryogenic temperatures, cryoharness...)
- The structural design, particularly the thermal impact
- The impact of the Observation strategy (spinning and low frequency precision) on the overall system such as communication, AOCS, thermal
- Growth potential of the telescope and system impacts
- Saving potentials to reduce cost / complexity

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Instrument

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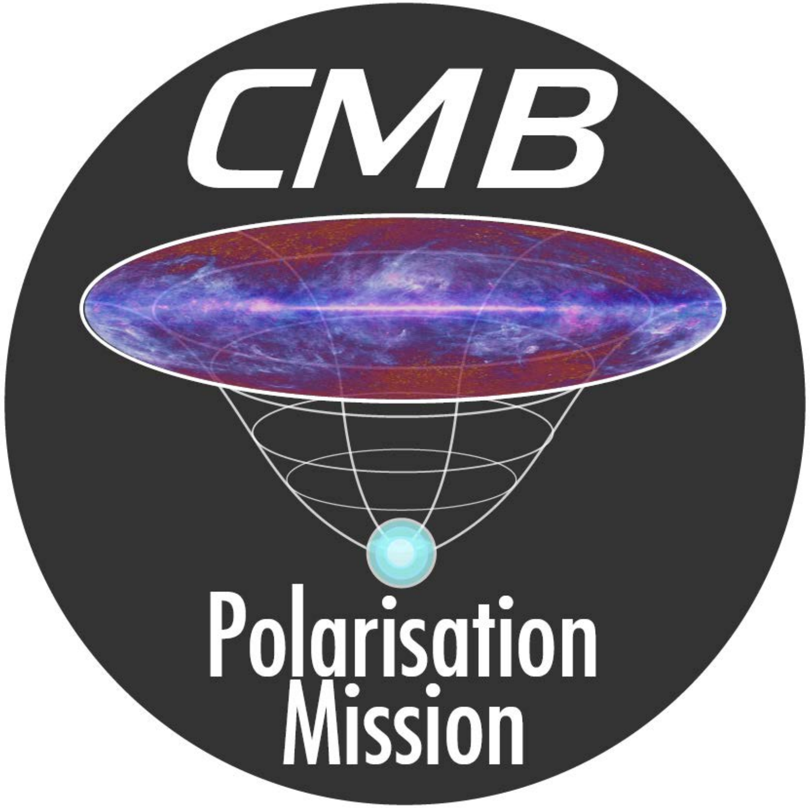
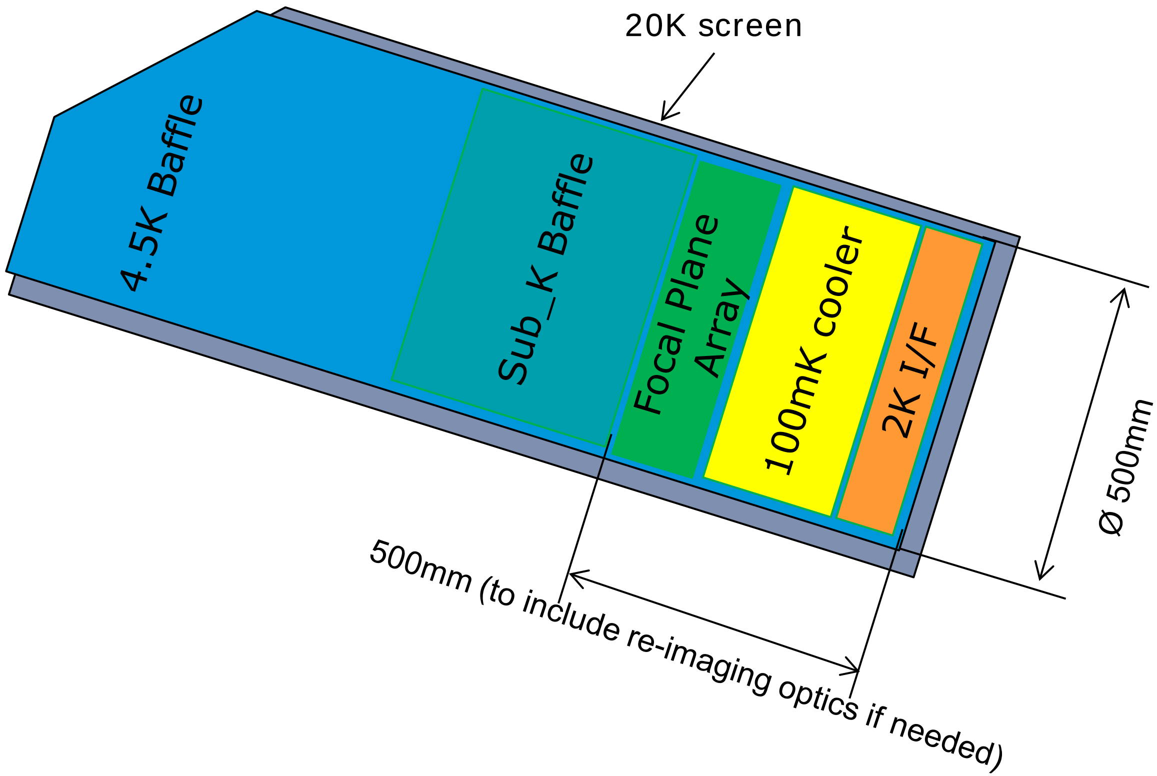


Payload-assumptions for the Study

- The Payload consists of a 1.2m aperture telescope below 60K and a Focal Plane Unit at 100mK
- From Litebird/Core+, a 50cm diameter Focal Plane Array should be sufficient to accommodate enough detectors to cover the Frequency range from 50-500GHz
  - The selected diameter enable the use of Japanese/European detectors and does not rely on US technology only
- A 4.5K baffle will be mounted in front of the FPA to open up the possibility to use lenslets or flat arrays instead of a horn based solution
  - Lower temperature baffles will then be part of the FPA, to be provided by the instruments
- In addition to a 4.5K I/F, a 2K I/F can be made available for the FPA
- The FPA will provide 100mK cooling starting from 2/4K

Focal Plane

- Assumed as a “black box”
- Ø 550 mm diameter Focal Plane Array assumed sufficient to accommodate enough detectors
- 500 mm height required to accommodate the coolers
- A 4.5K baffle mounted in front of the FPA to open up the possibility to use lenslets or flat arrays instead of a horn based solution
- In addition to a 4.5K I/F, a 2K I/F can be made available for the FPA



Detectors

- Both TES and KIDS technology possible:
- Heat load baseline for the study was a KID filled FPA to limit the number of read-out channels (large multiplexing factors already shown) and to define a reference harness design
- KID's detectors in Europe: TRL 3-4
- Use of cold baffles for straylight control and partially as cold stop (no horns assumed but it may be investigated in the future)

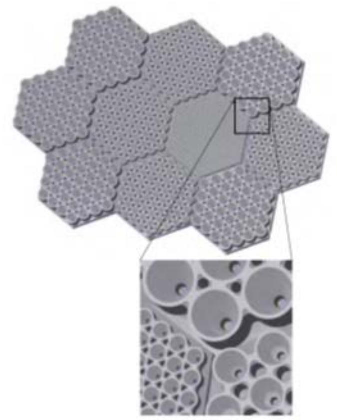


Figure 3. Conceptional design of an MKID focal plane array with direct machined corrugated horn arrays for LiteBIRD

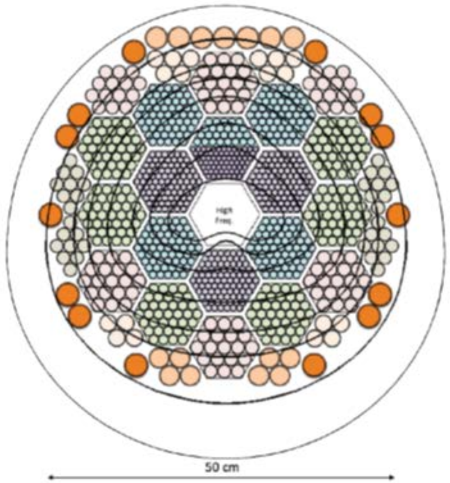


Figure 3: Sketch of the focal plane of COrE+ Light. Contours are Strehl= 0.8 for 60, 90, 130, 160, 220, 340, 450, and 600 GHz. The small colored circles correspond to feedhorns at these frequencies.

current facility

Instrument Budget allocations

- Size FPA+sub-K cooler: Ø 500mm, length 500mm
- Mass FPA+sub-K cooler+ sub-K baffle: 50kg
- Warm electronics: 100kg, 200W electrical power at 20°C, located in the SVM

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Optics

Prepared by the CDF* Team

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Starting Point

Different options have been identified to be used as input for the coming CDF.

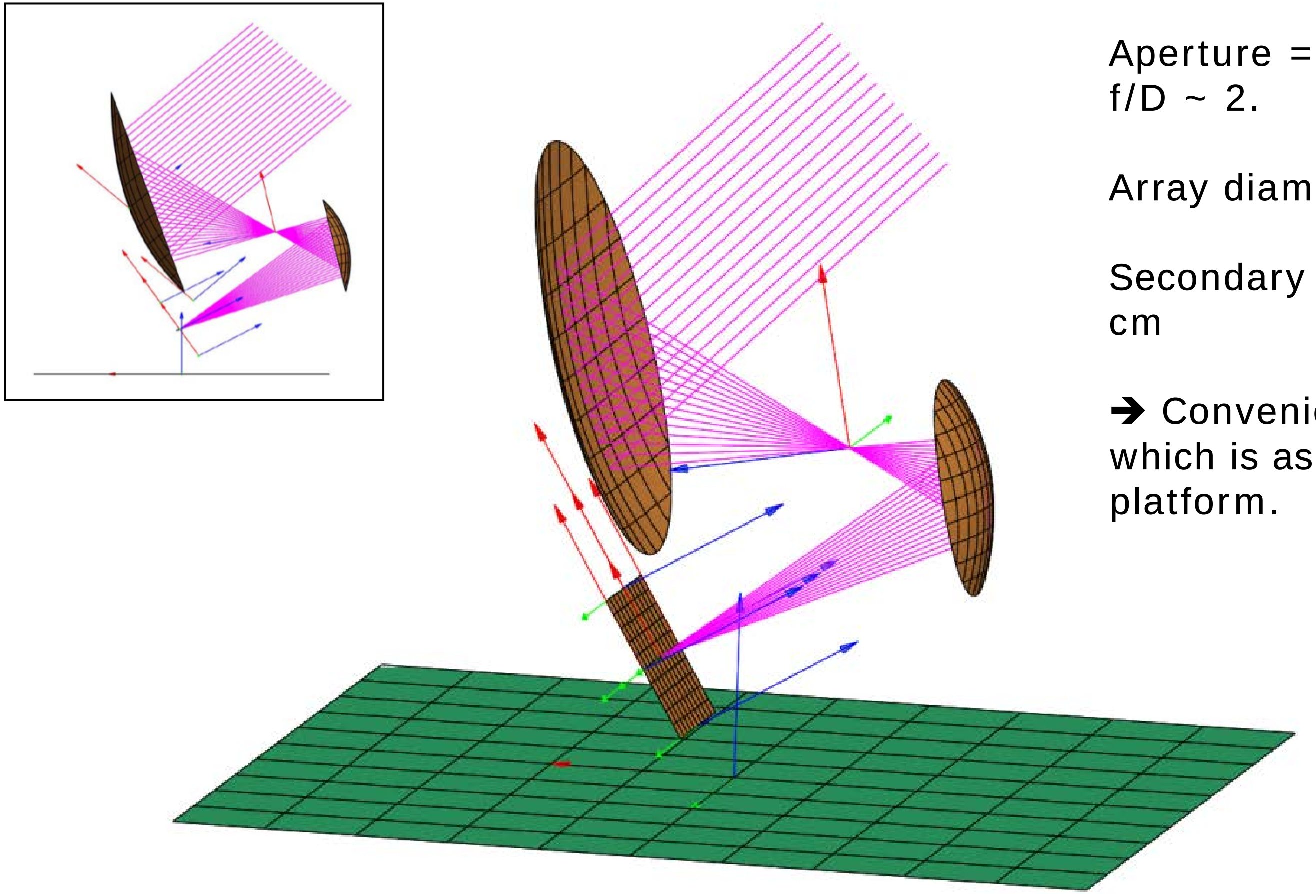
In common:

- Aperture ~1.2 m
- Array feed D=50 cm.
- Beam at 45deg out of the S/C

Configurations:

1. Gregorian.
2. Open Dragone.
3. Crossed-Dragone (upscaled Litebird).

Gregorian configuration – option1



Aperture =1.2 m
f/D ~ 2.

Array diameter = 50cm

Secondary reflector diameter ~ 70 cm

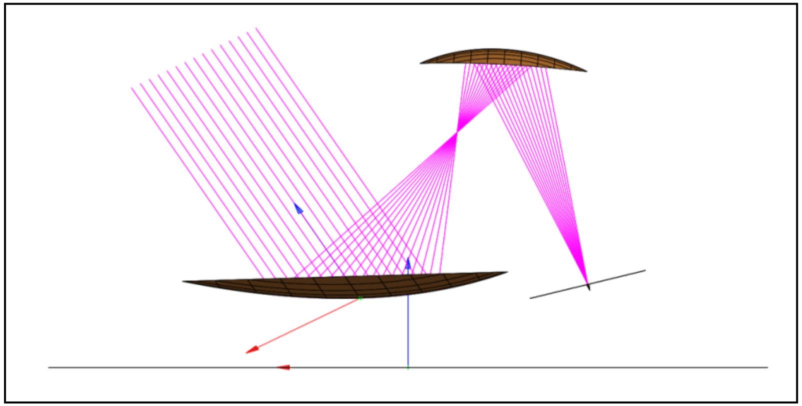
➔ Convenient position of the FPU which is as close as possible to the platform.

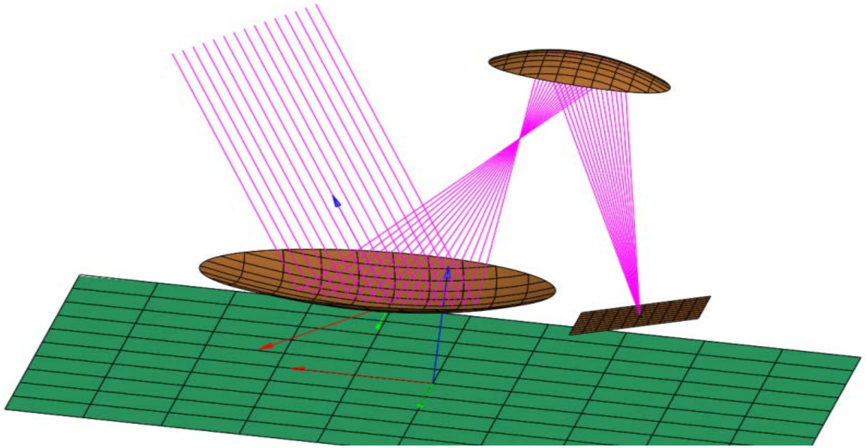
Gregorian configuration – option 2

Aperture =1.2 m
f/D ~ 2.

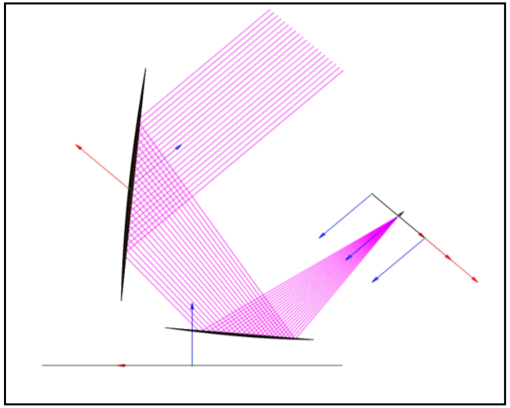
Array diameter = 50cm

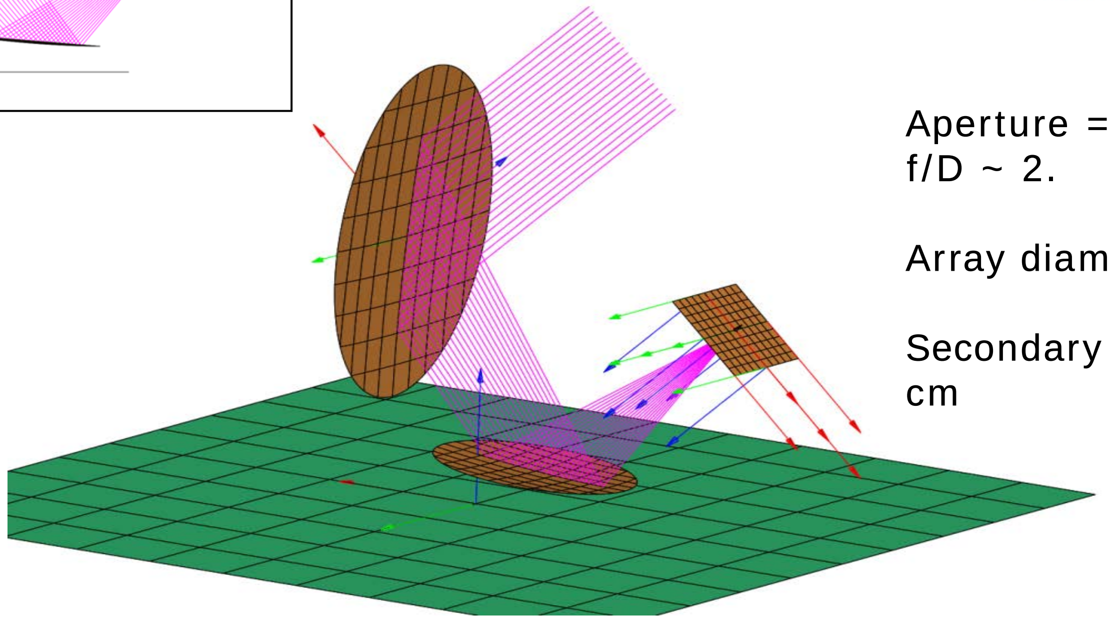
Secondary reflector diameter ~ 70 cm

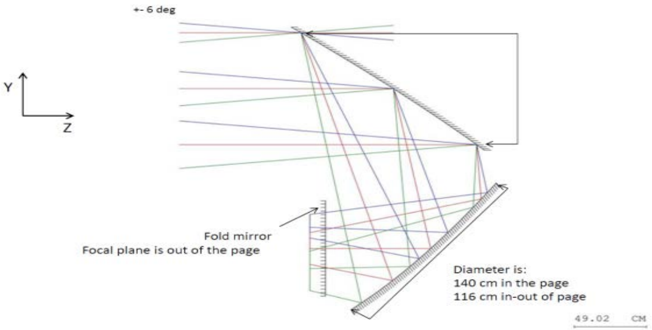




Open Dragone configuration





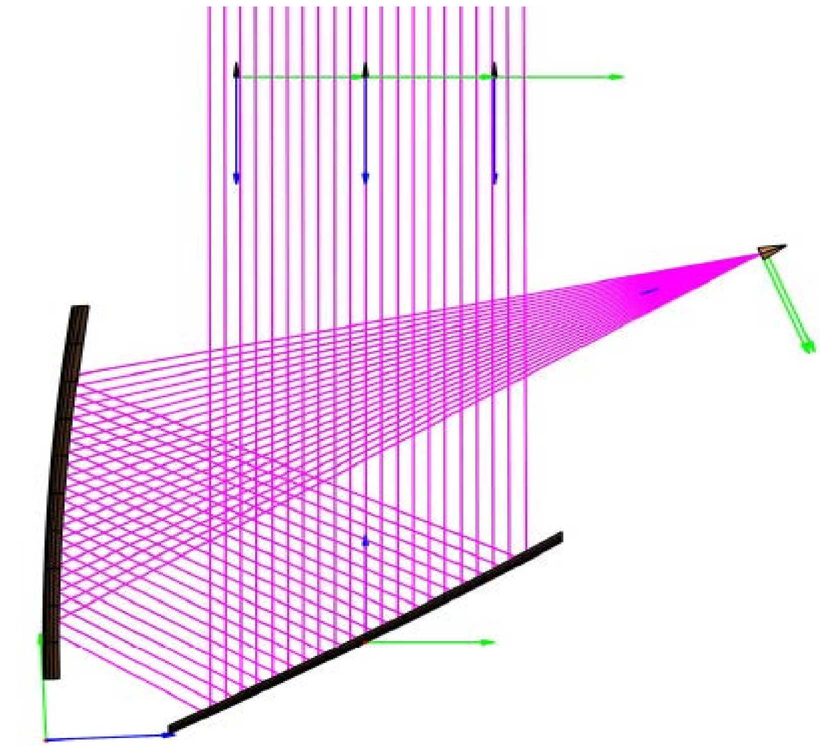


Aperture =1.2 m
f/D ~ 2.

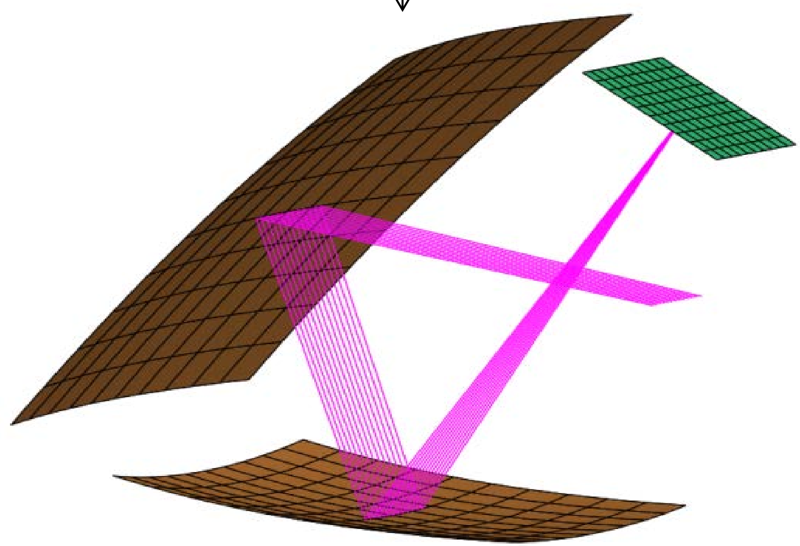
Array diameter = 50cm

Secondary reflector diameter ~ 90 cm

Cross-Dragone



Design with F/D=3.5 to be up-scaled.



Comparison and baseline selecion

- Gregorian:
  - + Secondary mirror smaller in size
  - + Configuration of option 1: easier mechanical installation. Fits inside the thermal shields
  - - Configuration of option 2: difficult mechanical installation of secondary, does not fit inside the thermal shields
- Open Dragone:
  - – Large secondary mirror
  - – Complex mechanical installation due to the position of the FPU, does not fit inside the thermal shields
  - + Flat focal plane.
- Cross Dragone:
  - + Compact
  - – Complex mechanical installation due to the position of the FPU
  - + Flat focal plane.

➔ Gregorian is selected as baseline for CDF.

Gregorian configuration baseline

Aperture =1.2 m - F/D ~ 2.

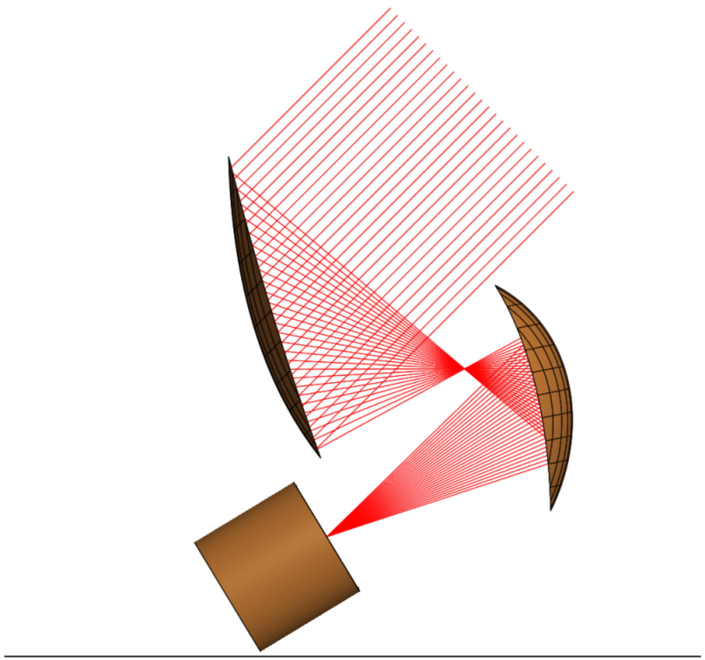
Array diameter = 50cm

Secondary reflector diameter = 1 m

FPU size: Ø = 55cm, h= 50 cm.

Non optimised surfaces:
Parabolic main reflector, ellipsoid secondary reflector.

Non optimised position of the feeds in the focal plane: sensors are placed in the focal plane on a flat surface.



Gaussian feed - Tapering

Input from Core+ is to use -23dB taper at the edge of primary

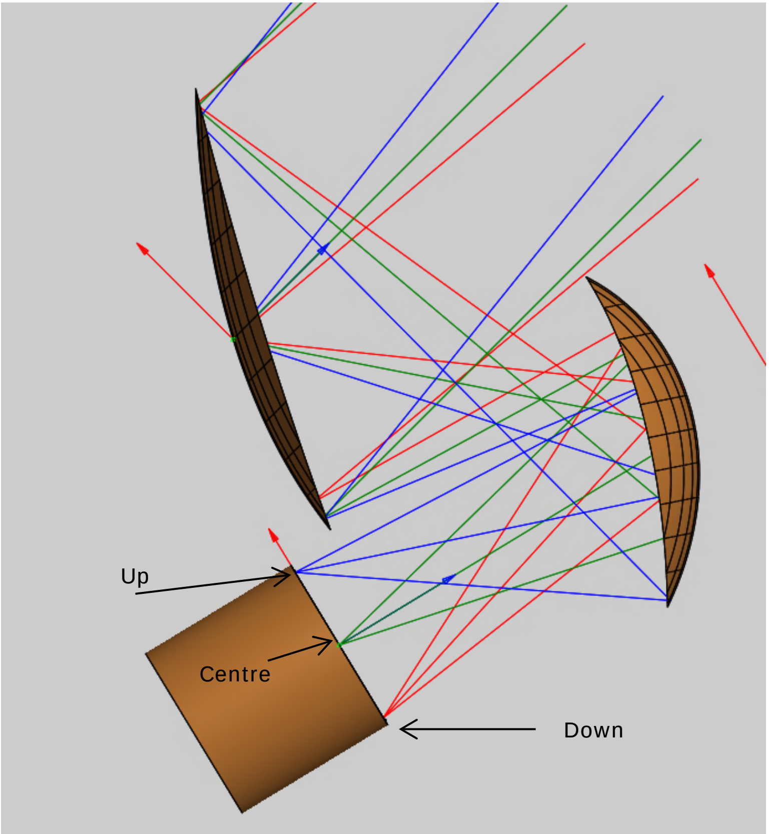
➔Gaussian beam with -23dB

Three feeds are considered for the optics analysis. One in the centre and two ad the edge of the FPU.

Feeds oriented to illuminate the centre of the main reflector with the central ray of each feed.

Taking into account the orientation of the feed, edge of primary is seen by FPU feeds at different angles:

- Feed up = 16 deg.
- Central Feed = 13 deg.
- Feed down = 9 deg.



Evaluation of the variation of the beam pattern across the focal plane

Gaussian beam vs real beam

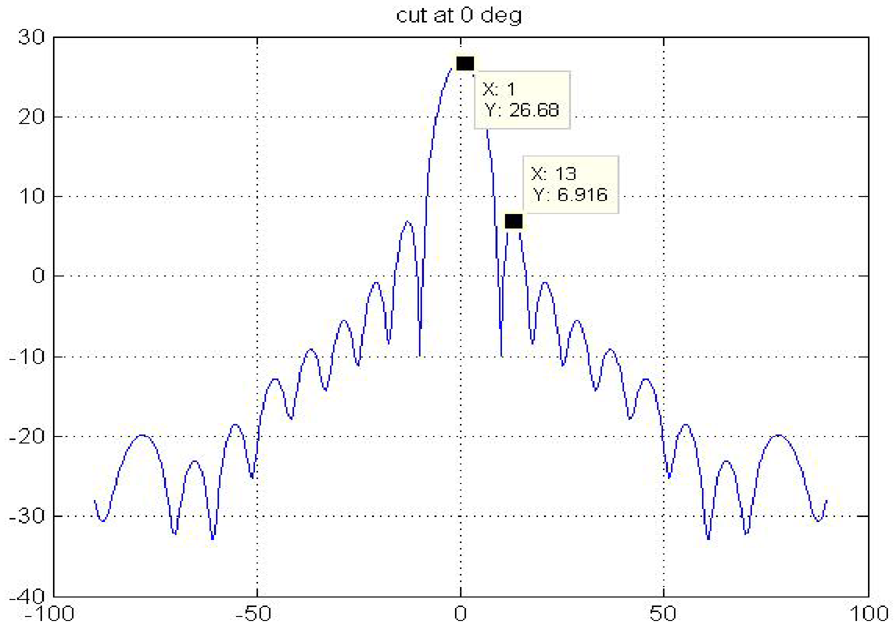
At this point the possible choices considered for the sensors are horns and lenses.

Horns are in general more directive but bulky.

Lenses are less bulky and less directive.

In terms of side lobes and spill over the pattern of a typical lens is considered as less conservative option.

Size and positioning of the lenses in the FPU plane is highlight sensitive point of the next optimised design steps.



Lens pattern – taper -23 dB at 13deg

Physical dimensions:

➔Diameter of about 15.5 mm at 150 GHz for taper -23dB at 13 deg.

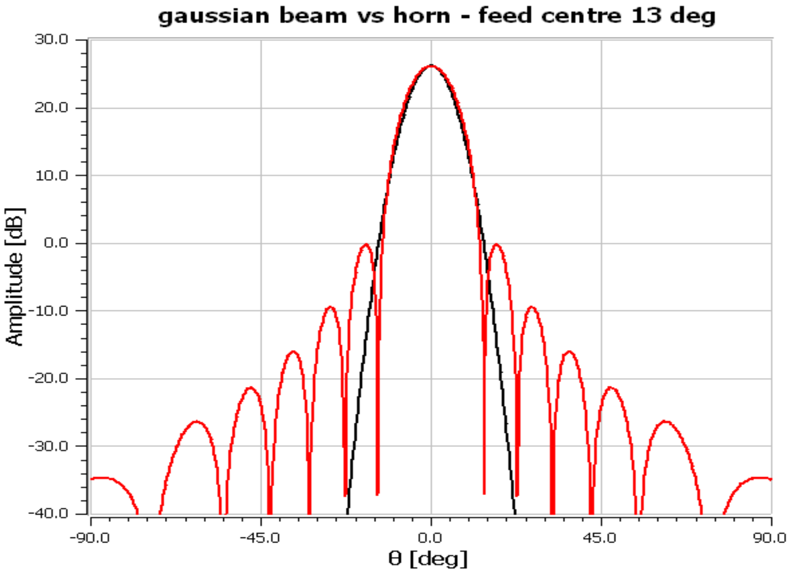
Gaussian feed vd Conical horn pattern

To approximate the pattern of a lens, a conical horn patter is preferred as compared to a gaussian beam: more realistic side lobes.

Analysis is a first approximation:

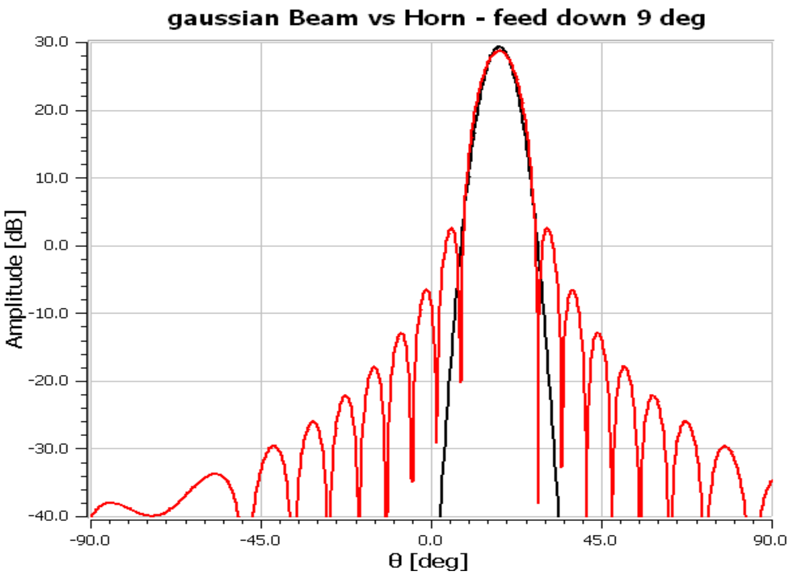
- Lenses present higher side lobes.
- Optics to be optimised.
- Sensor position to be optimised.

➔ With optimised optics, the pattern of the actual lens has to be used to validate this analysis.

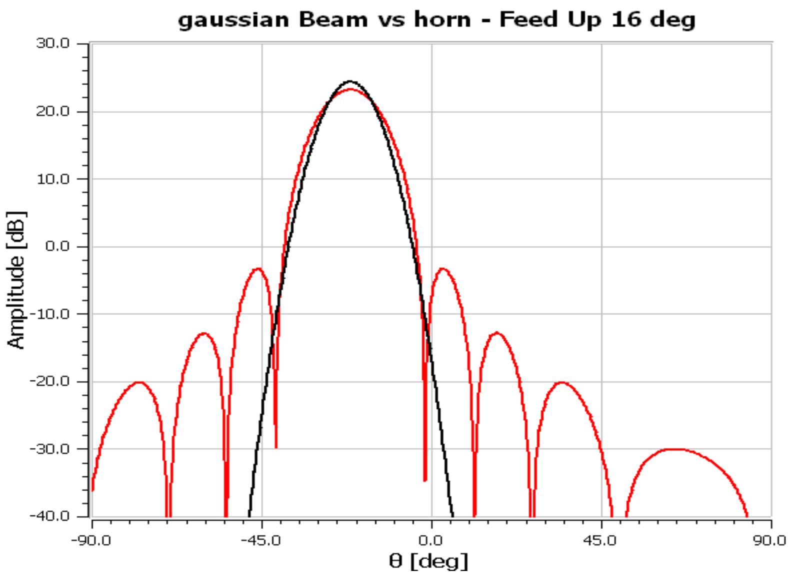


Patterns tapered -23db at 13 deg – Central feed

Gaussian feed vd Conical horn pattern



Patterns tapered -23db at 9 deg –Feed down

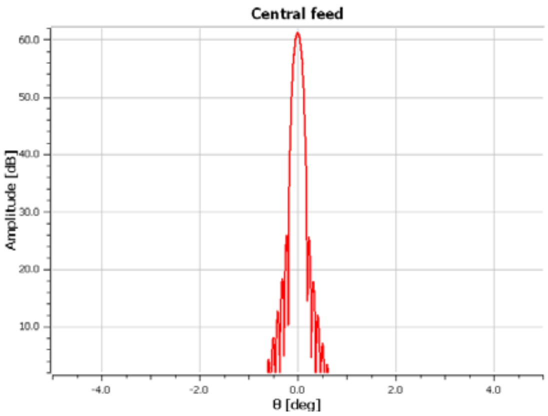


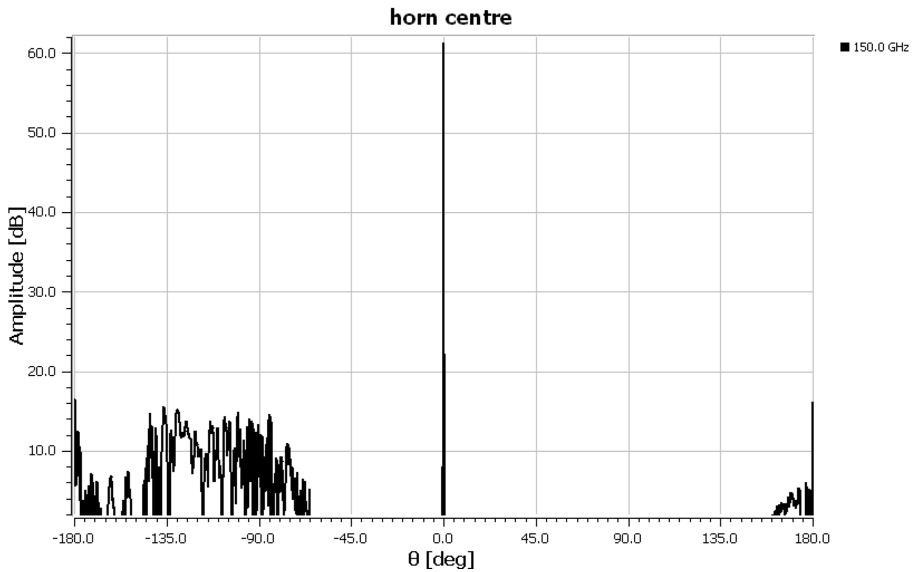
Patterns tapered -23db at 16 deg – Feed up

Field from central feed w/baffle

Horn feed illuminating the optics:

- Low level of side lobes and symmetrical beam in the $\theta = 0°$ cut
- For the central feed cuts at 45, 90 and 135 degrees show minor distortion.

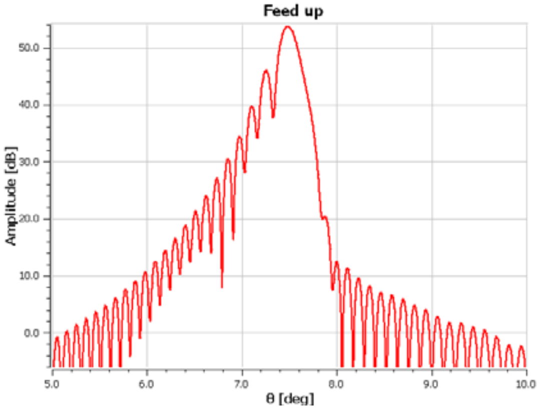


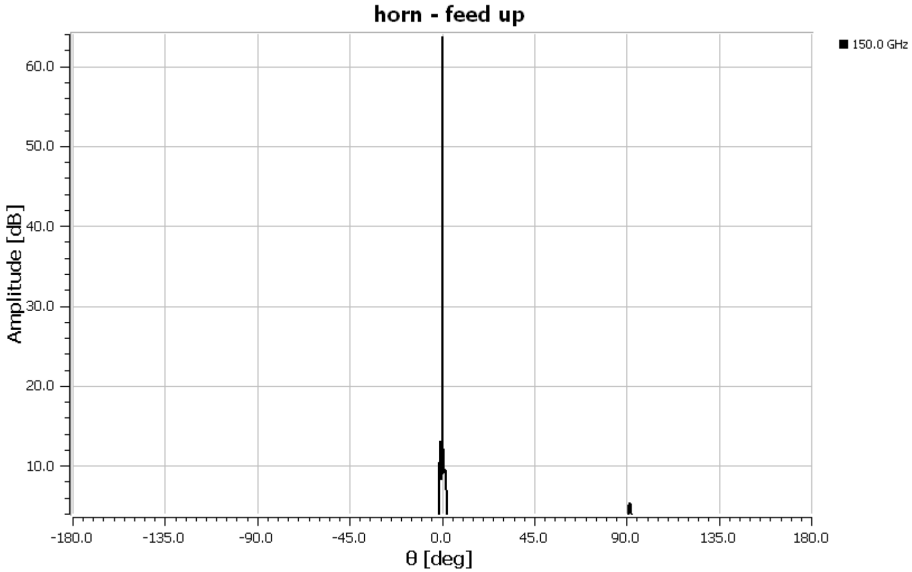


Field from feed-up w/baffle

Horn feed at the upper edge of the available area for the focal array:

- Main pattern is distorted even at θ = 0° mainly due to the non optimised position of the feed.

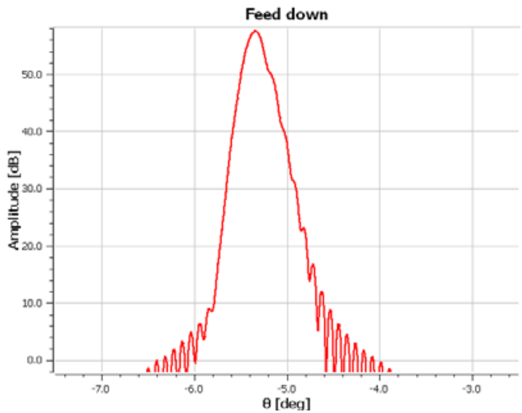


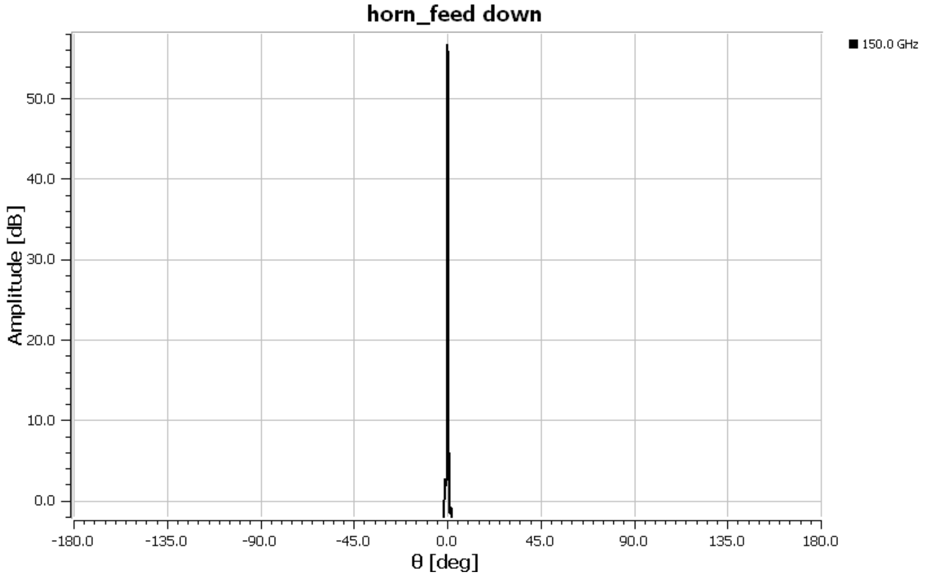


Field from central feed w/ baffle

Horn feed at the lower edge of the available area for the focal array:

- Main pattern is distorted even at θ = 0° mainly due to the non optimised position of the feed.
- Pattern in cuts at different θ are distorted due to the non optimised surfaces.





Conclusion

1. The optics as designed in first approximation shows focused central beam without main distortion.
2. Side lobes are under control for the horn feeds in the centre of the FPU but present distortion and side lobes for the feeds located at the edge of the FPU mainly due to the non optimised position of the feed.

Next steps:

1. Optimisation of the main and secondary reflector.
2. Optimisation of the position of the feed by optimising the focal plane shape.
3. Selection of sensor technology by taking into account beamwidth, sidelobes and dimensions.
4. Analysis of the optics with the actual beam patterns of the sensors in the optimised position.

Baffle – Evaluation of the effect on the pattern

Baffle design

Based on experience, the team has proposed to design a baffle to protect the FPU from direct light.

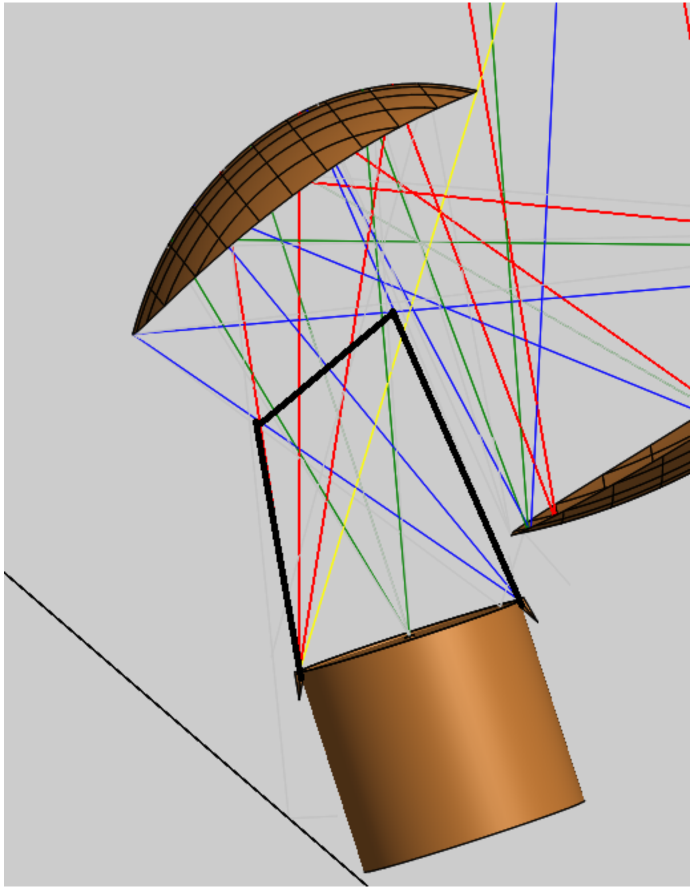
The baffle is meant to screen out the straight light to the FPU. It should play the role of a cold stopper without shadowing the primary/secondary reflector.

The baffle has been designed making use of ray tracing:

•most outer rays (as per tapering) from the sensors can reach the secondary mirror (blue and red);

•rays reflected by the secondary reach the primary mirror.

•Straight light from sky cannot reach the FPU (yellow)

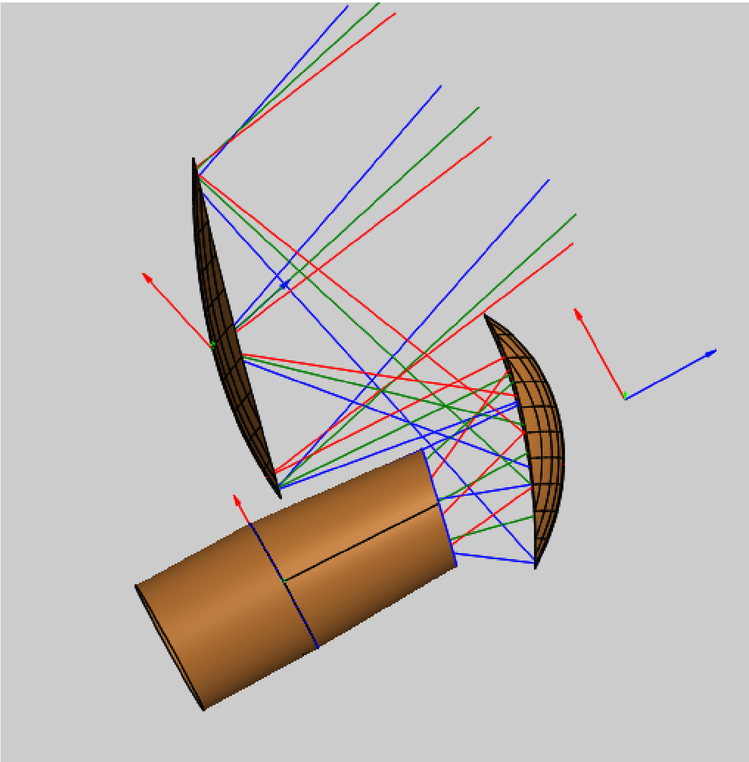


Final baffle geometry

Making use of ray tracing a baffle has been designed.

It assumes the beam tapering as described in the previous slides:
•Feed up = 16 deg.
•Central Feed = 13 deg.
•Feed down = 9 deg.

The baffle is designed in a CAD tool It is a truncated cone with two non-parallel faces.



Baffle modelling - options

Ideally the entire baffle should be modelled as an absorbing surface on the inside and reflective/diffusive surface on the outside.

To assess:

- Straight light screening.
- Shadowing to the reflectors.
- Reflection from the baffle to the reflectors.

➔ Full wave analysis taking into account the electrical properties of the entire structure

➔ Unfishable at the highest operational frequency of the instrument.

Three solutions with different level of approximation have been **identified as possible solution:**

- Assessment of the screening effect via an aperture on absorbing screen.
- Assessment of the reflection of the outer surface of the baffle via a PEC model.
- Combination of absorbing and PEC surfaces model.

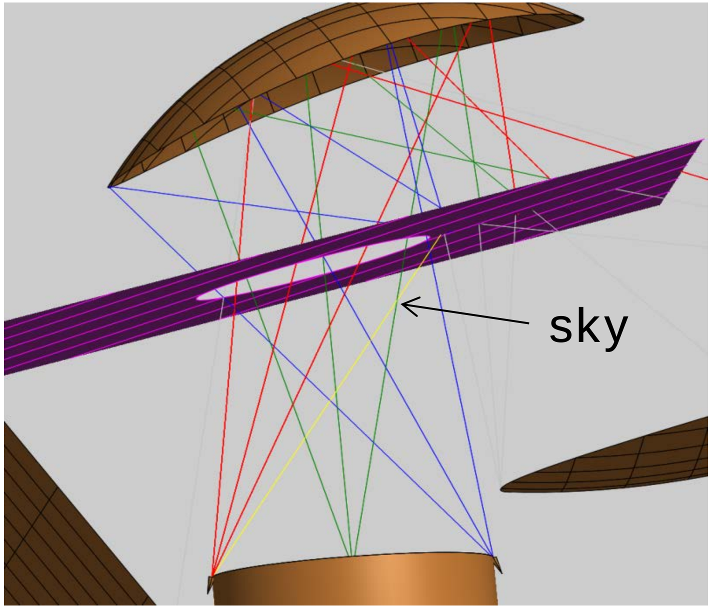
Baffle modelling – 1. Aperture on screen

GRASP allows to define a structure which acts as an aperture on screen.

The field from the feed through the aperture is represented by equivalent currents on the aperture and then radiated to the secondary.
The field that hits the screen is reflected back and doesn't contribute to the current on the secondary reflector.
Currents on secondary reflector are radiated to the main not taking into account the screen.

➔ Assessment of the effect on the feed pattern for the different feed positions.

Main limitation:
Scattering of the outer surface of the baffle cannot be assessed.
➔ Only the cold stopper effect can be assessed.

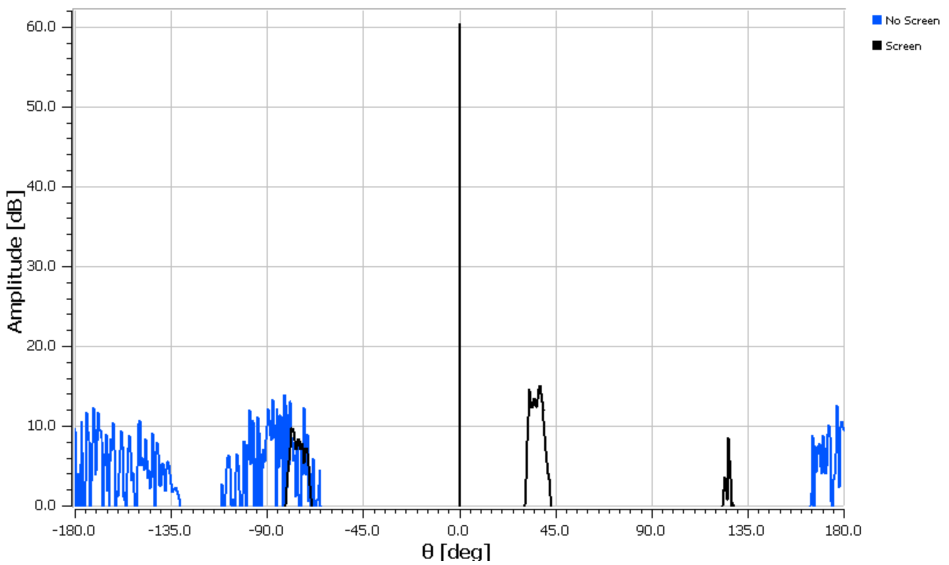


Field from central feed with screen

A first assessment of the feasibility and reliability of the baffle modelled as aperture on screen has been carried out.
The screen model shows as the feeds radiate through the screen.

Note:
Actual feeds should be placed on the focal plane to assess the screening effect to the actual side lobes and possible beam distortion.

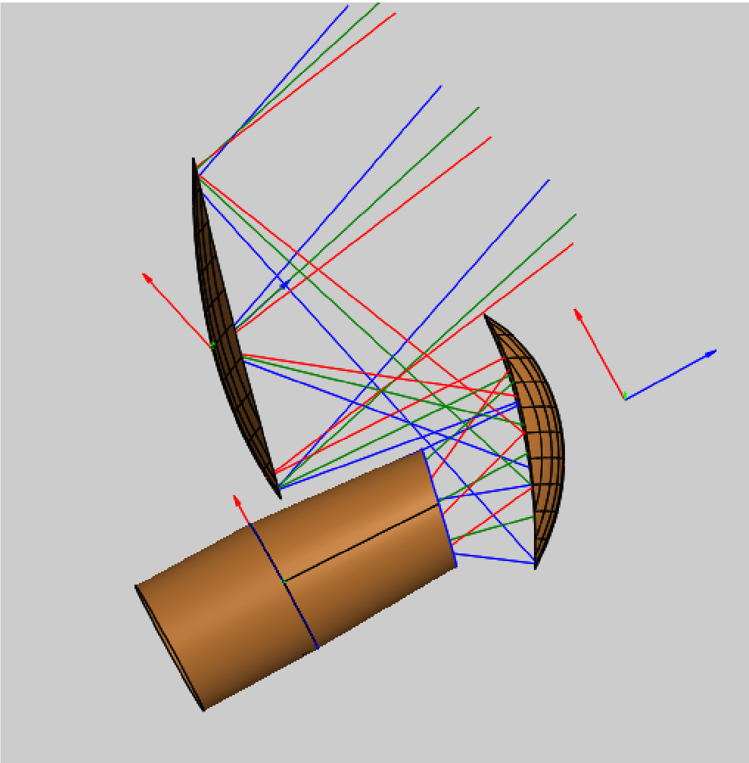
To do:
Analysis of the optics with screen making use of the SWE of realistic feeds placed in optimised positions.



Baffle modelling – 2. PEC baffle

Assessment via PO/GTD analysis of the reflection of the **outer surface of the baffle via a PEC model**.

- Representative feeds needs to illuminate the secondary reflector.
- PO/GTD: secondary mirror to the baffle and baffle to the main mirror.



<u>Limitation</u>

Feeds do not 'see' the baffle: Screening effect of the feeds to the secondary mirror is not taken into account.

It could be controlled by cutting the feed pattern at the required tape angle.

Feasibility assessment – Opt 3.

The possibility of defining absorbing properties for generic surface from CAD import is under test for next GRASP release.

The tool is available to ESA.

➔Baffle can be modelled as absorbing and PEC on the same surface.

Combination of absorbing and PEC surfaces:

- Import of CAD model of the baffle.
- Absorbing properties assigned to the baffle internal surface.

➔Equivalent currents are calculated on the inner surface of the baffle and radiated to the secondary mirror.

➔Equivalent currents can be calculated on the outer surface of the baffle and radiated to the primary mirror.

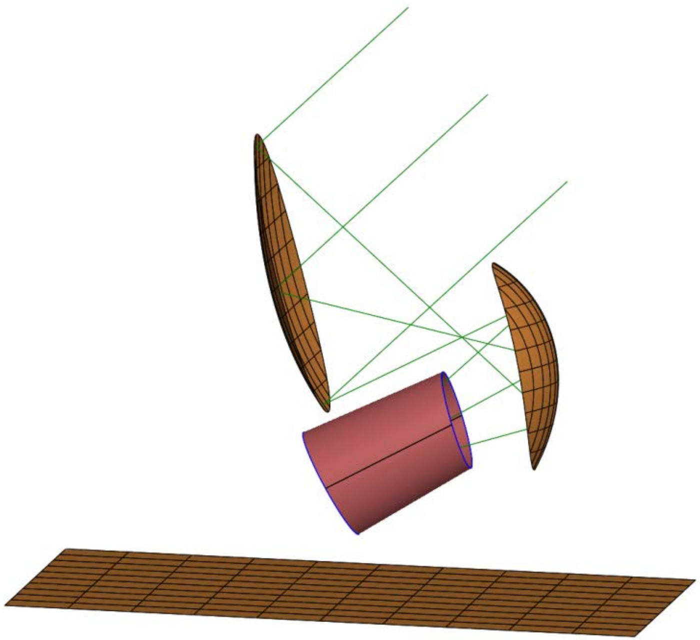
Baffle modelling – 3. Absorbing / PEC model

In order to assess the feasibility of this approach the model has been produced with absorbing properties on the inner surface of the baffle as imported from CAD.

Resulting equivalent currents on the baffle from the feed in the central position of the FPU are radiated.

Comparison of the field obtained with a PEC and an absorbing baffle are presented.

Reflectors are not included in the model.

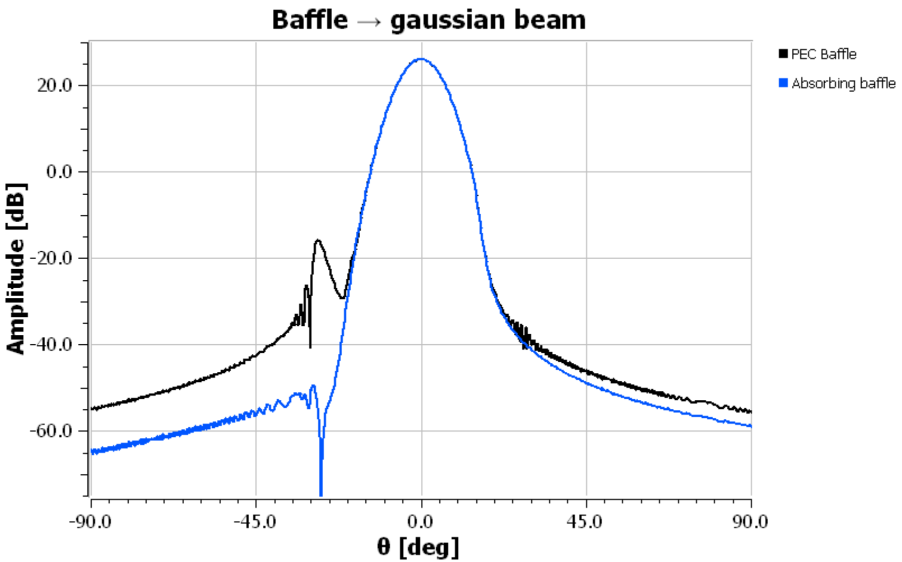


Baffle modelling – 3. Absorbing / PEC model

A gaussian feed is placed in the centre of the FPU:

- Field obtained fin presence of a PEC baffle (black curve)
- Field obtained in presence of an absorbing baffle (blue curve).

The difference between the two curves shows the effect of the absorbing properties applied to the inner surface of the baffle.

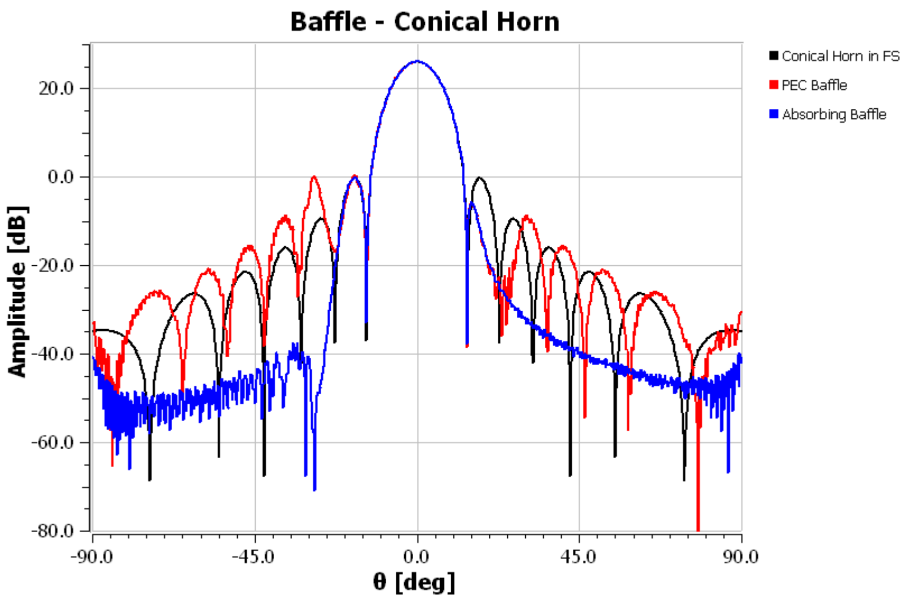


Baffle modelling – 3. Absorbing / PEC model

A conical horn is placed in the centre of the FPU:

- Field from the conical horn in FS (black curve).
- Field obtained fin presence of a PEC baffle (red curve) shows the effect of the reflection inside the baffle and the correspondent increased side lobes.
- Field obtained in presence of an absorbing baffle (blue curve) shows the absorption of the side lobes.

➔The comparison shows a reasonable effect of the inner absorbing surface of the baffle and prove the feasibility of the analysis.



Conclusions

The analysis of the effect of the baffle design is a problem with no straightforward solutions.

- A strategy to assess the effect of the presence of the baffle to the entire telescope beam pattern has been proposed.
- The assessment of the reflection of the outer surface of the baffle is proposed to be done via PEC model.
- Limitations of the modelling tools need to be better investigated in terms of feasibility, accuracy and computational time.
- **A complete analysis of the absorbing and reflecting surface is proposed via a combined model making use of representative feeds and it has been proved in terms of feasibility.**

CMB Polarisation Mission

Systems

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

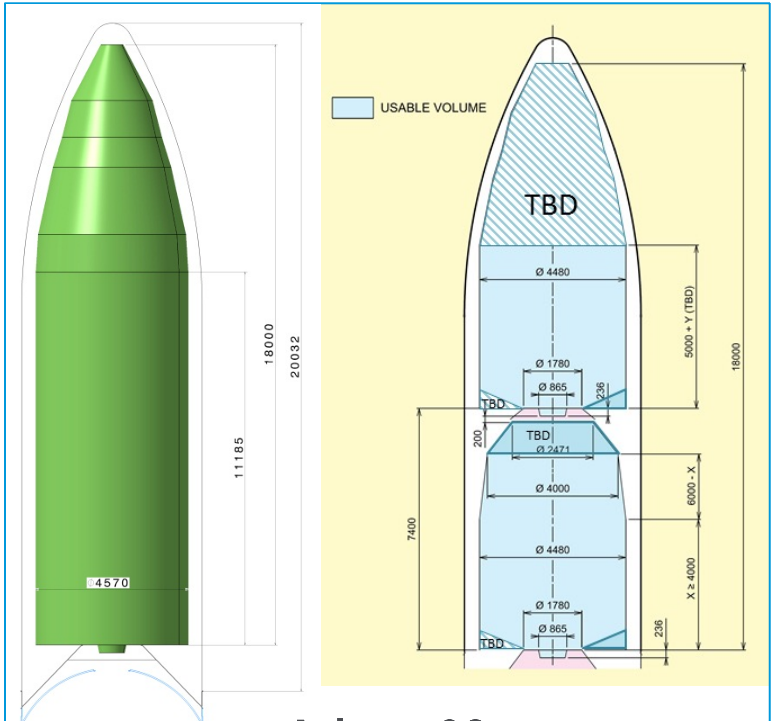
ToC

Requirements and Constraints

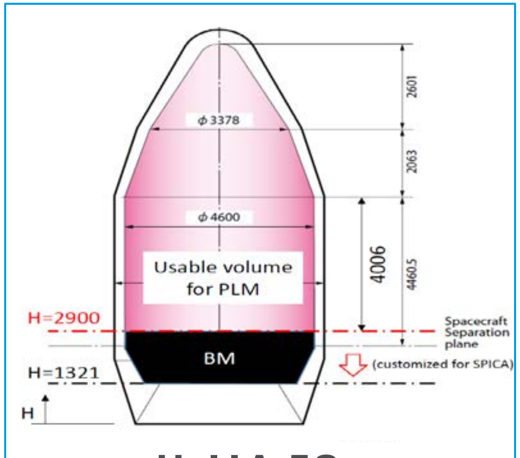
- At this stage, a limited set of requirements and constraints has been defined and is listed hereafter

Launcher	The spacecraft shall be launched either on a **Japanese H-II / H-3** launch vehicle or on a European **Ariane 62**.
Orbit	The science operations orbit shall be an **eclipse-free** (Earth and Moon) orbit around the **Sun-Earth Lagrange Point 2**.
Mission lifetime	The nominal mission lifetime shall include **3 years** observation time.
Launch date	The spacecraft shall be launched in **2027/2028** (in case of ESA-only mission), goal for JAXA: 2025.
Payload	The payload module shall accommodate a **cryogenically cooled telescope with a 1.2 m aperture**.
Cost	The ESA contribution shall be in the scope of an **ESA M-class** mission.

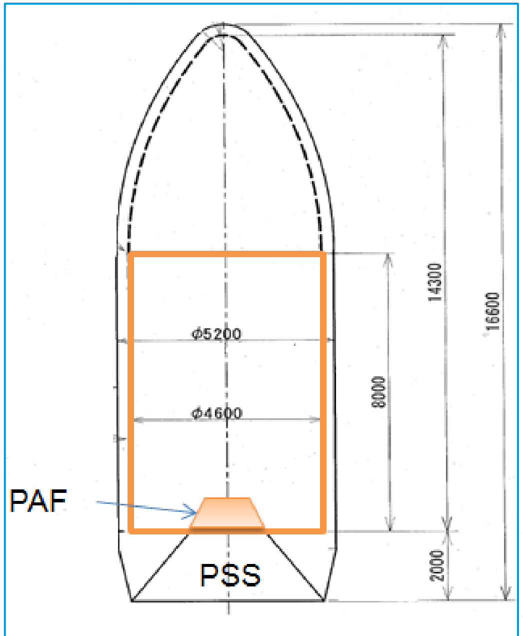
Launcher envelopes



Ariane 62



H-IIA 5S



H-3

- A62 dynamic envelope is most constraining in diameter: 4.48 m
- H-IIA is most constraining in height: 4 m plus conic volume

Delta-v budget

	CMB Polarisation **Delta-v Budget** Orbit type	**Herschel-based** Large amplitude Lissajous	**Planck-based** Small amplitude Lissajous	**Unit**	**Comments and references**
TCM#1	**Launcher dispersion correction manoeuvre (stochastic)**	45	45	m/s	Herschel/Planck Consolidated Report on Mission Analysis (CReMA) Issue 3.1, PT-MA-RP-0010-OPS-GMA
	Perigee velocity correction manoeuvre (deterministic)	26	26	m/s	
TCM#2	**Correction of TCM#1 (stochastic)**	3	3	m/s	
TCM#3	**Correction of TCM#2 (stochastic)**	2	2	m/s	
TCM#4	**Orbit injection and eclipse avoidance**	0	215	m/s	For a transfer to a large amplitude Lissajous orbit, a direct transfer along the stable manifold can be assumed.
TCM#5	**Correction of TCM#4**	0	2	m/s	For a transfer to a small amplitude Lissajous orbit, an orbit injection manoeuvre plus a correction manoeuvre is required (cf. Planck: 217 m/s before margin).
	Margin on stochasitic delta-v	0	0	%	Margin philosophy for science assessment studies, SRE-PA/2011.097/ iss. 2 rev. 0
	Margin on deterministic delta-v	5	5	%	
	Nominal lifetime	3	3	yrs	Nominal mission lifetime shall include 3 yrs observation
	Extended lifetime	0	0	yrs	
	Orbit maintenance per year	6.95	6.95	m/s/yr	Assuming an unbalanced thruster configuration and an unpredictable parasitic delta-v.
	Orbit maintenance	20.8	20.8	m/s	
	Margin on orbit maintenance delta-v	5	5	%	SRE-PA/2011.097/ iss. 2 rev. 0
	Disposal	10	10	m/s	Heliocentric Disposal, cf. Athena CReMA Iss. 1, Rev. 2
	RW offloading and safe mode recovery			m/s	To be assessed in follow-on study
	Margin on AOCS delta-v	100	100	%	SRE-PA/2011.097/ iss. 2 rev. 0
	Total without margin	**106.8**	**323.8**	**m/s**	
A	**Total incl. margin on MA delta-v and unbiased trajectory**	**109.2**	**336.9**	**m/s**	Assuming spherical thrust capability for transfer manoeuvres (20 N thrusters) as for Planck propulsion subsystem. No biased trajectory is required.
B	**Total incl. margin on MA delta-v and biased trajectory for orbit maintenance**	**131.1**	**358.8**	**m/s**	Assuming spherical thrust capability for transfer manoeuvres but biased trajectory during nominal operations (penalty factor 2 for orbit maintenance delta-v only).

Note: If a pre-defined attitude strategy can be assumed, the orbit maintenance delta-v can be reduced to 1 m/s/yr. In case of a balanced thruster configuration, the orbit maintenance delta-v is less than 0.8 m/s/yr.

Propellant budget

4 options have been considered:

1. Large amplitude Lissajous orbit with unbiased trajectory
2. Large amplitude Lissajous orbit with biased trajectory after transfer to target obit (spherical thrust capability for transfer manoeuvres but biased trajectory during nominal operations)
3. Small amplitude Lissajous orbit with unbiased trajectory
4. Small amplitude Lissajous orbit with biased trajectory after transfer to target obit

CMB Polarisation Propellant budget	Option 1	Option 2	Option 3	Option 4	Unit	Comments
Spacecraft dry mass	1830.0	1830.0	1830.0	1830.0	kg	NGCryo dry mass: 2500 kg
ISP	215.0	215.0	215.0	215.0	s	NGCryo: steady-state firing: 230s, pulse mode firing: 200s, average: 215s
Propellant required for Mission Analysis	97.2	117.3	317.0	339.4	kg	
Propellant required for AOCS	200.0	200.0	200.0	200.0	kg	Assuming thruster-based AOCS option
Total propellant mass excl. margin	**297.2**	**317.3**	**517.0**	**539.4**	**kg**	
Total propellant mass incl. 2% margin	**303.2**	**323.7**	**527.3**	**550.2**	**kg**	
Available propellant mass in Planck tanks (3x174l)	385.0	385.0	385.0	385.0	kg	

The currently available propellant mass in the NGCryoIRTel SVM allows for a large amplitude Lissajous orbit (Herschel-type). An optimisation of the size and/or number of propellant tanks could be envisaged in a follow-on study.

Mass Budget

Subsystem considered at subsystem level:

- Chemical Propulsion
- Data Handling: scaling from NGCryo to account for the additional data storage
- Power: scaling from NGCryo to account for the additional solar arrays.

S/C Mass Budget		Mass [kg]
Dry Mass PLM		**372.91**
Dry Mass SVM		**1151.51**
System Margin	20%	304.88
Dry Mass incl. System Margin		**1829.30**
CPROP Propellant Mass		318.00
CPROP Propellant Margin	2%	6.36
CPROP Pressurant Mass		5.20
CPROP Pressurant Margin	2%	0.10
Total Wet Mass		**2158.97**

Element Definition long nar Payload Module

Subsystem	Switch	PLM Mass Budget		Mass [kg]
STR	Product			284.15
TC	Product			11.00
INS	Product			60.00
MEC	Not used			0.00
		Harness	5%	17.76
		Dry Mass w/o System Margin		**372.91**

Element Definition long nar Service Module

Subsystem	Switch	SVM Mass Budget		Mass [kg]
PWR	Function			121.00
COM	Product			20.51
CPROP	Function			84.81
AOGNC	Product			25.26
TC	Product			354.20
DH	Function			52.25
STR	Product			374.85
MEC	Product			27.80
INS	Product			36.00
		Harness	5%	54.83
		Dry Mass w/o System Margin		**1151.51**

Power budget

- Subsystem considered at subsystem level:
  - Chemical Propulsion
  - Data Handling: scaling from NGCryo to account for the additional data storage

- Main contributor : Thermal Control

Thermal Control	P_mean [W]
2ST Cryocooler (8)	400
4K JT Cryocooler (2)	265
1K JT Cryocooler (2)	235
Cryocooler Electronics	510
SVM TCS Misc	125
Total	**1535**

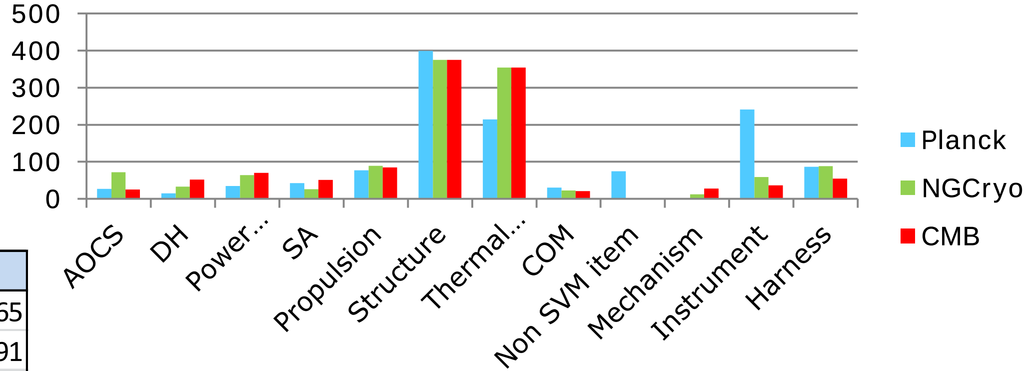
Power (W)	P_mean
PLM (Payload Module)	**0.00**
SVM (Service Module)	**1931.26**
AOGNC	37.50
COM	39.96
CPROP	1.00
DH	80.80
INS	222.00
MEC	15.00
TC	1535.00
Grand Total	**1931.26**

Mass comparison Planck-NGCryo-CMB

SVM	Planck	NGCryo	CMB
AOCS	27.2	71.44	25.26
DH	14.7	32.45	52.25
Power Subsystem	34.9	63.57	69.7
SA	42.1	26.3	51.3
Propulsion	77.1	88.79	84.81
Structure	399.5	374.64	374.85
Thermal Control	213.95	354.2	354.2
COM	30.1	22.41	20.635
Non SVM item	74.6	-	-
Mechanism	-	11.8	27.8
Instrument	241.4	58.8	36
Harness	86.1	88.35	54.84
Total	**1241.7**	**1192.8**	**1151.65**

PLM	Planck	NGCryo	CMB
Telescope Structure	170.8	534.12	284.15
Cryo Structure	127.9		
Thermal Control	-	10	11
Mechanism	-	27.75	-
Instrument	94.55	120.12	60
Harness	-	34.6	17.76
Total PLM	**393.25**	**726.59**	**372.91**

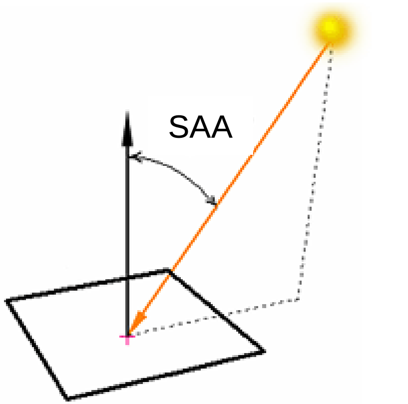
	Planck	NGCryo	CMB
Total SVM	1241.65	1192.75	1151.65
Total PLM	393.25	726.59	372.91
Dry Mass exclu. Syst. Margin	**1634.9**	**1919.34**	**1524.56**
System Margin	81.745	383.87	304.91
Total Dry Mass	**1716.6**	**2303.2**	**1829.47**



Solar array sizing

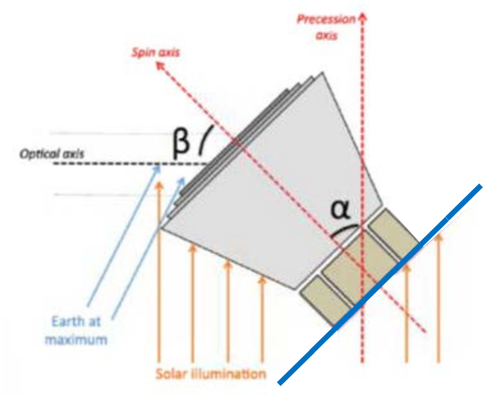
- The NGCryoIRTel SVM accommodates a 14.2 m^2 body-mounted solar array (triple-junction 3G30% GaAs cells) on the bottom panel of the SVM
- At a sun aspect angle (SAA) of 15 degrees, this solar panel generates around 2 kW at user level
- At a SAA of 50 degrees and assuming a power demand of around 2 kW, the body-mounted solar array area is not sufficient

	NGCryoIRTel	CMB Polarisation	Units	Comments
Power demand excl. system margin	2018	2018	W	
System margin	20	20	%	
Power demand incl. system margin	2421.6	2421.6	W	2073 W for CorE+ incl. 10% margin
Solar aspect angle	15		deg	
Required usable solar array area	14.2		m^2	
Solar aspect angle	0		deg	perfect illumination
Required usable solar array area	13.7		m^2	
Solar aspect angle		50	deg	
Cosine / corrected cosine of SAA		0.6401		Corrected cosine for SAA> 45 degrees
Required usable solar array area		**21.4**	**m^2**	



Solar array sizing

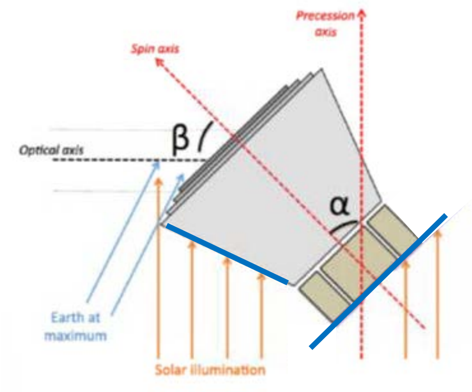
- Option 1: Deployable solar arrays extending the body-mounted S/A on the SVM bottom plate
  a) Re-use of 14.2 m^2 body-mounted S/A plus additionally required usable solar array area of 7.2 m^2
  b) Reduced 10 m^2 body-mounted S/A plus additionally required usable solar array area of 11.4 m^2



- Currently available area on SVM sides is 11.2 m^2
- The available area on the SVM sides is sufficient to store the deployable S/As of Option 1b (8 S/A flaps stored on each side of the SVM)
- 4 vs. 8 deployable solar panels should be assessed in a follow-on study (complexity vs. available space for storage)

Solar array sizing

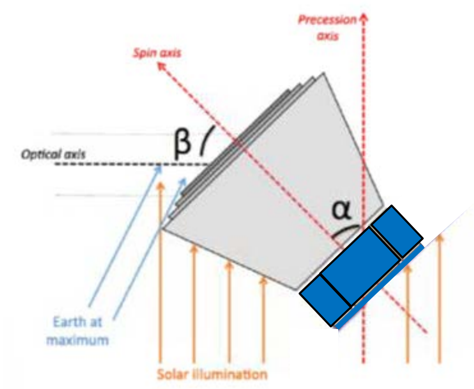
- Option 2: Re-use of body-mounted S/A plus body-mounted solar panels around sun-shield



		CMB Polarisation	Units
	Average power demand at user level that can be supported by 14.2 m^2	1604.7	W
	Additionally required power	816.9	W
	Additionally required usable S/A area at 0 deg SAA	4.63	m^2
Conical spinner	Required cone area for a spinner at 0 deg SAA	14.54	m^2
	sun shield semi opening angle	25	deg
	SAA for cone area	15	deg
	Cosine / corrected cosine of SAA	0.9659	
	Required cone area for a spinner	**15.0**	**m^2**
	Bottom radius of sun shield	1.4	m
	Top radius of sun shield	2.2	m
	Height of sun shield	1.96	m
	Available area on telescope sun shield	**23.94**	**m^2**

➢ The available area on the sun shield is sufficiently large for the additionally required solar array area

- Option 3: Reduced body-mounted S/A plus body-mounted solar panels on SVM sides



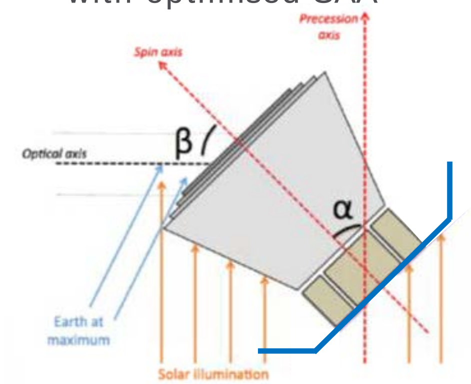
		CMB Polarisation	Units
	Average power demand at user level that can be supported by 10 m^2	1130.0	W
	Additionally required power	1291.6	W
	Additionally required usable S/A area at 0? SAA	7.32	m^2
Octagonal spinner	Required total area for a octagonal spinner at 0 deg SAA	24.39	m^2
	SAA for SVM side panels	40	deg
	Cosine / corrected cosine of SAA	0.7660	
	Required total area for an octagonal spinner at 40 deg SAA	**31.8**	**m^2**
	Height of SVM sides	0.94	m
	Length of SVM sides	2.985	m
	Number of SVM sides	4	
	Available area on SVM sides	**11.2**	**m^2**

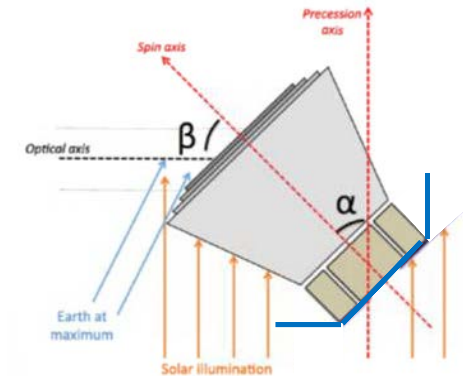
➢ The available area on the SVM sides is not large enough to accommodate the additionally required solar array area

Note: number of sides is set to 4 and includes 1 small and 1 large side of the octagon

Solar array sizing

- Option 4: Re-use of body-mounted S/A on the SVM bottom plate plus deployable solar arrays with optimised SAA





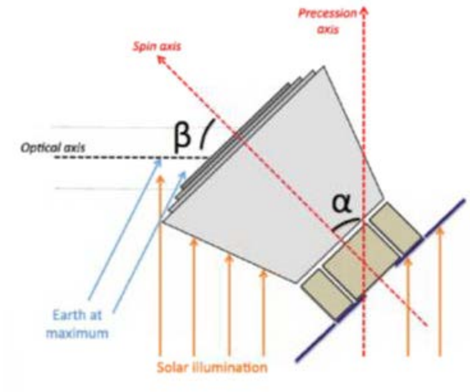
		CMB Polarisation	Units
	Average power demand at user level that can be supported by 14.2 m^2	1604.7	W
	Additionally required power	816.9	W
	Additionally required usable S/A area at 0 deg SAA	4.63	m^2
Deployable S/As with optimised SAA	Required cone area for a spinner at 0 deg SAA	14.54	m^2
	Solar panel semi opening angle	40	deg
	SAA for cone area	0	deg
	Cosine / corrected cosine of SAA	1.000	
	Required cone area for a spinner	**14.5**	**m^2**

		CMB Polarisation	Units
	Average power demand at user level that can be supported by 10 m^2	1130.0	W
	Additionally required power	1291.6	W
	Additionally required usable S/A area at 0 deg SAA	7.32	m^2
Deployable S/As with optimised SAA	Required cone area for a spinner at 0 deg SAA	22.98	m^2
	Solar panel semi opening angle	40	deg
	SAA for cone area	0	deg
	Cosine / corrected cosine of SAA	1.000	
	Required cone area for a spinner	**23.0**	**m^2**

- Canting the deployable S/As to achieve a SAA of 0 degrees does not reduce the additionally required S/A area (compared to Option 1), since only half of the deployable S/A is illuminated
- The optimum deployment angle needs to be assessed
- Stored configuration needs further assessment (available area on SVM sides < area of deployable S/A)

Solar array sizing conclusion

- For CMB Polarisation the body-mounted solar array on the NgCryoIRTel SVM is not sufficient, due to the large SAA
- Multiple options exist to increase the usable solar array area
- All options need to be further assessed e.g. w.r.t. thermal effects, complexity (mounting, stored configuration), available radiator area, modifications of SVM bottom plate, mass impact, thruster accommodation



- Current baseline: Reduced 10 m^2 body-mounted S/A plus deployable solar panels extending the body-mounted S/A
- Alternative: Re-use of body-mounted S/A plus body-mounted solar panels around sun-shield

CMB Polarisation Mission

AOCS

Prepared by the CDF* Team

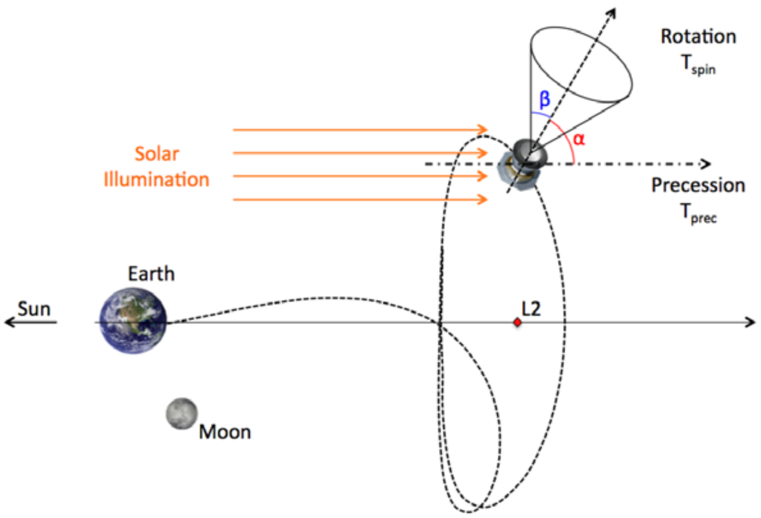
(*) ESTEC Concurrent Design Facility

Summary

- AOCS requirements
- Sensors
- Pointing knowledge performance
- Control strategy and actuators

AOCS Requirements

- The SC must be capable of following a scanning law consisting of:
    - Fast spinning at 2 rpm
    - Slow precession with a period of 4 days (spin axis offset from the precession axis by an angle of 50 deg)
    - Continuous scanning
- Absolute knowledge error (AKE) < 1 arcsec
- Absolute pointing error (APE) 0.4 arcminutes
- Sun Aspect Angle 50 deg ±15 deg



Sensors

- Equipments:
  - Gyro (GYR) (internally redundant)
    - RRW: 1.67 arcsec/sec^(3/2) (3sigma)
    - ARW: 0.012 arcsec/rt-sec (3sigma)

Performances		
• Noise	0.0001 °/√h	(BOL)
• Bias stability over one hour	0.0005 °/h	
• Scale Factor stability over one month	30 ppm	In [-10 50°C] range

Budgets	
• Mass	12,7 kg (ICU 7,5 kg, GEU 4,5 kg + harness)
• Volume	ICU ø330 x h280, GEU 295x150x145 mm3
• Power	5.5 W typ. BOL per ON channel Up to 7.5W EOL per ON channel

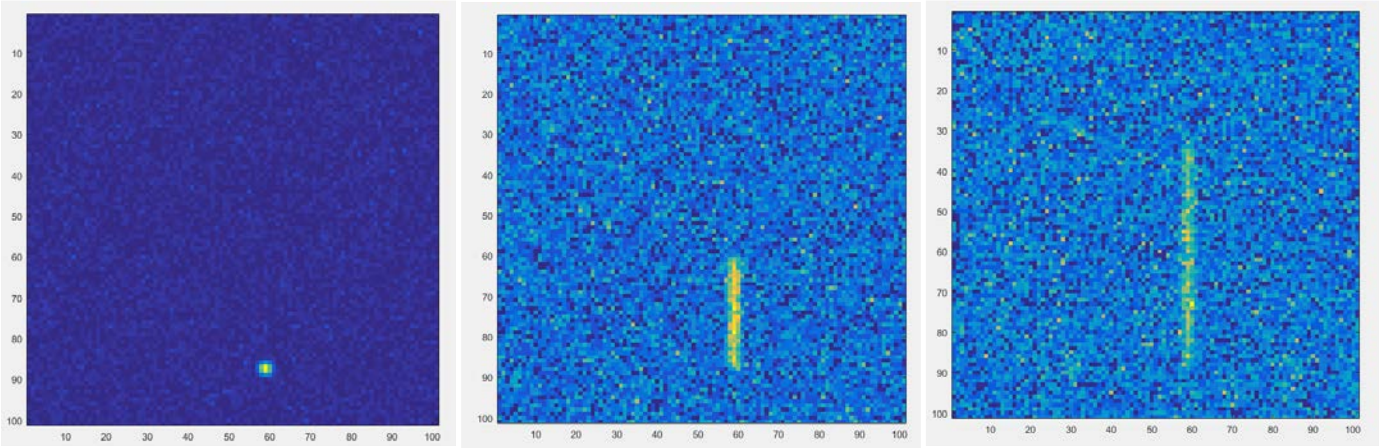
  - Star tracker (STR) (2 units)
    - Technology <u>not available</u> off the shelf for operation at 12 deg/s with required accuracy: need of dedicated technology development
  - Fine sun sensor (FSS) (3 units)
  - Coarse rate sensors (CRS) (2 units)

Pointing Knowledge Performance

- Star tracker performance is affected by the angular rate of the stars relative to the pixels in the FOV
- Commonly used star tracker can provide attitude measurement up to 6-8 deg/sec rate
- Above the 6-8 deg/sec value, the star tracker measurement reliability and performance are compromised (dim star detection not possible due to large amounts of image smear)

- In order to compensate for the spinning rate, Time Delay Integration (TDI) technique is needed
- TDI provides high sensitivity to moving image for application on spinning spacecrafts (Planck, New Horizon)

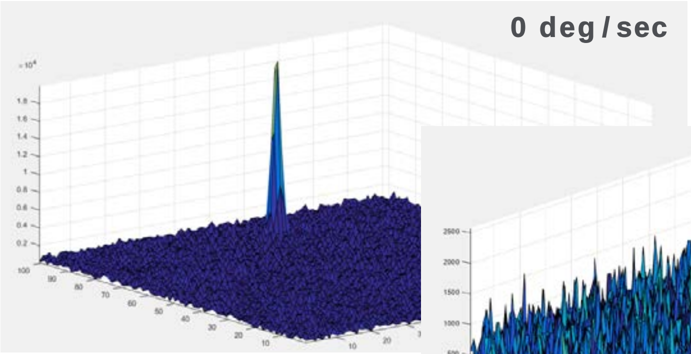
Examples of star spot smearing due to angular rate in STR images without TDI (0 deg/sec, 6 deg/sec, 12 deg/sec)



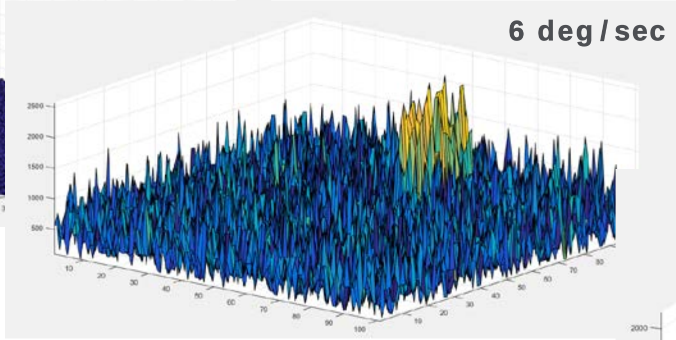
Pointing Knowledge Performance

Examples of star spot smearing due to angular rate in STR images without TDI

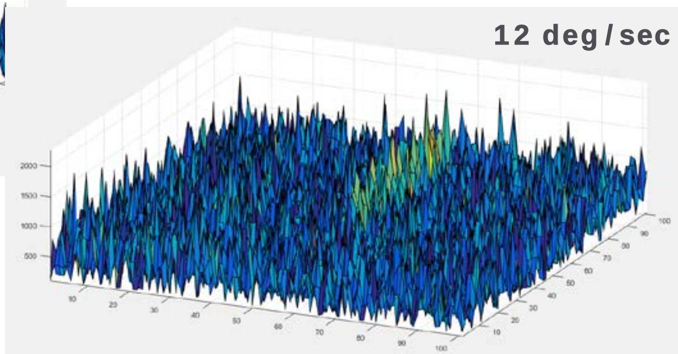
0 deg/sec



6 deg/sec



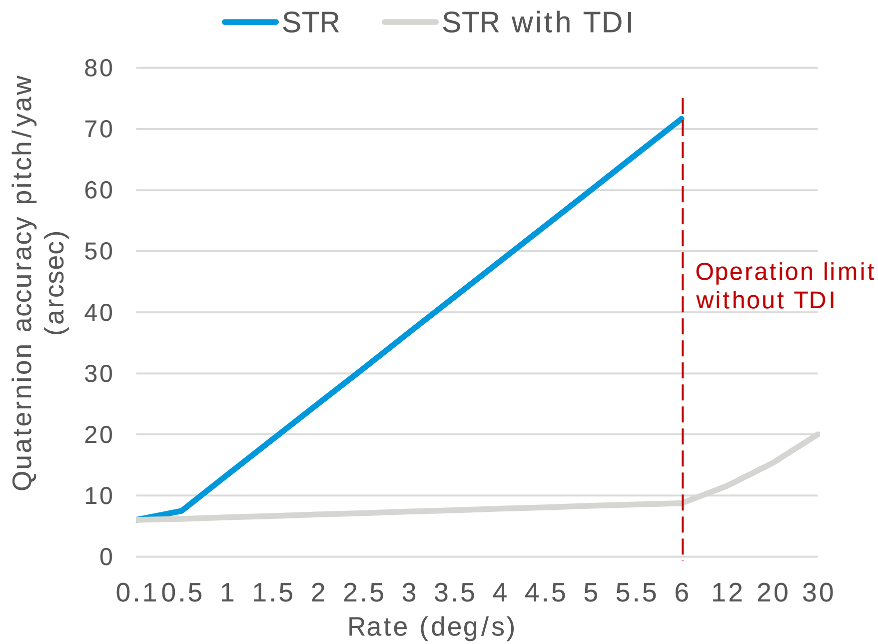
12 deg/sec

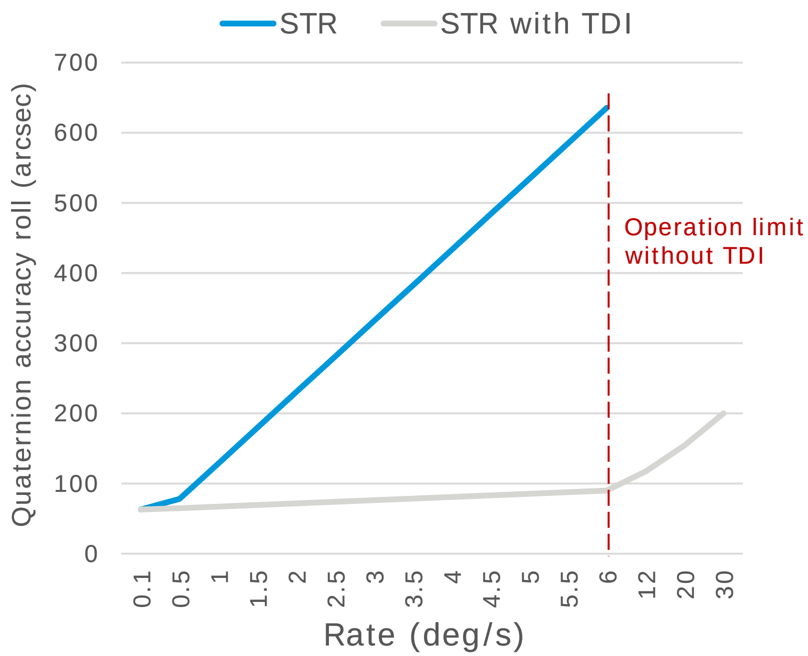


At 6 deg/sec and above the star signal is spread over too many pixels and the signal-to-noise ratio (SNR) significantly decreases. This strongly affects the star detection capability and centroiding performance.

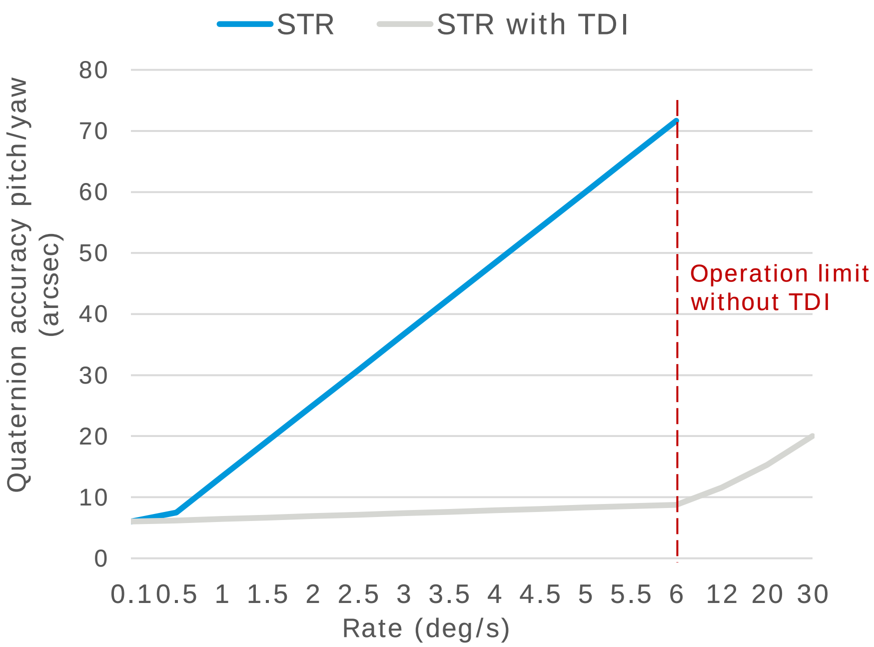
Pointing Knowledge Performance

- Comparison of accuracy performance (NEA, random error contribution) for a conventional star tracker and a star tracker using TDI (time delay integration) technique (ref. Planck, New Horizon)





Pointing Knowledge Performance



Rate [rpm]	Rate [deg/sec]	STR NEA pitch/yaw [arcsec]	STR NEA pitch/yaw (with TDI) [arcsec]
0.016	1	13.33	6.42
0.5	3	36.67	7.36
1	6	71.67	8.76
2	12	-	11.57

Pointing Knowledge Performance

STR	STR with TDI
Tracking rate up to 6÷8 deg/s (1 ÷ 1.3 rpm)	Tracking rate up to 60 deg/s (10 rpm)
Accuracy* pitch/yaw (NEA) 71.67 arcsec @ 6 deg/s	Accuracy* pitch/yaw (NEA) 8.76 arcsec @ 6 deg/s 11.57 arcsec @ 12 deg/s
Attitude estimation error* (STR @10 Hz) (gyrostellar estimator) 13.91 arcsec @ 6 deg/s	Attitude estimation error* (STR @10 Hz) (gyrostellar estimator) 2.82 arcsec @ 6 deg/s 3.49 arcsec @ 12 deg/s
Non stringent mounting alignment requirement	Stringent mounting alignment requirement
Available off the shelf	Not available off the shelf (TRL 3÷4 due to need of re-development but flight-proven)

*** 3-sigma values**

Control strategy design drivers and trade-offs

- The actuators configuration and sizing depends mainly on the total angular momentum of SC, that is given by:

$$H = I_x \omega_x \cong 420\ Nms$$

Where:

- I_x is the inertia about the spin axis (total inertia of the SC assumed equal to Planck)

$$I \cong \begin{bmatrix} 2000 & 0 & 0 \\ 0 & 1800 & 0 \\ 0 & 0 & 1800 \end{bmatrix} \frac{kg}{m^2}$$

- ω_x is the spin rate:

$$\omega_x = 0.209 \frac{rad}{s}\ (2\ rpm)$$

- Two options have been evaluated:
  - Thruster based
  - Momentum exchange based

Thruster-based scenario

- SAA correction maneuver every 4 days (4 deg of pointing error, estimated propellant consumption 3 Kg)
- Precession motion achieved by changing the inertial orientation of the angular momentum
- Considering one reorientation every spin period (30 sec):
  - Maneuver angle of 0.03 deg
  - Small and frequent pulses of about 0.23 N (considering 1 m arm)

$$\mathrm{dt} \to 0 \qquad d\theta = 2\delta \sin\frac{\omega_x dt}{2} = \frac{T_z dt}{I_x \omega_x}\frac{\sin\frac{\omega_x dt}{2}}{\frac{\omega_x dt}{2}} \cong \frac{T_z dt}{I_x \omega_x}$$

  - About 11 500 pulses are needed to achieve 1 complete precession (about 3 200 000 for all mission)
  - Actuators: 1N hydrazine thruster

    Considering that one unit is qualified for 375 000 pulses, 10 units are needed

  - Estimated propellant consumption: 250 kg (considering 1.5 m lever arm)

Thruster-based scenario

- Trade-offs
  - By decreasing the spin-axis reorientation rate the number of pulses and the number of thrusters decrease

Reorientation rate	N# pulses	N# thrusters
every 30 s	about 3 000 000	10
every 60 s	about 1 500 000	5

  - By increasing the precession period the mass of propellant decreases

Precession period	Propellant mass
4 days	about 250 kg
6 days	about 150 kg
8 days	about 125 kg

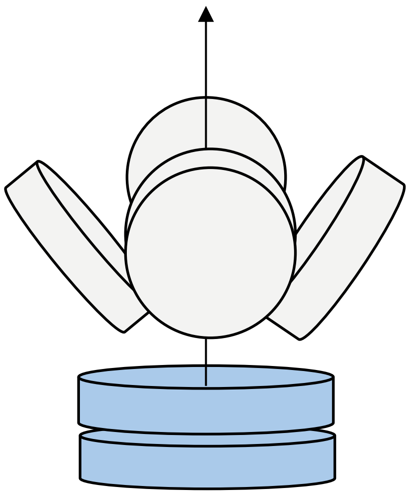
Momentum-exchange-based scenario

- Use of reaction wheel assembly to cancel the spacecraft momentum and to move the spin axis about the precession cone.
  - Momentum of the spacecraft about 420 Nms
  - The RWAs should be capable of:
    - maintaining the system momentum near zero
    - applying the desired control torque 5.8 mNm
  - Possible actuators configuration:
    - Four 70 Nms reaction wheels in pyramid configuration
    - One or more reaction wheels providing 400 Nms total momentum arranged about the spin axis
  - Trade-offs:
    - Reducing the spin rate to reduce the total spacecraft momentum

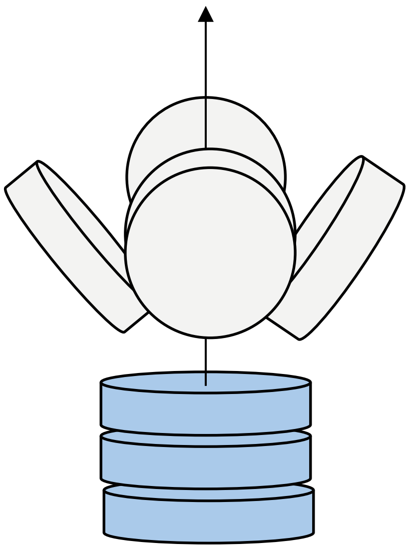
Momentum-exchange-based scenario

x4 RW in pyramid configuration	
Angular Momentum	70 Nms
Dimensions	374 mmm diameter 124 mm height
Mass	9.5 Kg
Power	20 W

S/C Spin rate	S/C Angular Momentum	# of RWs
1 rpm	200 Nms	3 x 70 Nms RWs or 2 x 100 Nms RWs
2 rpm	400 Nms	6 x 70 Nms RWs or 4x 100 Nms RWs



@ 1 rpm
x4 70 Nms RWs
x2 100 Nms RWs



@ 1 rpm
x4 70 Nms RWs
x3 70 Nms RWs

CMB Polarisation Mission

Communications

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Outline

- Design Drivers
  - Science Data Volume
  - Observation Strategy
- Design Trade-Offs
  - Frequency Bands
  - Ka-Band Pointing Strategy
  - Ka-Band Amplifier Technology
- Link Budget Analysis
- On-Board Transmit Parameters (EIRP Design & Sizing)
- Early Preliminary Design
  - Technologies
  - Budgets – Mass/Power/Maturity
- Conclusions
- Acronyms

Design Drivers (I) – Science Data Volume

- Science Data Volume
  - Data Rate – Option 1 (O1):
    - 4.8 [Mbps] (@ 2 [RPM]) → 414.72 [Gbit/day]
  - Data Rate – Option 2 (O2):
    - 2.4 [Mbps] (@ 1 [RPM]) → 207.36 [Gbit/day]
  - Includes compression (factor of 4)
  - 0% scientific data outage

↓

Requires compromise between…

Link Availability + (Large) Bandwidth + Technology Heritage

Design Drivers (II) – Observation Strategy

- Observation Strategy
  - Continuous...
    - Spinning @ 2 [RPM] or 1 [RPM] ⇨ constraints data rate
    - Precession @ 50 [°] , 4-day period ⇨ constraints data transfer
    - Translational motion over Sun-Earth L2 (large-amplitude)

⇩

Requires...

- High on-board transmitted power (high data rate)
- Antenna repointing during downlink to avoid science outage and maximize FOV

  (but no repointing of spacecraft)

Design Trade-Offs – Frequency Bands

Compromise between...

Link Availability + (Large) Bandwidth + Technology Heritage

...required

Frequency Bands				
	Data Rates	**TRL**	**Ground Stations**	**Ground Contacts**
X-Band	Between 5~7 [Mbps] achievable - NOK for 2 [RPM] - OK for 1 [RPM] (band occupation at its limit for 1 [RPM] case)	Heritage (high reusability possible from Herschel & Planck, reducing costs) (Category A/B)	3/3 DSAs with X-band capabilities, but longer contact times required (low DR) Might require additional ground stations (added complexity)	At least 8 [h/day] (not including HK TM & TC data); may not suffice for such low DR; may not be possible with just the DSA network
Ka-Band	> 10 [Mbps] - OK for 2 [RPM] - OK for 1 [RPM]	High TRL for most components; transponder/transmitter to need delta-developments (Category A to C)	2/3 DSAs with Ka-band capabilities	Around 4 [h/day] 28.8 [Mbps] @ 2 [RPM] ; < 3 [h/day] feasible @ 50 [Mbps] 14.4 [Mbps] @ 1 [RPM] ; < 2 [h/day] feasible @ 50 [Mbps]

Ka-Band selected for early preliminary subsystem design & sizing

Best
Good
Poor
Not Feasible

Design Trade-Offs – Ka-Band Pointing Strategy

Required...

- High on-board transmitted power
- Antenna repointing during downlink to avoid science outage and maximize FOV

Ka-Band Pointing Strategy								
	Bit Rate	**Complexity**	**TRL**	**Scientific Outage**	**FoV**	**Mass**	**Power**	**Cost**
Fixed	HGA can accommodate required DRs	Heritage	Category A/B equipment		Needs antenna with wide beamwidth			Low
Mechanically Steered	HGA can accommodate required DRs	Heritage	Category A/B equipment	0%		HGA dish can be < 3 [kg], only accounts for ~10-20 [%] of the mass; ~80-90 [%] of the mass is allocated to the APM and APME	Low power consumption	Nominal
Electrically Steered	Low EIRP	Needs major development to accommodate for Ka-band & for larger variation in elevation	Category C/D equipment (different frequency band than GAIA, plus high EIRP required)	0%	Large variation in elevation (± 78 [deg])	Heavy (~ 30 [kg]) and large (1.5 [m] diameter for GAIA)	Very high power consumption	High

Best
Good
Poor
Not Feasible

Mechanically steered antenna selected for early preliminary subsystem design & sizing

Design Trade-Offs – Ka-Band Amplifier Technology

- Investigations on current status of Ka-band SSPA vs TWTA technologies

Ka-Band Amplifier Technology				
	Efficiency	TRL	Mass	Output Power
SSPA	~10%	- Mostly Category D equipment - GaN SSPAs' robustness in space not assessed yet, even less for Space Research / Deep Space missions - Limited Ka-band SSPA suppliers (Thales, Teledyne)	~1 [kg]	1-3 [W]
TWTA	53%	Category A/B equipment	2.3 [kg] (TWT+EPC)	10-30 [W]

→ TWTAs are selected (availability of Ka-band technologies)

Best
Good
Poor
Not Feasible

Design Trade-Offs – Summary

- Design choices for early preliminary subsystem design & sizing (based on design drivers):
  - Ka-band (25.5 – 27 [GHz])
  - Mechanically steered high gain antenna
  - Ka-band TWT amplifiers

- These design choices help define the assumptions for the early preliminary link budget analysis

Link Budget - Assumptions

- Link Availability → Assume contact of 4 [h/day] (shared facilities) ; Cebreros G.S. (35 [m]) ; 20 [deg] elev. ; 95% Link Availability

  Atmospheric attenuation affects Ka-band transmissions

  Max. Link Distance: 1.7×10^6 [km]
- (Large) Bandwidth → No restrictions in Ka-band (25.5 – 27 [GHz])

  Ka-band suitable for data rates > 10 [Mbps]
- Technology Heritage → Current transponder technology enables a number of modulations and coding schemes suitable for high data rate tx (e.g. SRRC-OQPSK, Turbo-Codes, etc.)

- High on-board transmitted power + Antenna repointing during downlink

  → highly directional antenna (high gain, narrow 3-dB beamwidth)

Link Budget - Analysis

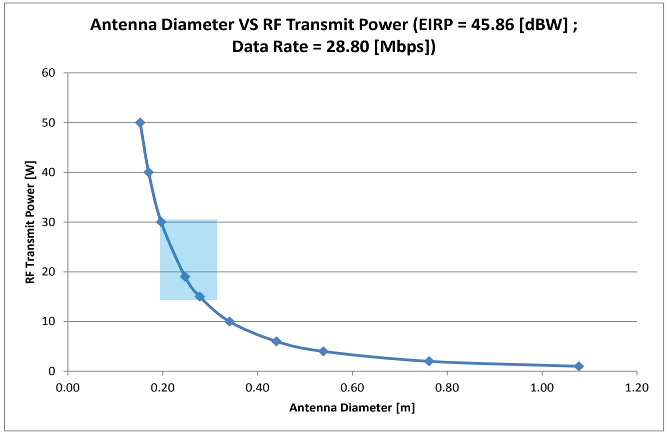
Parameter	Ka-band (O1)	Ka-band (O2)	Unit	Comment
	Option 1	Option 2		
Frequency	26000	26000	MHz	25.5 [GHz] to 27 [GHz] band
EIRP	45.86	42.85	dBW	Calculated
Range	1.70E+09	1.70E+09	m	Large Amplitude L2
Lpath	245.35	245.35	dB	Worst-case (calculated)
Latm	1.72	1.72	dB	(Ka-band) Average Annual, 95% CD, 20 deg elev to Cebreros (typically <2 dB)
Demod Loss	1	1	dB	Assumptions
Eb/No req	1.1	1.1	dB	Turbo Code 1/2, FER<1e-4
Margin	5	5	dB	> 3 dB (pre-pre-Phase A)
(G/T)Rx	54.3	54.3	dB/K	35 m Cebreros, 20 deg elev (Ka-band)
Data Rate	28.80	14.40	Mbps	Possibly SRRC-OQPSK Mod. (0.5 roll-off)
Contact Time	4	4	h	Realistic assumptions from previous studies/missions
Data Volume	414.72	207.36	Gbit/day	Calculated

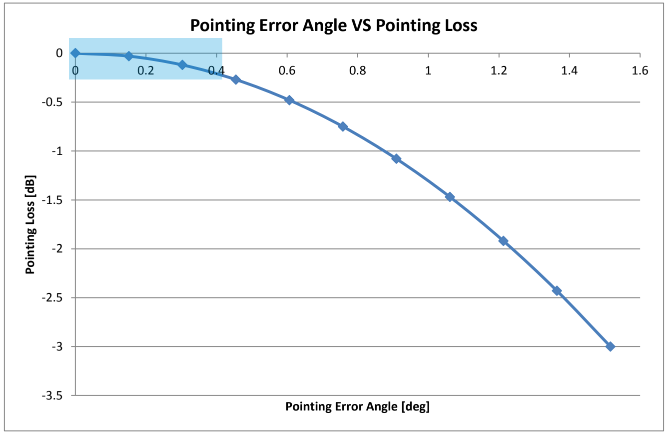
On-Board Transmit Parameters (EIRP Design & Sizing) (I)

EIRP=45.86 [dBW]

Ka-band (26 [GHz]) @ 2 [RPM]

- HGA parameter range:
  - Diameter: [0.20 , 0.28] [m]
  - Boresight Gain (max): [32.8 , 35.8] [dBi], 3dB Beamwidth: < 4 [deg]
  - Pointing Loss: < 0.20 [dB] (assuming APM Accuracy < 0.4 [deg])
- RF transmit power range:
  - [15 , 30] [W]



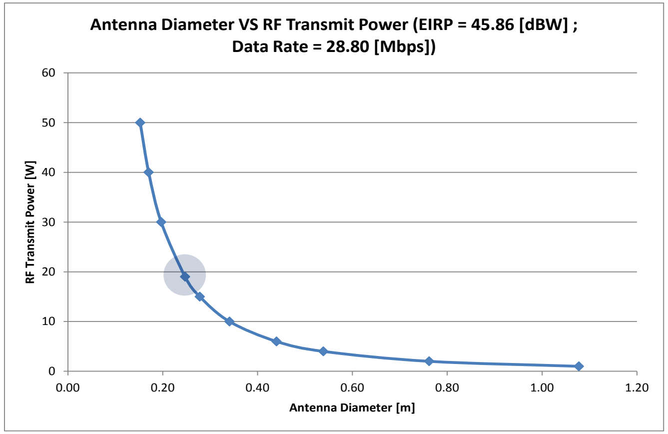


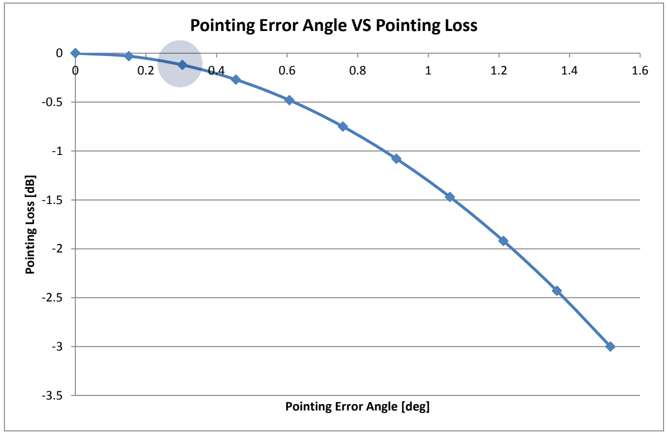
On-Board Transmit Parameters (EIRP Design & Sizing) (II)

EIRP=45.86 [dBW]

Ka-band (26 [GHz]) @ 2 [RPM]

- Proposed HGA parameters:
  - Diameter: 0.25 [m]
  - Boresight Gain (max): 34.70 [dBi], 3dB Beamwidth: 3 [deg]
  - Pointing Loss: 0.12 [dB]
- RF Transmit Power:
  - 19 [W] ; 12.79 [dBW]





Early Preliminary Design

Rationale: keep simple architectural concept (considering heritage, cost)

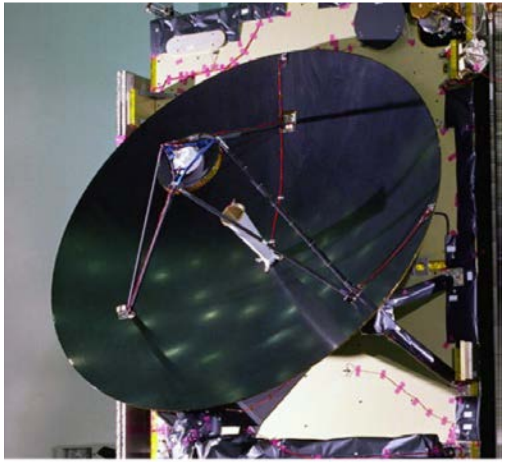
- X/X/Ka-Band Transponder (x2)
  - X-band for nominal TT&C operations (H/K TM, TC, ranging, Doppler).
  - Ka-band for science data downlink.
- HGA Ka-Band Antenna
  - Parabolic reflector dish for science data transmission (mech. steerable).
- LGA X-Band Antenna (x2)
  - To provide omnidirectional coverage during LEOP, contingency cases and ranging, HK TM & TC data (typically 4 [kbps]).
- Ka-Band TWT Amplifiers (x2) & Ka-Band EPC (x2)
  - To provide necessary RF signal amplification.
- RFDN
  - Interconnecting elements of the whole subsystem.

Early Preliminary Design - Technologies

- X/X/Ka-Band Transponder (x2)

X/X/Ka DS TRSP

- HGA Ka-Band Antenna



Rosetta's HGA

- LGA X-Band Antenna (x2)

X-Band LGA

- Ka-Band TWT Amplifiers (x2) & Ka-Band EPC (x2)

K-Band TWT

- RFDN

Early Preliminary Design – Budgets - Mass

Early Preliminary Design (Ka-Band - 25.5-27 [GHz])				
Component	**Mass [kg]**	**Margin [%]**	**Total Mass w/ Margin [kg]**	**Comments**
ANT (HGA)	1.2	10	1.28	
ANT (LGA)	0.95	5	1.00	Mass incl. bracket
ANT (LGA)	0.95	5	1.00	Mass incl. bracket
X/X/Ka XPDR	3.2	10	3.52	Up to 50 [Mbps] Ka-band
X/X/Ka XPDR	3.2	10	3.52	Up to 50 [Mbps] Ka-band
Ka TWT	1	5	1.05	10-30 [W] output pwr, 53% efficiency (TH4606)
Ka TWT	1	5	1.05	10-30 [W] output pwr, 53% efficiency (TH4606)
Ka EPC	1.3	5	1.37	Up to 95% efficiency
Ka EPC	1.3	5	1.37	Up to 95% efficiency
RFDN	4	20	4.8	

Total	**18.06 [kg]**		**19.94 [kg]**

Early Preliminary Design – Budgets - Power

Early Preliminary Design (Ka-Band - 25.5-27 [GHz])				
Component	**Power ON Actual Rx [W] (STBY)**	**Power ON Actual Tx [W]**	**Mean power [W]**	**Comments**
ANT (HGA)	0	0	0	
ANT (LGA)	0	0	0	Mass incl. bracket
ANT (LGA)	0	0	0	Mass incl. bracket
X/X/Ka XPDR	16	32	18.67	Up to 50 [Mbps] Ka-band
X/X/Ka XPDR	16	16	16.00	Up to 50 [Mbps] Ka-band
Ka TWT	0	37.74	6.29	10-30 [W] output pwr, 53% efficiency (TH4606)
Ka TWT	0	0	0.00	10-30 [W] output pwr, 53% efficiency (TH4606)
Ka EPC	0	2	0.33	Up to 95% efficiency
Ka EPC	0	0	0.00	Up to 95% efficiency
RFDN	0	0	0	

Total	**32 [W]**	**87.74 [W]**	**41.29**	**[W]**

Early Preliminary Design – Budgets – Maturity

Early Preliminary Design (Ka-Band - 25.5-27 [GHz])						
Component	TRL	Maturity	Dimensions			Comments
			Length [mm]	Width [mm]	Height [mm]	
ANT (HGA)	6	To be modified	250	250		
ANT (LGA)	9	Fully developed	132	132	209	Mass incl. bracket
ANT (LGA)	9	Fully developed	132	132	209	Mass incl. bracket
X/X/Ka XPDR	6	To be modified	250	175	130	Up to 50 [Mbps] Ka-band
X/X/Ka XPDR	6	To be modified	250	175	130	Up to 50 [Mbps] Ka-band
Ka TWT	9	Fully developed	300	60	80	10-30 [W] output pwr, 53% efficiency (TH4606)
Ka TWT	9	Fully developed	300	60	80	10-30 [W] output pwr, 53% efficiency (TH4606)
Ka EPC	9	Fully developed	185	670	126	Up to 95% efficiency
Ka EPC	9	Fully developed	185	670	126	Up to 95% efficiency
RFDN	5	To be developed	500	500	100	

- Transponder (XPDR) options (shall need further investigation):

1) Delta development for Ka-band XPDR @ [25.5,27] [GHz] (currently [31.8,32.3] [GHz])
2) Dedicated Ka-band transmitter @ [25.5,27] [GHz] + X/X-band XPDR (DST)

Conclusions

- Baseline: **Ka-band-based design**
  - Balanced compromise between:
    - Link availability
      - Smaller operational cost ; no compromise on science data return
    - Bandwidth
      - Extra filtering shall be needed for cancelling harmonics in the frequency range of the scientific observations (> 60 [GHz])
    - Technology heritage
      - TRL of baseline design: **5-9**
    - High power transmission & antenna repointing (by means of an APM)
- Options:
  - X-band could be feasible at the expense of data quality, bandwidth limitations and potentially larger operational costs (longer contact times required).
- Conclusions from this early preliminary study:
  - Feasible design from the point of view of telecommunications.
  - Strong baseline for a potential full-fledged pre-Phase A study.

Acronyms

APM	Antenna Pointing Mechanism
APME	APM Electronics
DR	Data Rate
DSA	Deep Space Antenna
DST	Deep Space Transponder
Eb/No	Energy per bit to noise power spectral density ratio
EIRP	Equivalent Isotropic Radiated Power
EPC	Electronic Power Conditioner
FER	Frame Error Rate
FOV	Field Of View
GaN	Gallium Nitride
GS	Ground Station
HGA	High Gain Antenna
HK	House-Keeping
LGA	Low Gain Antenna
OQPSK	Offset Quadrature Phase Shift Keying
RFDN	Radio Frequency Distribution Network
RPM	Revolutions Per Minute
SRRC	Square-Root Raised Cosine
SSPA	Solid State Power Amplifier
TC	Telecommand
TM	Telemetry
TRL	Technology Readiness Level
TWTA	Travelling Wave Tube Amplifier
XPDR	Transponder

CMB Polarisation Mission

Mechanisms

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

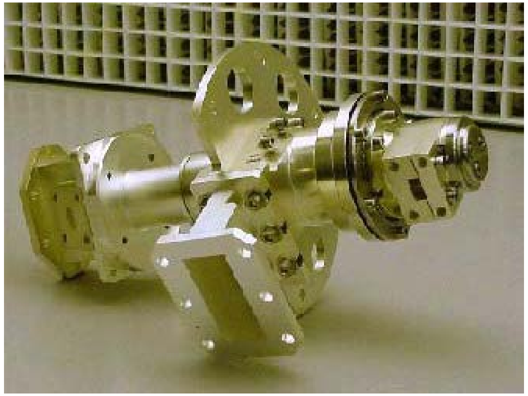
Agenda

1. Antenna pointing mechanism:
   - previous CDF studies;
   - previous missions with similar requirements for the antenna pointing mechanisms;
2. Antenna pointing strategy;
3. Technical specification and requirements for the APM for CMB Polarisation Mission;
4. Solar Array Deployment Mechanism;
5. AOCS support: available momentum wheels in case of bias momentum stabilization strategy.

Antenna Pointing Mechanism – CMB Polarisation Mission

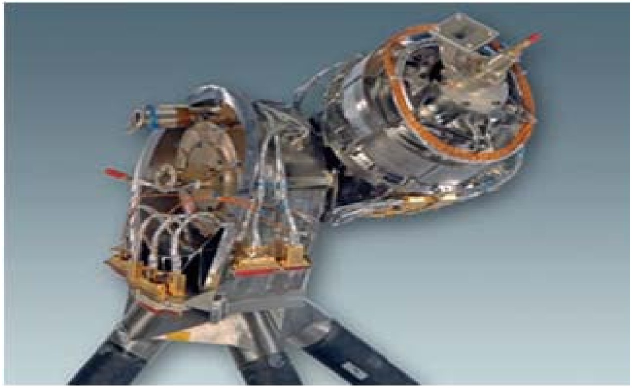
Critical features:

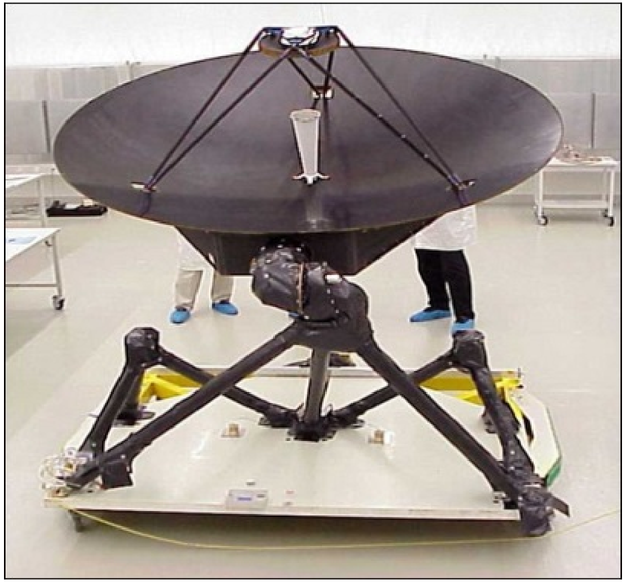
- 2DoF, preferable unlimited azimuth rotation;
- Lifecycle (for 2RPM, duty cycle: 4h out of 24h, 3 years): 525600 revolutions;
- Continuous rotation applications require power and signals be carried over the rotating interface, therefore can integrate pointing mechanisms with slip ring;
- Slip rings for electrical harnesses – space heritage (speed requirement to be further investigated):
  - scanning mechanism,
  - solar array drive mechanism;
- Ka-Band rotary joints (BepiColombo, METOP SG);
- Need of 1 or 2 HDRM for the Antenna, depending on diameter and mass.



Antenna Pointing Mechanism – NG-CryoIRTel Study

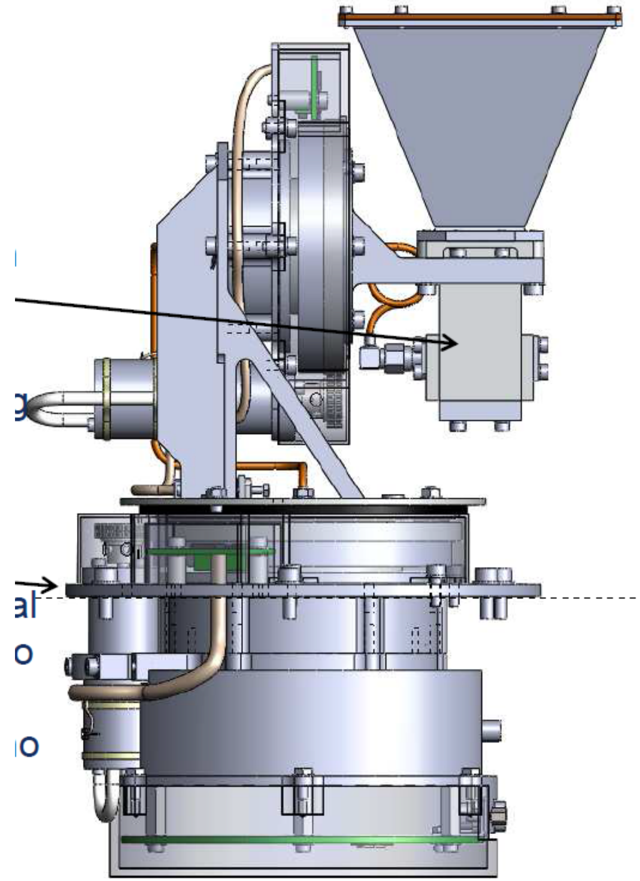
- High Gain Antenna: 40cm diameter, about 1kg mass;
- Pointing accuracy of 0.5deg and 2DoF;
- Motors: 2x stepper motors;
- Power consumption, peak <12W;
- Mass: 5kg (excluding Antenna and HDRM);
- 1x HDRM.





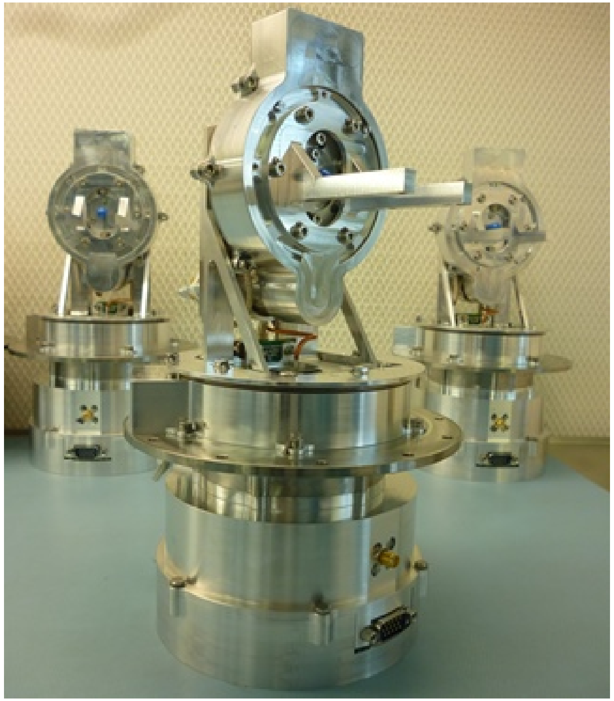
Antenna Pointing Mechanism – ARIEL study from SSTL

- (X-Band antenna in the picture);
- Medium Gain Antenna 2DoF Pointing;
- accuracy of 0.25deg and resolution of 0.025deg
- Motors: 2x stepper motors;
- Power consumption, peak <5 W;
- Mass: 4kg (excluding Antenna and HDRM);
- Operation: every 48hours, a repointing shall be done lasting typically 1minute.



Antenna Pointing Mechanism – ARIEL study from SSTL

- (X-Band antenna in the picture);
- Two rotary modules (Azimuth and Elevation), aligned perpendicular to one another to point and support antennas (small to medium sized);
- Two independent axes of rotation with each rotation axis comprising of a hybrid stepper motor, spur gear transmission and magnetic encoder;
- The steering function can be controlled by either the APM integral electronics or a dedicated APM-Electronic unit.



Performance Characteristics	
Pointing Accuracy	< 0.25°
Step size	≤ 0.024°
Slew rate	≤ 20°/s
Azimuth range	±270°
Elevation range	±110° (depending upon space-craft mounting)
Number of qualification cycles	>28,500 cycles (TVAC) >280,000 cycles (VAC only)

Antenna Pointing Mechanism – BepiColombo HTHGA APM

The Antenna Pointing Assembly consists of two almost identical Antenna Pointing Mechanisms (APM) mounted orthogonally onto each other. Each APM consists of a drive unit and a dual channel RF Rotary Joint in X and Ka-band.

Technical data

- Rotation range azimuth stage: 360°
- Rotation range elevation stage: 215°
- Pointing speed: up to 2.0°/s
- Pointing accuracy: better than 0.02° half cone
- Power consumption: < 9 W

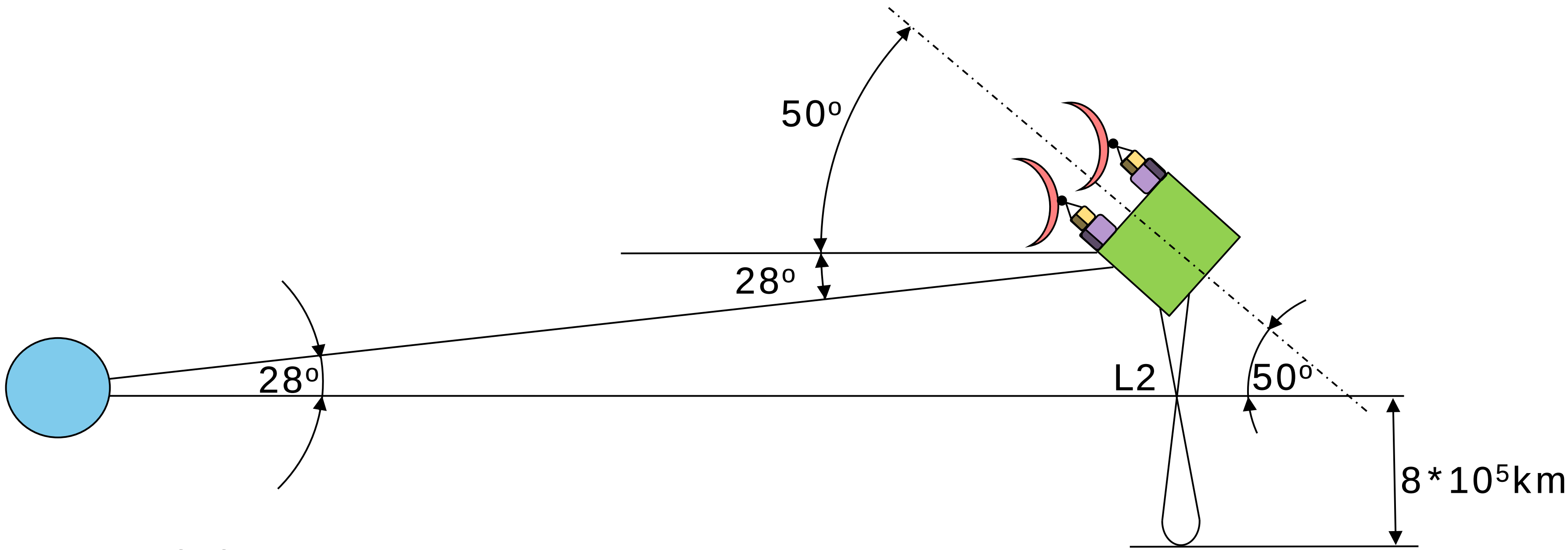
Antenna Pointing Mechanism – Rosetta HGAMA APM

The APM is a dual drive (azimuth over elevation) unit for X-band antenna. The main functions of the APM are to provide accurate and stable pointing of the reflector and elevation axes and to route the RF signals between the antenna and the spacecraft.

Technical Data

- Rotation range azimuth stage: 237°
- Rotation range elevation stage: 340°
- Pointing speed: up to 2.5°/s
- Pointing accuracy: better than 0.1°
- Power consumption: < 6 W/stage

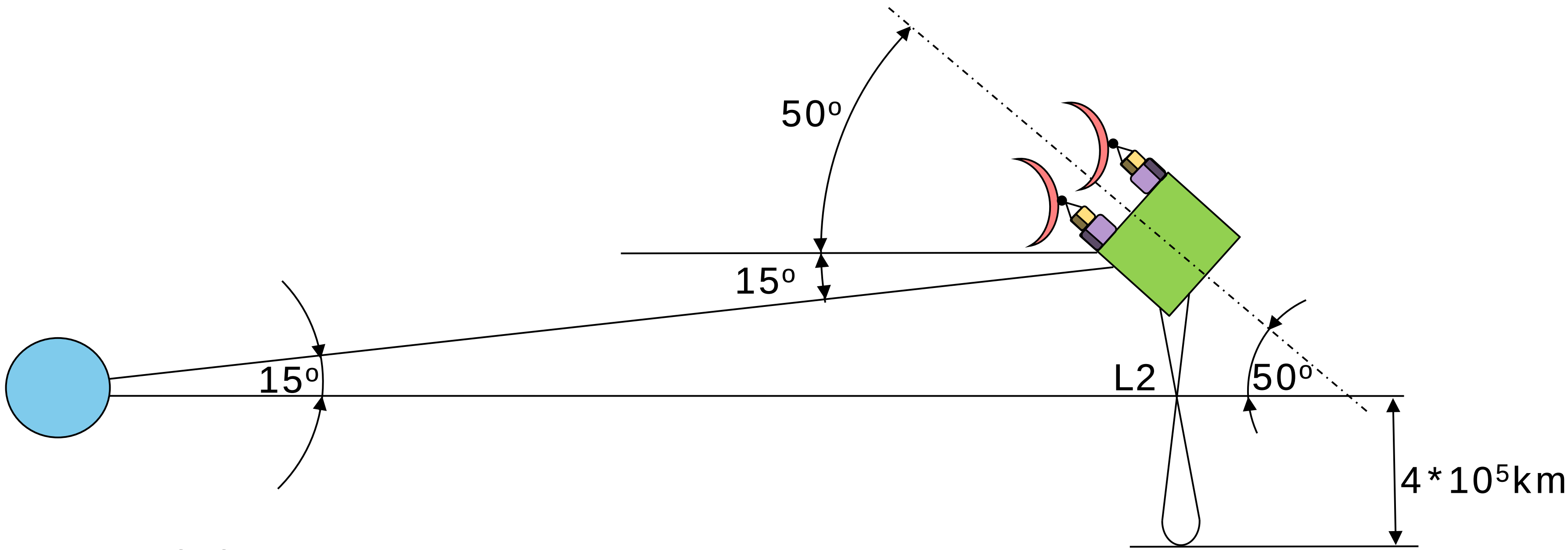
Antenna pointing strategy – orbit: baseline



Antenna pointing strategy:

- Rotation range azimuth stage: continuously rotates to de-spin the antenna;
- Rotation range elevation stage: +/-78°.

Antenna pointing strategy – orbit: option 1



Antenna pointing strategy:

- Rotation range azimuth stage: continuously rotates to de-spin the antenna;
- Rotation range elevation stage: +/-65°.

Antenna Pointing Mechanism – Baseline Summary

Technical Specifications:

- Rotation range azimuth stage: unlimited;
- Rotation range elevation stage (min): +/-78° or +/- 65° (orbit depending);
- Pointing speed for azimuth axis: 12°/s;
- Pointing accuracy: better than 0.1°;
- Mass (including Control Electronics and 1xHDRM, excluding the Antenna): 10 kg;
- Power consumption: < 8W for azimuth;
- Lifecycles on azimuth axis: 525600 revolutions;
- Additional features: with Slip Ring for azimuth stage;

- Ka-Band Antenna reference dimensions and mass: 200 mm diam., 1 kg mass.

Solar array deployment mechanism

Currently study assumes that there is a need of 11.2m^2 of solar deployable panels area extending the body-mounted solar arrays.

A configuration of 8 deployable solar panels, i.e. one panel stored on each SVM side, seems to be a good solution. The octagonal shape of the SVM is not regular, therefore 2 different shapes of solar panel area need to be considered. As a first estimation, following configuration was assumed (with estimated panel area density of 4kg/m^2):

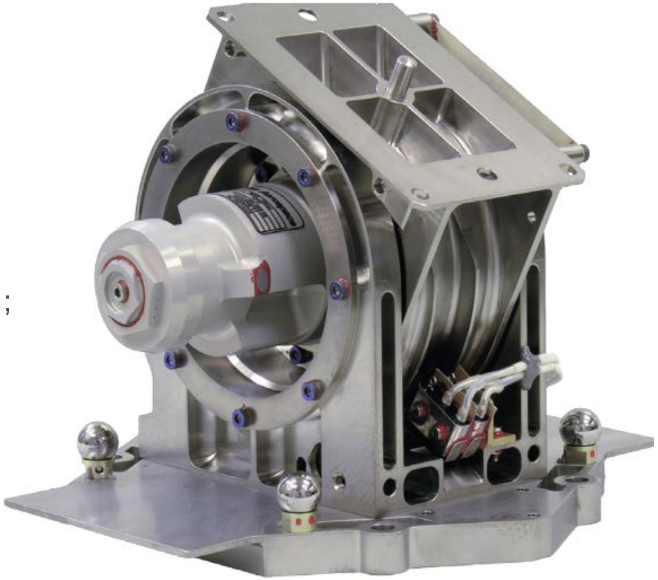
- 4 panels of 2x0.94m – SA mass per panel 7.52kg;
- 4 panels of 0.985x0.94m – SA mass per panel 3.7kg.

Solar array deployment mechanism – RUAG - example

Following device is probably oversized for the purpose of panels for CMB mission. It was included in the presentation as an example of SA Deployment Mechanism. A smaller unit shall be used.

RUAG Space offers a spring driven, non-reversible Deployment System, which is focusing on high position accuracy and stiffness in the deployed configuration. Locking mechanism to provide high position accuracy and stiffness in the deployed con-figuration

- Angular contact ball bearing in O-arrangement;
- Dimensions: 122 mm x 110 mm x 70 mm;
- Mass: 1500 g;
- Deployment range: up to 180°;
- Torque: 4 Nm - 10 Nm;
- Positioning accuracy after deployment in each direction: 0.006 degree;
- Temperature range survival: -150°C / +150°C;
- Temperature range operation: -30°C / +50°C.



AOCS support: available reaction / momentum wheel

- One of the options to stabilize the spacecraft is to use a bias momentum stabilization: to orient the additional momentum wheel's axis to be parallel to the orbit-normal vector;
- To satisfy the AOCS needs, a wheel characterized by a maximum momentum of 400Nms needs to be used. Currently that device does not exist as COTS. However an alternative solution can be implemented (if that is the chosen strategy of AOCS) – for instance it is possible to put reaction wheels in a stack and add momentum vectorially.

AOCS support: MOOG Bradford W45ES: 70Nms

Specifications	W18	W18E	W18ES	W45	W45HT	W45E	W45ES
Momentum Storage at 4000 RPM [Nms]	18	29-24	25	40	22	23-69	70
Balance: - static [gcm] - dynamic [gcm2]				0.5 5			
Speed range max operational [RPM]	4000	4000	4000	4000	2200	4000	4000
Speed range max qualified [RPM]	6000	6000	6000	6000	6000	6000	6000
Max gross torque [Nm]	0.248	0.248	0.248	0.248	0.403	0.248	0.248
Max torque loss at 4000 RPM [Nm]	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Typical torque loss at 4000 RPM [Nm]	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Dimensions RWA [mm]	Ø295x123	Ø295x123	Ø295x123	Ø365x123	Ø365x123	Ø365x123	Ø365x123
Dimensions WDE [mm] – 1 channel	81 x 259 x 181	81 x 259 x 181	81 x 259 x 181	81 x 259 x 181	81 x 259 x 181	81 x 259 x 181	81 x 259 x 181
RWA Mass [kg]	5	5.1-5.9	6	6.9	6.9	7-7.9	8
WDE Mass [kg]				2.3			
Max Power [W], full speed full torque				169			
Max Power [W], full speed zero torque	29	29	29	29	16	29	29
Number of slots in shutter ring	240	240	240	240 / 360	240 / 360	240 / 360	240 / 360

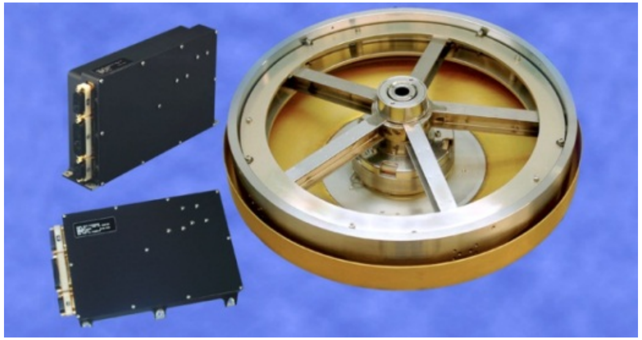
AOCS support: Rockwell-Collins RDR68-3: 68Nms

Performance:

Angular Momentum at Nominal Speed	68 Nms
Operational Speed Range	± 6,000 rpm
Speed Limiter (EMF)	< 7,500 rpm
Motor Torque at Nominal Speed	75 mNm
Loss Torque (maximum)	< 20 mNm

Physical specification:

Dimensions - Wheel (RDR)	
Diameter	345 mm
Height	118 mm
Mass	< 7.6 kg
Dimensions - Wheel Drive Electronics (WDE)	
Ground plane	52 X 247 mm
Height	145 mm
Mass (incl. radiation shielding)	1.25 kg
Total Mass (RDR + WDE)	< 8.85 kg



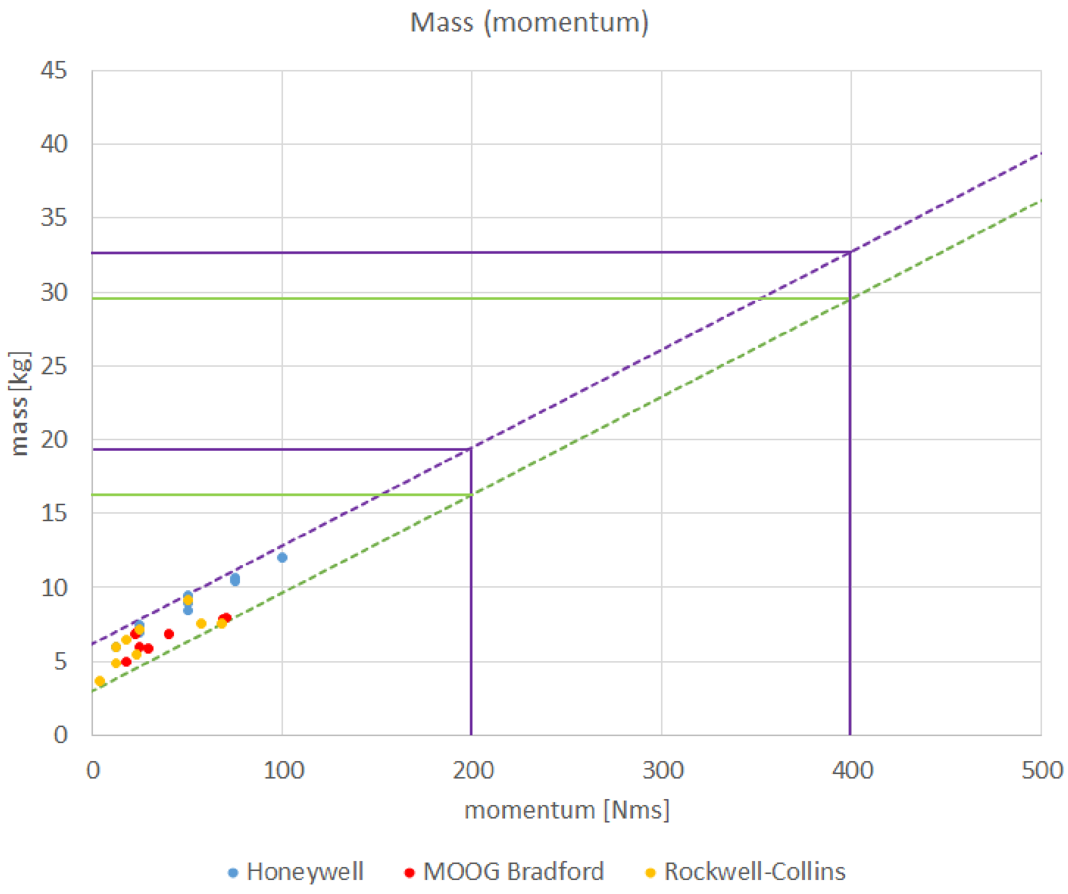
There is an activity driven by ESA towards more comprehensive flying wheels. By the time CBM mission takes place, European technology “should be capable” of producing single wheels up to 100+ Nms as COTS.

AOCS support: Honeywell customized: 150Nms

PERFORMANCE ITEM	UNIT	CAPABILITY HR12	HR14	HR16
Momentum	N-m-s	12, 25, 50[2]	25, 50, 75	50, 75, 100[1]
Reaction torque				
Nominal	N-m		0.1 to 0.2[3]	
Extended	N-m		up to 0.4 (@3000 rpm)[4]	
Rotor Balance[6]				
Static	g-cm	0.15, 0.24, 0.44	0.22, 0.35, 0.48	0.28, 0.38, 0.48
Dynamic	g-cm^2	2.2, 4.6, 9.1	4.6, 9.1, 13.7	7.7, 11.5, 15.4
Peak Power	Watts		105, 195[5]	
Steady State (@ 6000 rpm)	Watts		< 22 typical	
Bus Voltage Range	Volts		14 up to 80	
Wheel Speed	rpm		± 6000	
Mass	kg	6.0, 7.0, 9.5	7.5, 8.5, 10.6	9, 10.4, 12
Integrated Wheel Outline (Height x Width)	mm	159 x 316	159 x 366	178 x 418
Separate Electronics Outline	mm	WU H148X316D WDE H60XW169XL230	WU H148X366D WDE H60XW169XL230	WU H152X418D WDEH60XW169XL230
Life				
Storage	Years		> 5	
On-orbit Operation	Years		> 15	
Radiation Hardness Capability	Krads (Si)		> 300	
Parts Screening			S	
Operational Temperature Range (Qual)	°C		-30 to 70	
Vibration	Grms		13.8	
Interface	NA		Analog/Digital	

Note 1: Additional momentum designs are available including 68, 125 and 150 N-m-s.
Note 2: Additional momentum designs are available including 18 and 37.5 N-m-s.
Note 3: At maximum speed.
Note 4: Extended high torque capability exists at specified operating conditions relative to bus voltage, duty cycle and operating temperature.
Note 5: At 0.1 N-m and 0.2 N-m and a 50V regulated bus respectively.
Note 6: Balance performance represents BOL, Fine Balance Option, in a fully flight assembled configuration following ATP environmental exposure, as delivered. Further improvement of balance performance of >2X is possible.

AOCS support: single big momentum RW mass estimation



Extrapolation of mass from datasheet (single wheels from Honeywell, MOOG Bradford and Rockwell-Collins) gives the following numbers:

- 16.5-19.5kg for200Nms;
- 30-33kg for 400Nms.

It is here assumed that the mass grows proportionally with the momentum, but this has to be carefully verified: constraints from launch-locking needs, vibrations emitted etc. could affect significantly the design (and mass) of over-sized RW.

Alternative to the single RW:
- A momentum of 200 Nms can be reached with a stack of 2x Honeywell 100 Nms RE, with a mass of 24 kg.

AOCS support: alternatives

Current technology is capable of producing single big flying wheels (technically even up to 1000Nms), but it is not available off the shelf. It needs to be developed and proven. Therefore that solution needs to be considered cost-wise and time-wise.

Summary

Antenna Pointing mechanism:

- 2 DoF: rotation range azimuth stage: unlimited;
  rotation range elevation stage (min): +/-78° or +/- 65° (orbit depending)
- slip ring for azimuth stage: needs to be further developed in order to fulfill the requirement of 2RPM;
- lifecycles on azimuth axis: 525600 revolutions;

Solar Array Deployment Mechanism;

- Solar Array Deployment Mechanism are available as COTS;

Momentum wheel (only in case of bias momentum stabilization):

- Within current technology it will possible to achieve the requirements for that particular AOCS strategy.

CMB Polarisation Mission

Cryogenics

Prepared by the CDF* Team

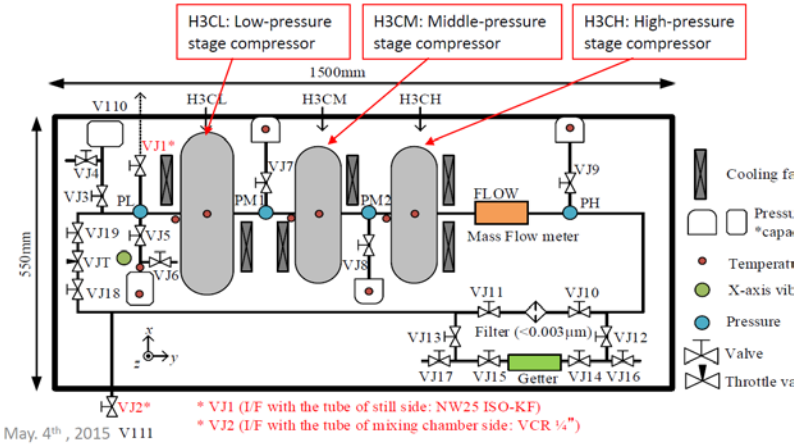
(*) ESTEC Concurrent Design Facility

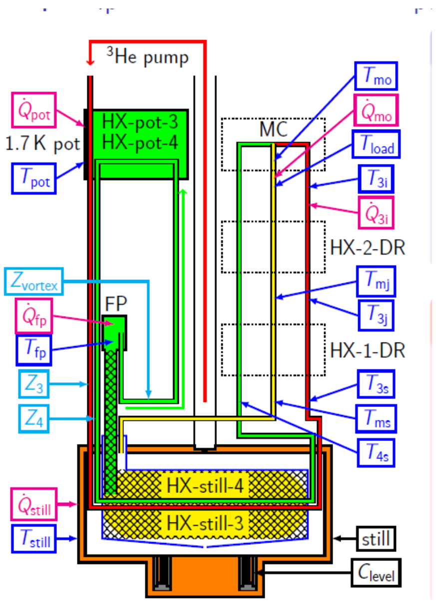
Cryogenic architecture

- Requirements: Optics < 60K, Detectors at 100mK
- Assume ~1µW cooling power required at Detector level, additional dissipations at intermediate temperature (500mK, 2K) levels for SQUID's etc
- Redundant coolers down to 2K assumed
- Architecture
- Passive cooling down to 60K using V-Grooves
- 100mK using either CCDR or tandem ADR/Sorption
  - Requiring ~2K and/or 4K pre-cooling using JT coolers
  - JT coolers require pre-cooling between 15-20K
- 4K shields and 20K shields required to intercept load at higher temperatures and to reduce load at lower temperatures

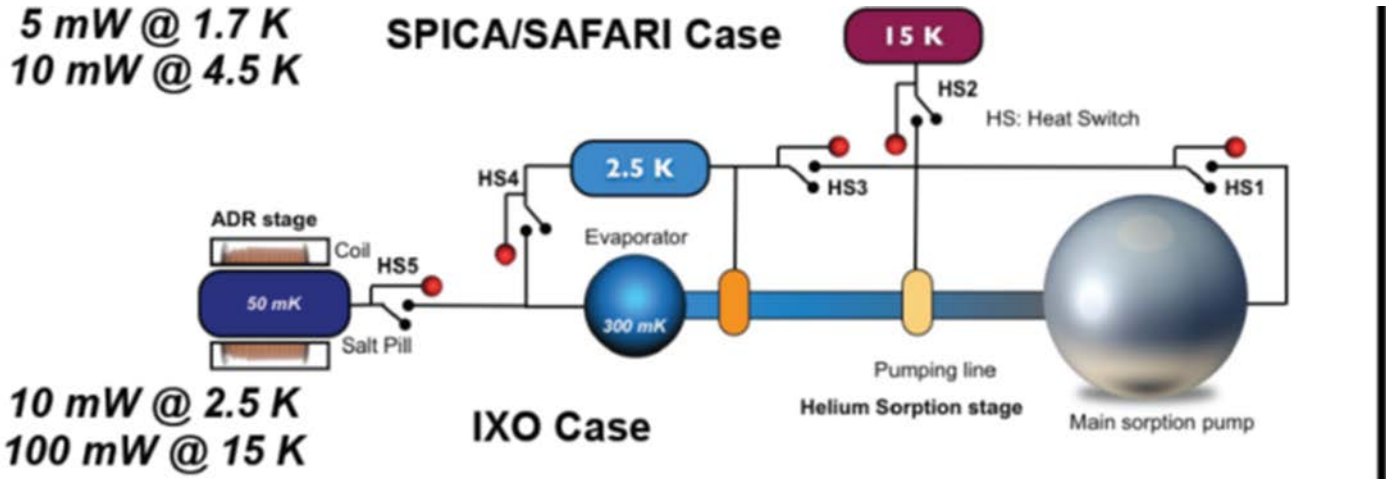
Last stage cooler-CCDR

- Closed cycle dilution under development at Institute Neel(F) based on OCDR used for Planck
- Baseline architecture using He3 circulator from JAXA
- Provides ~1µW at 100mK, requires ~5mW at 1.7K
- TRL~3-4



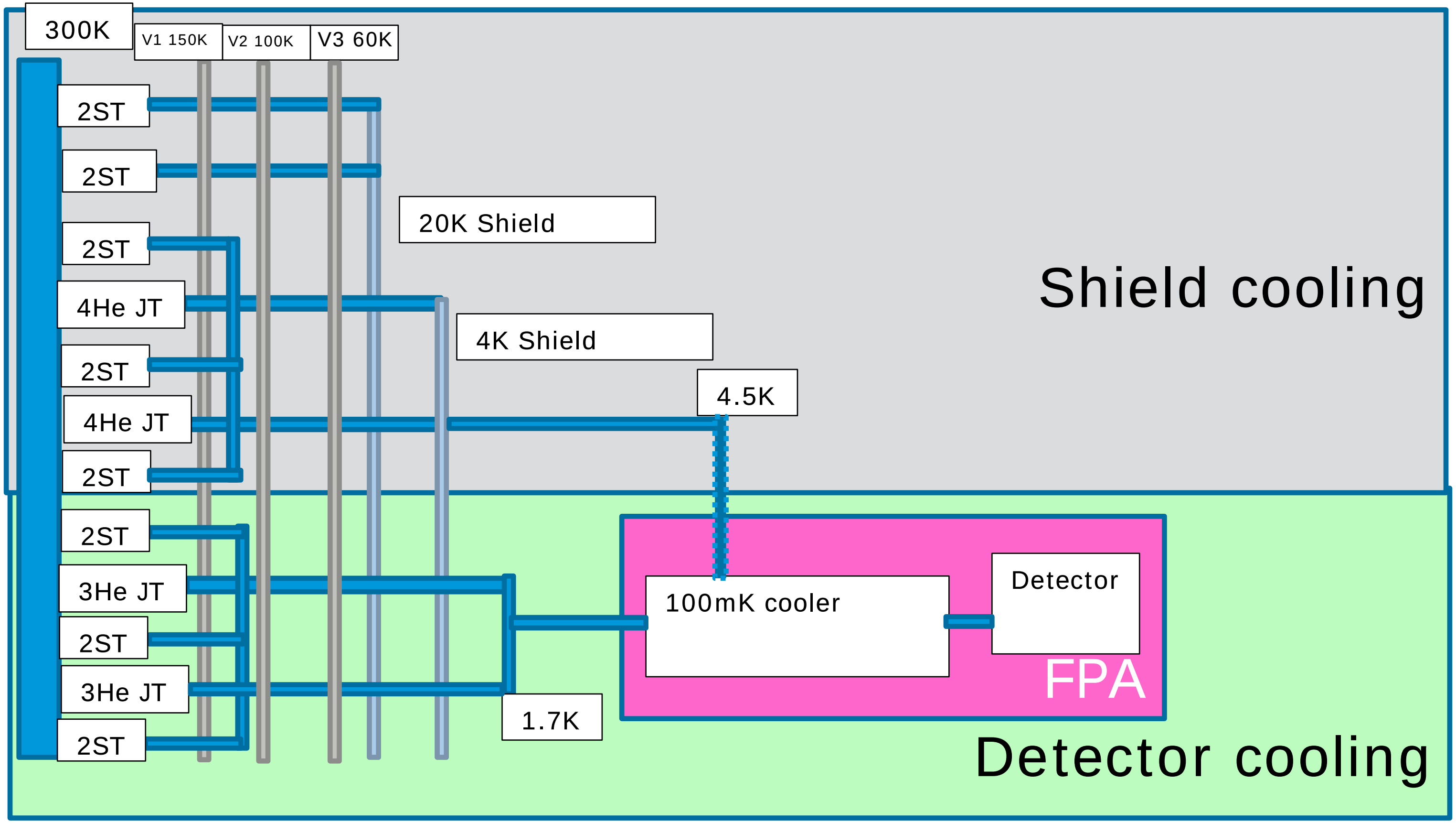


Last stage cooler –ADR-sorption



- Developed for Athena/Spica. Single shot cooler, continuous operation requires tandem similar to Bliss configuration
- Cooling power ~1µW at 50mK
- Single shot TRL~5, continuous TRL ~3

Baseline cryogenic architecture



FPA heat loads

- From Core+ M4 proposal:

Detector, MUX	100mK	4K	20K	300K	# wires 100mK-4K	# wires 4K - 300K
TES, TDM	0.7 nW	0 nW	300 mW	65 W	169	493
TES, FDM	0.9 nW	640 nW	0 nW	110 W	64	256
KID, FDM	0.5 nW	0 nW	30 mW	150 W	12	12

- KID harness assuming Herschel HIFI coax without Silver coating, using the following cross-sections and lengths

	Crosssection SS		3	mm2	
		PTFE	6.3	mm2	
		BeCu	0.7	mm2	
Stage [K]	length [m]	k-SS [W/mK]	k-CuBe [W/mK]	k-PTFE [W/mK]	Total/coax [mW]
1.7	0.2	0.2	1.4	0.04	0.31
4.5	0.2	0.7	7.2	0.096	7.20
20	0.5	5	20	0.196	29.03
60					

Heatloads

	Temp	dia [mm]	height [mm]	thickness [mm]	Surface [m2]	Mass [kg]	Radiative load [mW]	Conductive load [mW]	Harness [mW]	FPA dissipation [mW]	Total [mW]
2K	1.7	500	500	0.8	1.18	2.55	0.0	2	0.7	5	7.7
4K	4	520	1500	0.8	2.88	6.23	1.3	9	14	10	34.3
25K	20	560	1500	0.8	3.13	6.78	56.8	75	60	30	221.8
60K	60										
Note							Au coating/ 2Layer SLI (20K)	Planck +50%	12 coax +100%	dissipation sub_K + LNA	

Additional cooling power required for routing of the coolers through the V-Grooves:
20K stage: 5K gradient through the link
4K stage: 2.3mW from NgCryo/SPICA
1.7K stage: 1mW estimate

Heatload vs. Cooling Power

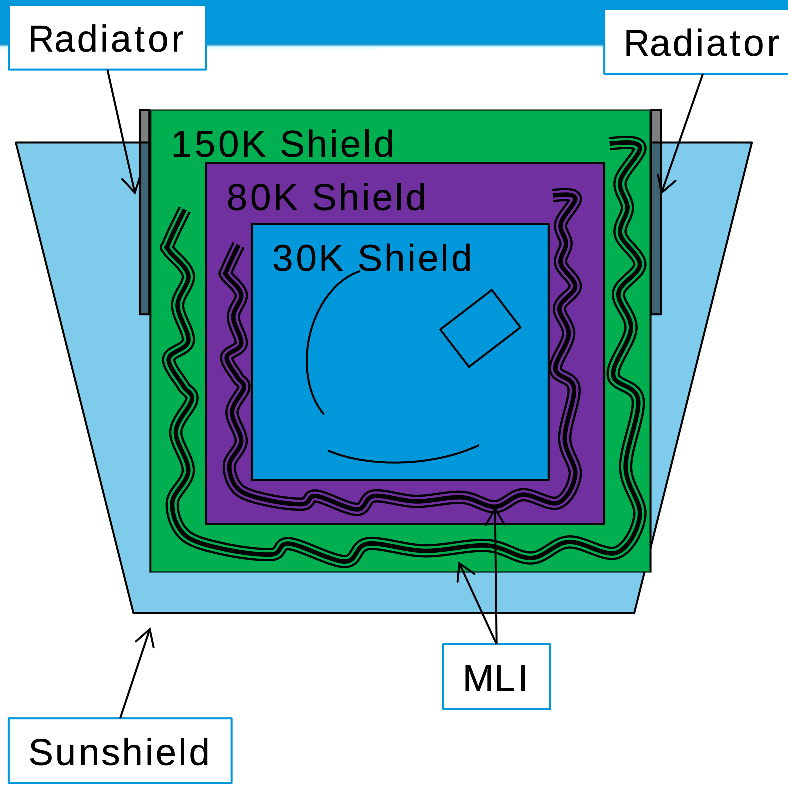
Cooler	Power	Cooling power	Support / Radiative	Cable	Dissip ation (FPA)	Total	Margin
Shield cooler	2x50 = 100W	200-450mW (17-25K)	132 mW	60mW	30mW	220 mW at 20K	33%
4K JT pre-cooler	3x50 = 150W	N/A					
4K JT cooler	2x100 = 200W	40mW at 4K	10.3 + 2.3 mW	14mW	10mW	36mW	11%
1.7K JT pre-cooler	3x60 = 180W	N/A					
1.7K JT cooler	2x70 = 140W	10mW at 2K	2 + 1mW	0.7 mW	5mW	8.7mW	15%
Total Cooler	770W						
Total Cooler+CDE	1100W						

Cryogenics-conclusion

- Low margin on 4K and 1K cooling stages requires some further optimisations
- A better definition of the coax harness is required in the future to assess the total load
  - Use of superconducting coax below 4K is required

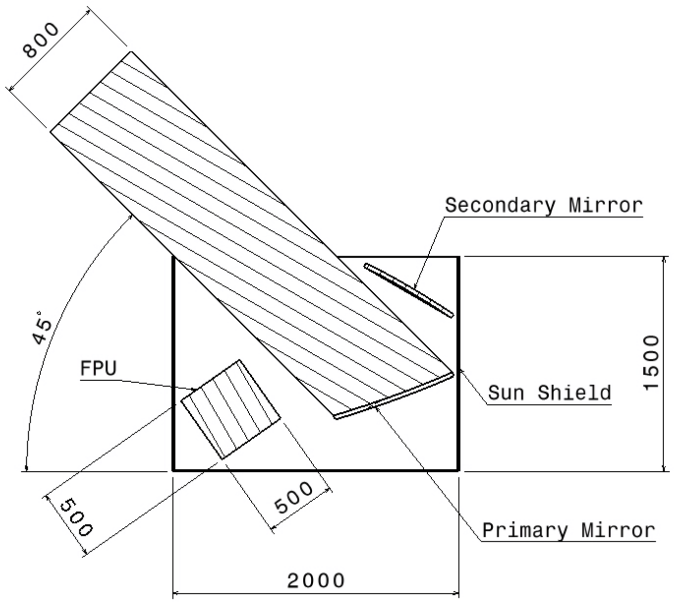
Cryogenic architecture-without V-grooves (option 1)

- Architecture similar to Litebird
- Passive cooling down to 150K using sunshield + radiator
- Active Shield cooling using 15K Pulse Tube cooler at 80K and 30K
- Dis-connectible support structure similar to NGCryo/SPICA
- 4K/2K cooling as in baseline configuration

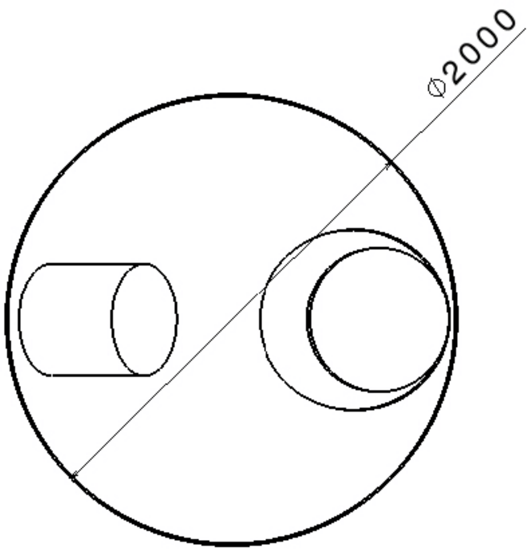


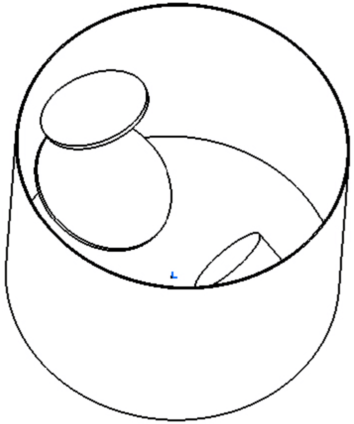
System simplification options

3. Smaller telescope without V-grooves



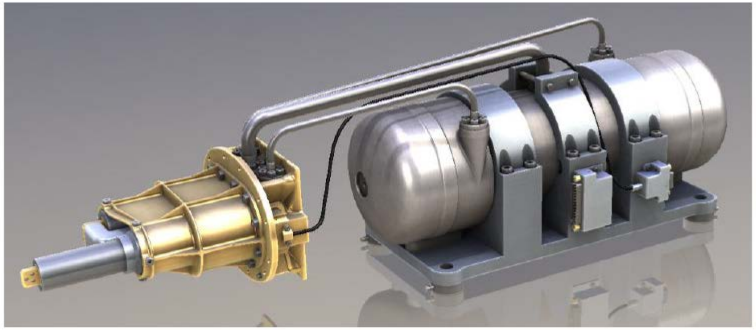
Cross Dragone Concept





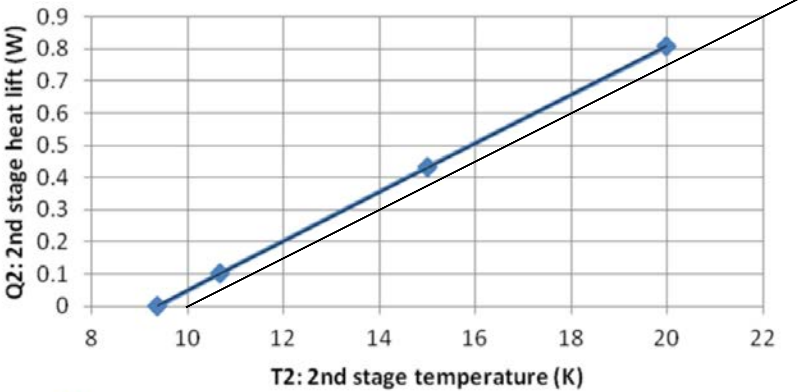
15K Pulse Tube cooler

- 15K cooler, providing up to 400mW at 15K with 300W input power, development just finished by ALAT, TCBv and CEA
- To be used for Athena as pre-cooler for 2K JT cooler
- Can also be used as a powerfull shield cooler



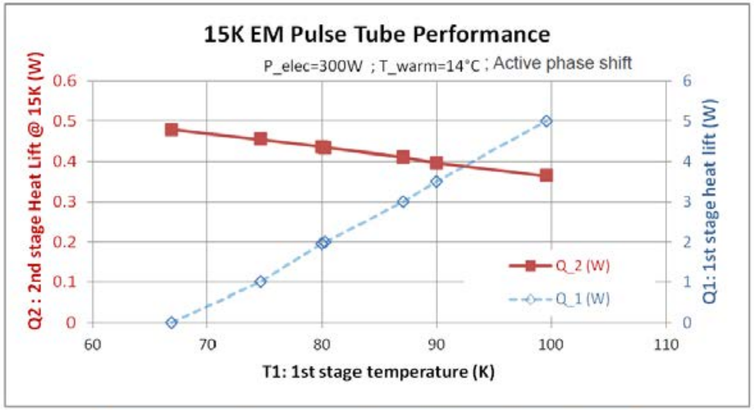
Designation	mass	
Cylindrical Compressor	7,9	
Specific Support + 3x Brackets	3,9	
2x Buffer + inertance assembly	2,0	
3x Helium Pipes	0,2	
Cold Finger Assembly	2,1	
Connectors + wires + accessories	0,2	
total mass:	**16,3**	**kg**

15K PT cooler-ALAT performance



- T_{min}=9.2K
- **435mW @ 15K**
- 650mW @ 18K

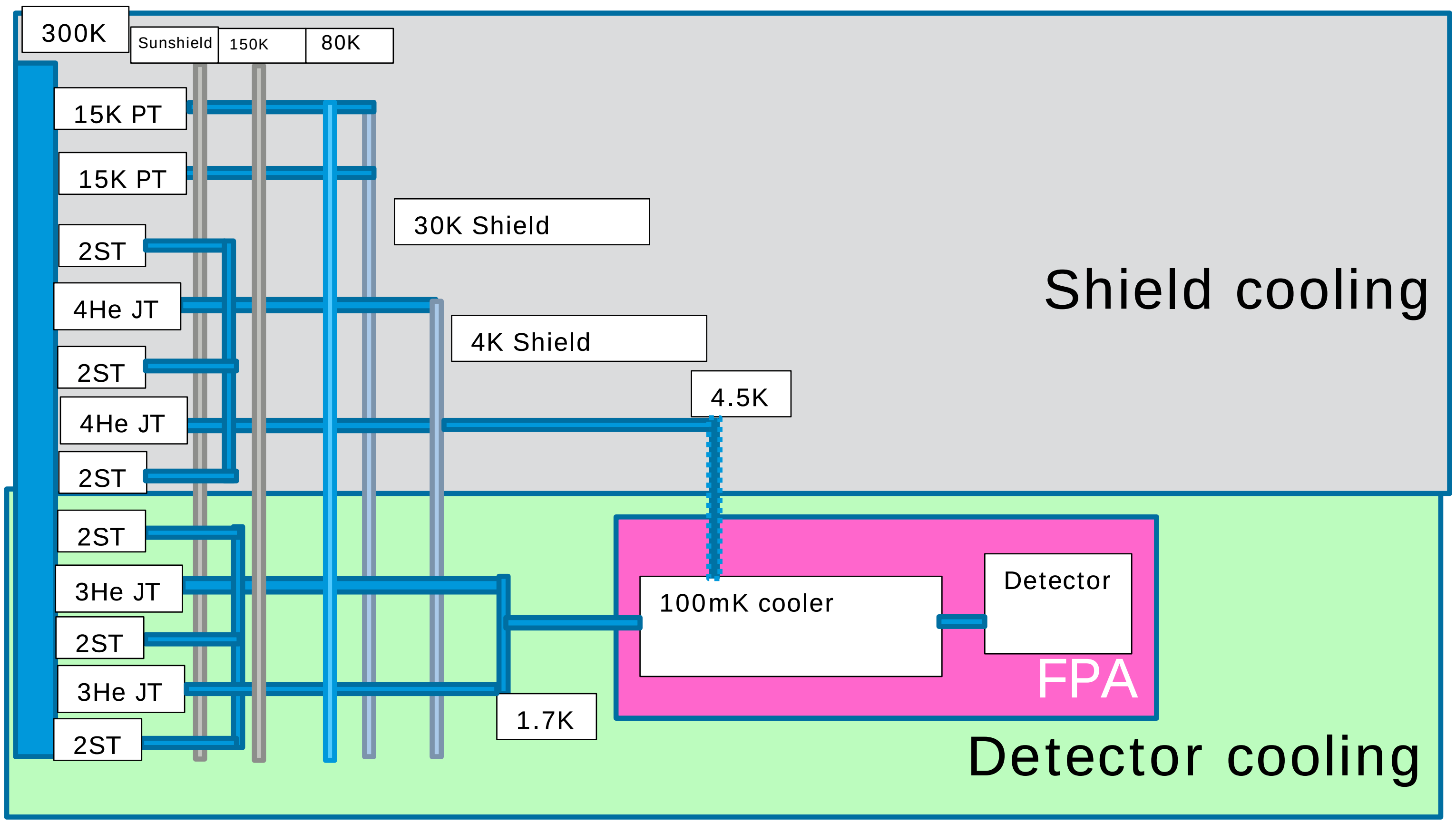
P_{elec}=300W elec
P=21Bar
T1=80K
F=41Hz



Q_1	T1	Q_2	T2
0.0	67	479	15.0
3.5 W	**90 K**	**0.4 W**	**15 K**
5.0	100	365	15.0

- Estimated performance at 30K: ~1.5W with 3.5W at 90K

optional cryogenic architecture 1



Heatloads – optional architecture 1

Temp	dia [mm]	height [mm]	thickness [mm]	Surface [m2]	Mass [kg]	Radiative load [mW]	Conductive load [mW]	Harness [mW]	FPA dissipation [mW]	Total [mW]
1.7	500	500	0.8	1.18	2.55	0.0	2	0.7	5	7.7
4	520	1500	0.8	2.88	6.23	6.6	9	12	10	37.6
30	2000	1500	0.8	15.71	34.02	859.9	150	60	30	1099.9
90	2100	1600	1.8	17.48	85.19	2341.3	400	100		2841.3
150										0.0
						Au coating/ 20layer/ 40layer MLI	T<20K: Planck +50% T>20K: NGCryo	12 coax +100%	dissipation sub_K + LNA	

Additional cooling power required for routing of the coolers through the V-Grooves:
20K stage: 5K gradient through the link
4K stage: 2.3mW from NgCryo/SPICA
1.7K stage: 1mW estimate

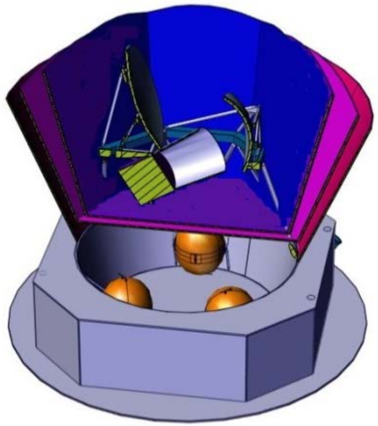
optional architecture -1

Cooler	Power	Cooling power	Needed	Margin
Shield cooler	2x150 = 300W	1500mW at 30K	1100mW at 25K	
4K JT pre-cooler	3x50 = 150W	N/A		
4K JT cooler	2x100 = 200W	40mW at 4K	40mW	
1.7K JT pre-cooler	3x60 = 180W	N/A		
1.7K JT cooler	2x70 = 140W	10mW at 2K	8.7mW	15%
Total Cooler	970W			
Total Cooler+CDE	1390W			

Cryogenics option 1-conclusion

- Use of 15K Pulse Tube enables to actively cool 30K and 80K in case Volume is limited to 2m diameter and 1.5m height
- Low margin in overall system ➔ further improvements required
- System can be tested in standard facilities using LN2 shrouds, reducing costs ➔ optical tests still require LHe facilities
- Requires dis-connect in-orbit and 15K Pulse Tube qualification
  - ➔ cost saving only in case these two items will be further developed and qualified for Athena/SPICA
- Other cost saving options: use of ADR starting from 4K allows to remove 1.7K stage

Cryogenic architecture-option 2



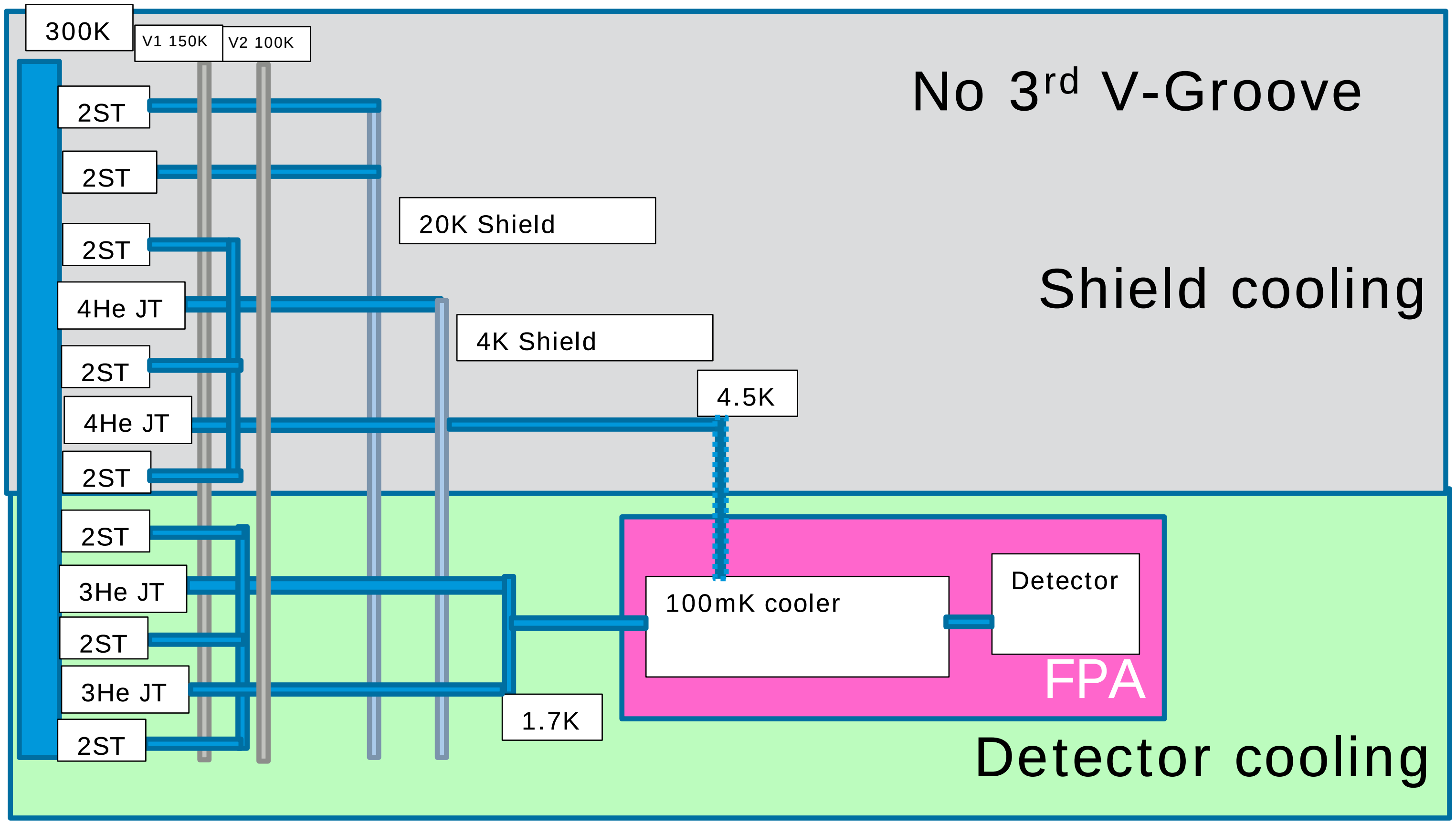
- Two V-grooves, passive cooling down to 100K only ➔

\+ No testing required in LHe chamber in CSL (Telescope and System)

– Higher Telescope temperature ➔ higher background

- Load on the active cooling at 20K increased ➔ additional 20K JAXA shield cooler or ESA 15K PT might be required
- Active cooling looks feasible, but still low margins on 4K/2K cooling stages ➔ further optimisation will be required

Cryogenic architecture – option 2



Telescope
~100 K

Heatloads-option 2

	Temp	dia [mm]	height [mm]	thickness [mm]	Surface [m2]	Mass [kg]	Radiative load [mW]	Conductive load [mW]	Harness [mW]	FPA dissipation [mW]	Total [mW]
2K	1.7	500	500	0.8	1.18	2.55	0.0	2	0.7	5	7.7
4K	4	520	1500	0.8	2.88	6.23	1.3	9	14	10	34.3
25K	20	560	1500	0.8	3.13	6.78	237	150	120	30	537
100K	100										
Note							Au coating/ 20/40 layer MLI (20K)	Planck +50%	12 coax +100%	dissipation sub_K + LNA	

Additional cooling power required for routing of the coolers through the V-Grooves:
20K stage: 5K gradient through the link
4K stage: 2.3mW from NgCryo/SPICA
1.7K stage: 1mW estimate

Heatload vs. Cooling Power option 2

Cooler	Power	Cooling power	Support / Radiative	Cable	Dissipation (FPA)	Total	Margin
Shield cooler (15K PT)	2x150W = 300W	~800mW at 20K	387 mW	120mW	30mW	537 mW at 20K	>45%
4K JT pre-cooler	3x50 = 150W	N/A					
4K JT cooler	2x100 = 200W	40mW at 4K	10.3 + 2.3 mW	14mW	10mW	36mW	11%
1.7K JT pre-cooler	3x60 = 180W	N/A					
1.7K JT cooler	2x70 = 140W	10mW at 2K	2 + 1mW	0.7 mW	5mW	8.7mW	15%
Total Cooler	970W						
Total Cooler+CDE	1400W						

CMB Polarisation Mission

Thermal

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

V-Groove thermal analysis – Session #4

- The thermal analysis has the SVM as a boundary at 300 K, covered by MLI (Al external) with an effective emissivity of 0.04 (cf. SPICA MDD, JAXA_SPICA_SYS_MSS_01)
- Sunshield: GFRP, outside white paint (α/ε = 0.4/0.8), inside Al (α/ε = 0.05/0.05)
- V-groove lateral sides:

  1st and 2nd GFRP, outside and inside Al (α/ε = 0.05/0.05)

  3rd (innermost) Al 6063, outside Al (α/ε = 0.05/0.05), inside black open honeycombs (α/ε = 0.8/0.8 at 60K)
- V-groove bottom panels:

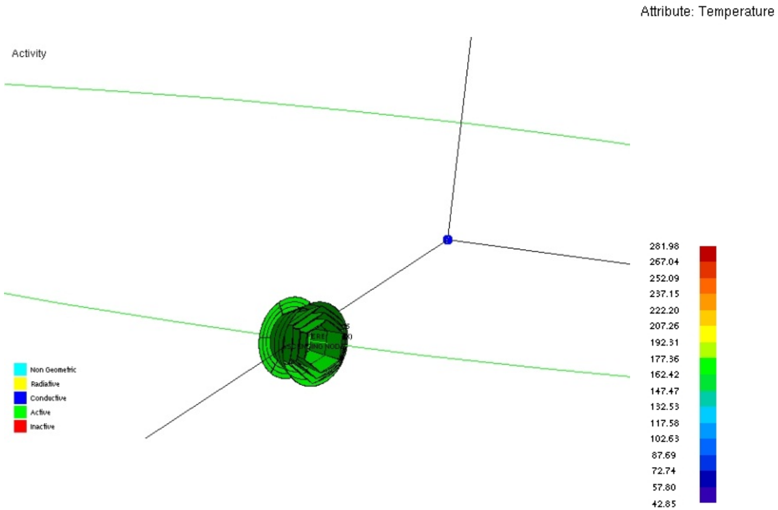
  1st and 2nd GFRP, outside MLI (Al external) (α/ε = 0.15/0.05), inside Al (α/ε = 0.05/0.05)

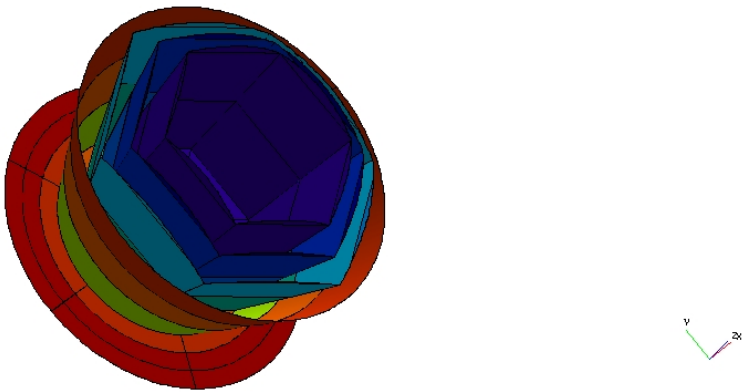
  3rd (innermost) Al 6063, outside MLI (Al external) (α/ε = 0.15/0.05), inside black (α/ε = 0.8/0.8)
- The spacecraft is considered to be spinning (1 rpm[1]) in a sun-centered orbit, with the spinning axis turned 50° away from the velocity vector in the orbit plane
- The V-groove panels have boundary heat fluxes representing the coupling to the SVM

[1] ESATAN-TMS will generate average fluxes

V-Groove geometry results – circular SVM

- From Session 3, Configuration made a set of changes to the V-groove geometry to make it compatible with fairing dimensions
- The data on the new geometry have been implemented in the GMM





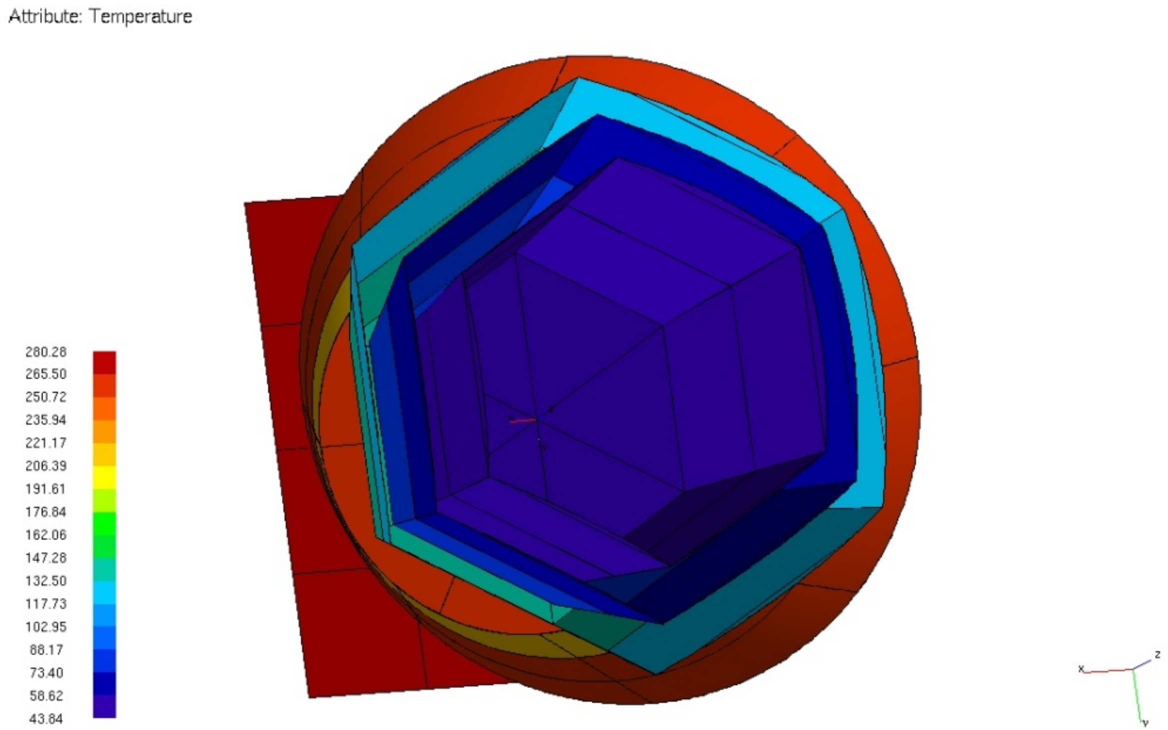
V-Groove thermal analysis – Session #5

- From Session #4, the following actions items were defined for thermal evaluation

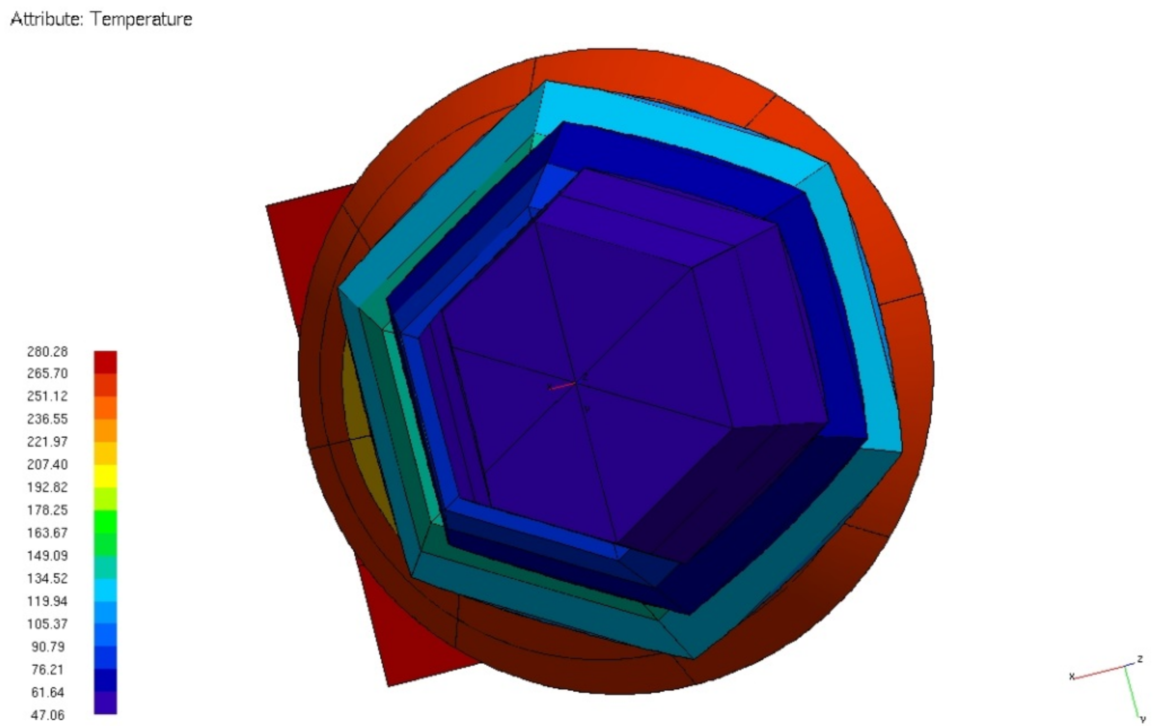
8	Actions	Thermal study of internal surface unpainted Al	Study the thermal impacts of having unpainted aluminium as the surface of the most internal V-Groove.
9	Actions	Thermal study internal study 0.5 emissivity	Study the thermal impacts of having a surface with emissivity 0.5 for the most internal V-Groove.
10	Actions	Second Sun shield left over from NGCryo	Make a note on the thermal model that the second sun shield has been removed and the the lower surface is now smaller

- Action #8: Thermo-optical properties for oxidized aluminium were implemented with $\alpha = 0.13/\varepsilon = 0.23$
- Action #9: Taking results on black anodization from Herschel (ref. HP-ASED-TN-0091) and extrapolating to 50-µm at 50 K, $\alpha = 0.40/\varepsilon = 0.50$ was applied
- Action #10: Based on input from Systems, giving a side length of 3441 mm for the square SVM structure, the V-groove model geometry was adapted

Action #9, Thin black anodization



Action #8, Oxidized aluminium



Conclusion

- The change of the SVM interface has minor impact on the Sunshield
- Lowering of the emissivity of the innermost V-groove surface tends to slightly increase the temperature. Going from $\varepsilon = 0.50$ (black anodization) to $\varepsilon = 0.23$ (oxidized aluminium) raises the minimum temperature from 43.8 K to 47.1 K

CMB Polarisation Mission

Structures

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

List of contents

- Heritage and targets
- Configuration
- Main assumptions
- Structural design layout
- First assessment
- Conclusions

Heritage and targets

Targets:

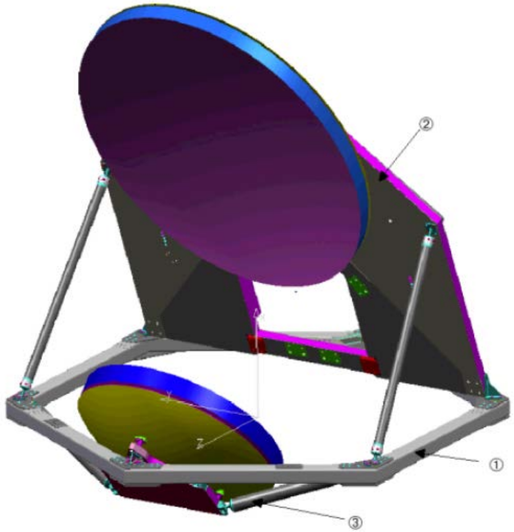
- Mass breakdown for the structural parts
- First geometry layout for of cryo structures and main the supporting frames
- First stiffness assessment (not optimizated!)
- Coupled thermal effects and Balancing not yet realistic for this study phase

Plank mission →

Payload module structural baseline

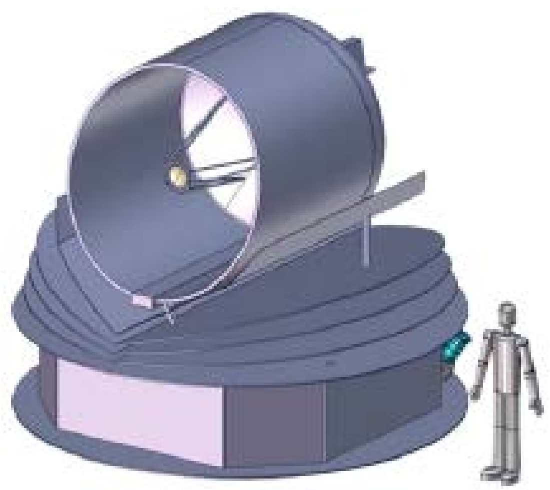
Materials

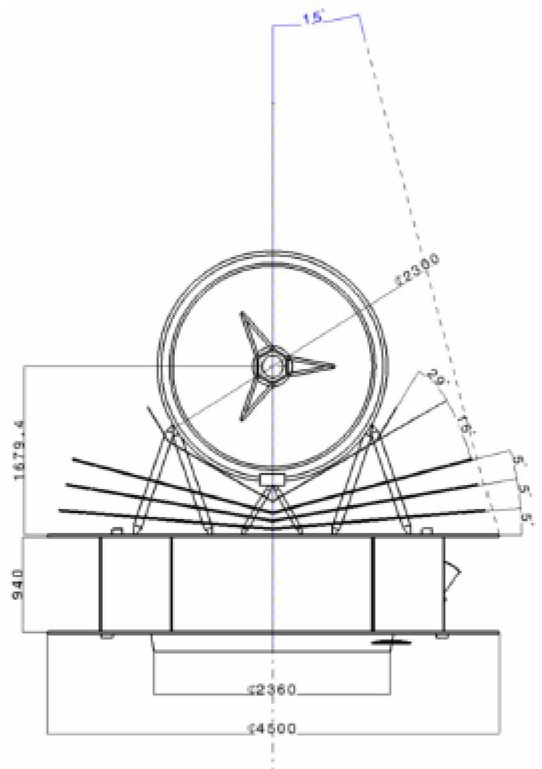
Telescope configuration



NGCryo mission →

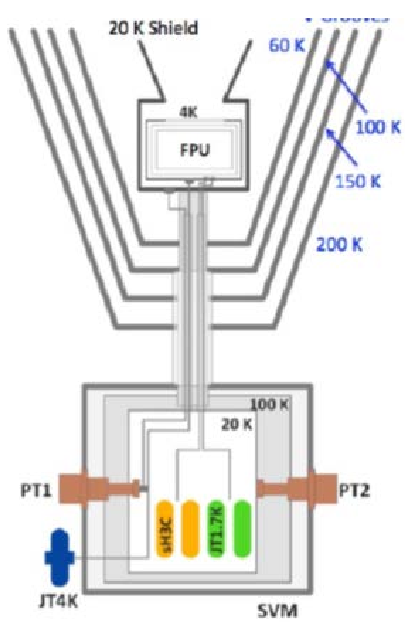
- Service module dimensions
- Materials (Mirrors and truss)

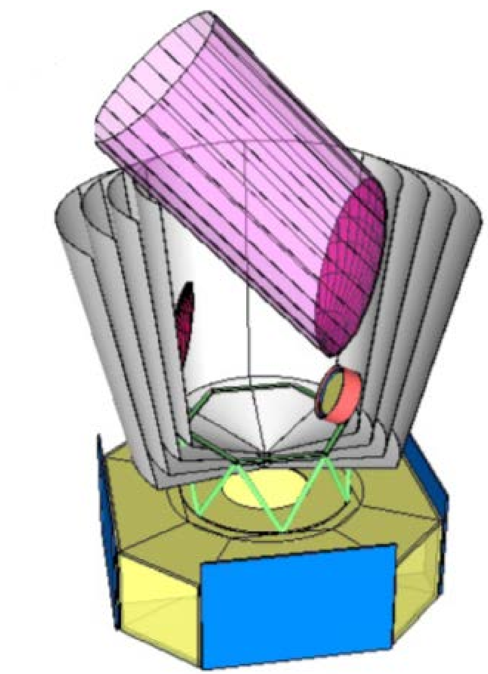




Heritage and targets

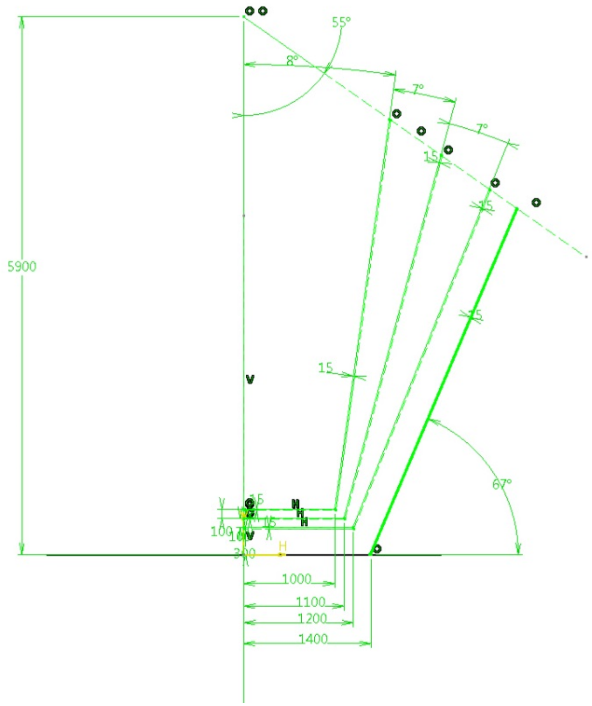
Core+ → Cryogenic structure concept on Gregorian configuration

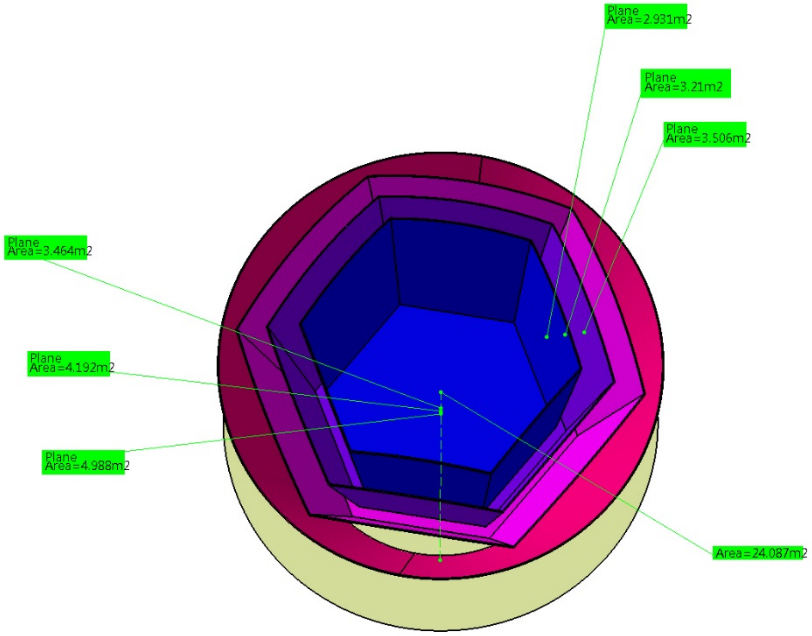




Baseline Configuration

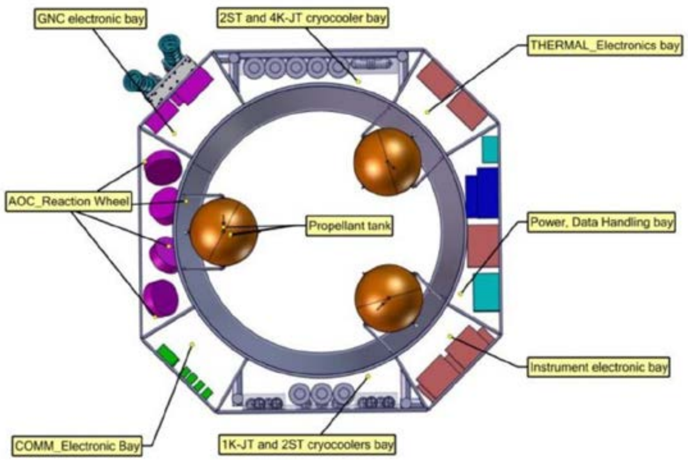
Thermal design baseline:

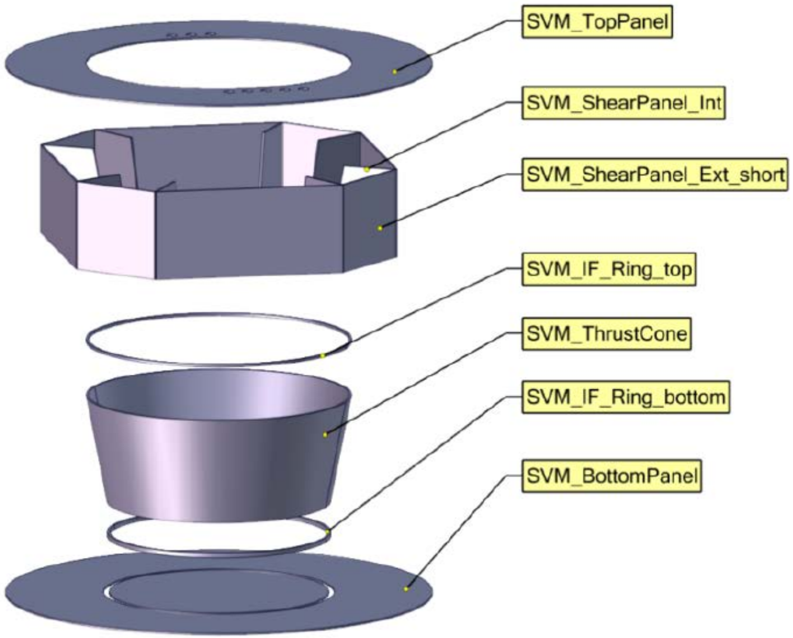




Baseline Configuration

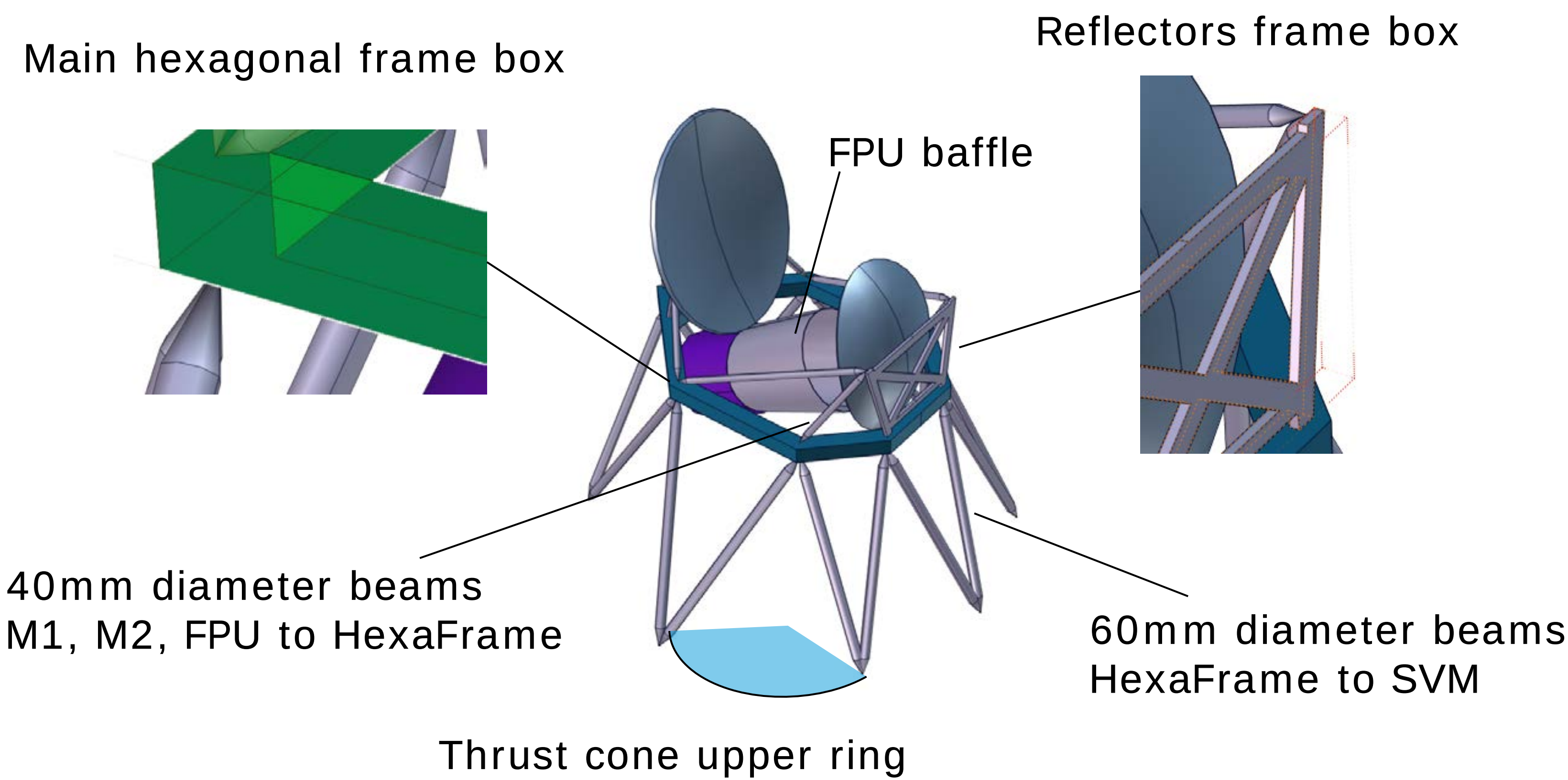
Service module (SVM) :



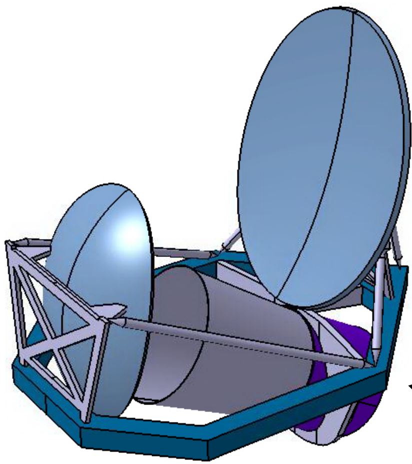


Stiffer and heavier configuration → better suitable for bending issues on CMB

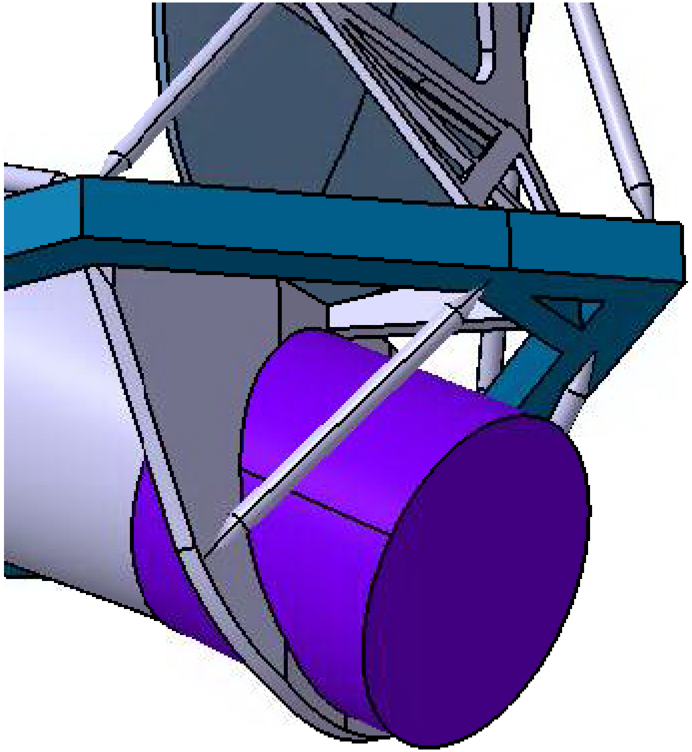
Structural layout PLM



Structural layout PLM

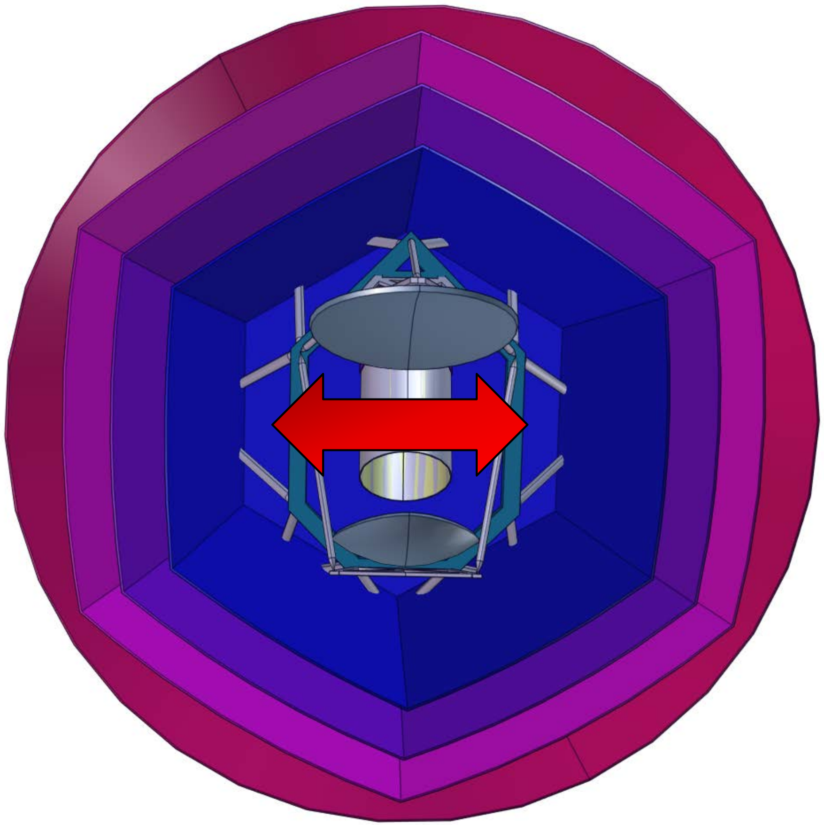


FPU support, combined solution



current facility

Structural layout PLM

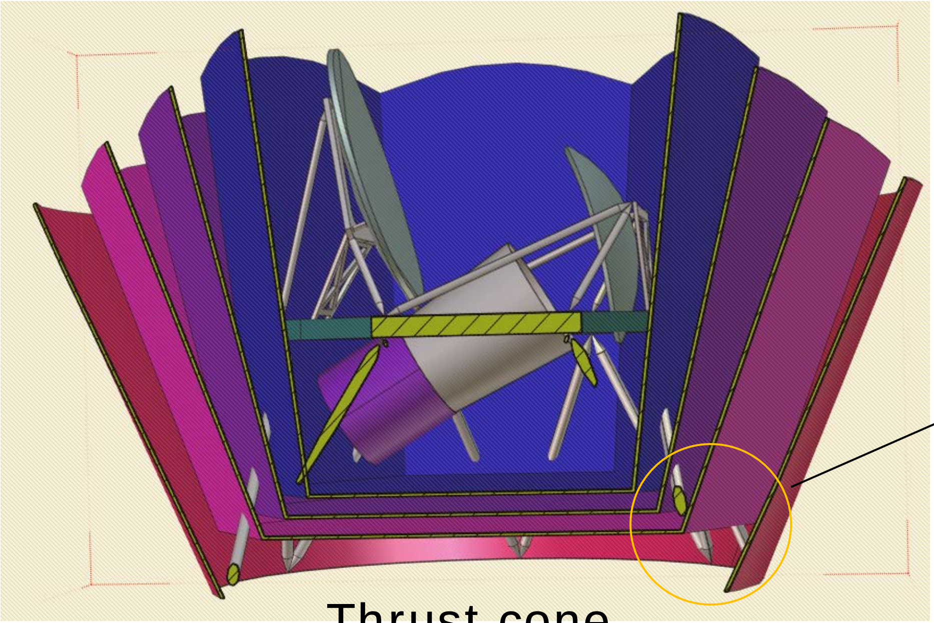


Lateral extra room to increase lateral stability

HexaFrame can be narrowed or fractioned if necessary

Structural layout PLM

Connection struts-cryo panels



Optimization joints around corners

Thrust cone upper ring

Mass break down

S/C STRUCTURE MASS - SUM								549
Module	Parts		Material/Construction	A [m2]	V [m3]	m/S	m/V	m
SVM								312
	Thrust cone		CFRP sandwich with alu core - 1.8 mm / 30 mm / 1.8 mm	10.0		7.62		76.1
	Bottom sunshield		CFRP sandwich with alu core - 0.5 mm / 20 mm / 0.5 mm	15.2		2.7		41.0
	Top sandwich panel		CFRP sandwich with alu core - 0.5 mm / 20 mm / 0.5 mm	8.1		2.7		21.9
	Exterior shear panels		CFRP sandwich with alu core - 0.5 mm / 20 mm / 0.5 mm	11.2		2.7		30.3
	Interior shear panels		CFRP sandwich with alu core - 0.5 mm / 20 mm / 0.5 mm	4.5		2.7		12.2
	Cone upper ring		Al ring A=2*100*5 mm2 D=2360 mm		7.41E-03		2700	20.0
	Cone lower ring		Al ring A=2*100*6 mm2 D=3000 mm		1.13E-02		2700	30.5
	Tank struts & brackets		Al					40
	2 cryocooler panels		CFRP sandwich with alu core - 1.0 mm / 50 mm / 1.0 mm	2.82		5.9		16.6
3 tanks	12 dampers		isolators of cryo-cooler panels					9.2
	12 brackets		isolator brackets					14.4
PLM								237
	Hexa frame box		Rectangular hexagonal box (CFRP 100*100 mm, 3 mm thick)		6.91E-03		1700	11.7
	SVM connection platform		Truss of cylindrical tubolar beams (CFRP 60mm diameter, 3 mm thick) btw SVI		1.17E-02		1700	19.9
	Extra Struts		Truss of cylindrical tubolar beams (CFRP 40mm diameter, 3 mm thick) btw M1		2.31E-03		1700	3.9
	TOB		margin on the mirror supporting structure					1.3
	M1 Structure		Frame supporting the M1 (2 box elements, CFRP, 3 mm thick)		2.60E-03		1700	4.4
	M2 Structure		Frame supporting the M2 (1 box elements, CFRP, 3 mm thick)		1.18E-03		1700	2.0
	FPU Structure		Frame supporting the FPU(1 box elements, CFRP, 3 mm thick)		1.18E-03		1700	5.0
	Telescope							
		M1	SiC, D=1200 mm, t=3.5 mm, Surface_Rib_fitting_factor=1.2 + fittings	1.21	6.10E-03		3770	23.0
		M2	D=500 mm, t=3.5 mm, Surface_Rib_fitting_factor=1.2+fittings(x1.2)	0.72	3.63E-03		3770	13.7
		FPU baffle	A=1.22 m2, sandwich with alu skins & core - 0.1 mm /15 mm / 0.1 m	1.2		1.53		1.9
		FPU	allocated for infrastructure support					5.0
	Thermal Shields							
		shield 1	Al sandwich with alu core - 0.10 mm / 15 mm / 0.10 mm	21.1		1.53		32.2
		shield 2	Al sandwich with alu core - 0.10 mm / 15 mm / 0.10 mm	23.5		1.53		35.9
		shield 3	Al sandwich with alu core - 0.10 mm / 15 mm / 0.10 mm	26.0		1.53		39.8
		baffle	Al sandwich with alu core - 0.20 mm / 15 mm / 0.20 mm	24.1		1.54		37.1
						nominal SVM+PLM		549.1
S/C						20% margin on total		659

Stiffness requirements

Ariane 5

Spacecraft design and verification requirements — *Ariane 5 User's Manual, Issue 5 Revision 1*

4.2.3.4. Frequency Requirements

To prevent dynamic coupling between the low-frequency launch vehicle and spacecraft modes, the spacecraft should be designed with a structural stiffness which ensures that the following requirements are fulfilled. In that case the design limit load factors given in next paragraph are applicable.

Lateral frequencies

The fundamental (primary) frequency in the lateral axis of a spacecraft cantilevered at the interface must be as follows (provided that a off the self adapter will be used for flight):

S/C mass (kg)	Launcher interface diameter (mm)	1st fundamental lateral frequency (Hz)	Transverse inertia wrt separation plane (kg.m²)
< 4500	< Ø2624	≥ 10	≤ 50,000
	Ø2624	≥ 9	
4500 ≤ M M ≤ 6500	≤ Ø2624	≥ 8	≤ 90,000
M > 6500	Ø2624	≥ 7.5	≤ 535,000
	< Ø2624	TBD	TBD

No secondary mode should be lower than the first primary mode.

Longitudinal frequencies

The fundamental frequency in the longitudinal axis of a spacecraft cantilevered at the interface must be as follows (provided that an off-the-self adapter will be used for flight):

≥ 31 Hz for S/C mass < 4500 kg
≥ 27 Hz for S/C mass ≥ 4500 kg

No secondary mode should be lower than the first primary mode.

Nota on Definition of primary and secondary modes:

Primary Modes: modes associated with large effective masses (in practice there are 1 or 2 primary modes in each direction)
Secondary mode: the mode that is not primary i.e. with small effective mass.

HII A

4.3 Stiffness of spacecraft

To avoid dynamic coupling modes in the low-frequency between the launch vehicle and the spacecraft during the ascent phase, the spacecraft should be designed with a structural stiffness which satisfies the fundamental frequency requirements.

Under the assumption that the spacecraft is connected rigidly to the separation plane, its primary structure fundamental frequency should be as follows:

(1) Lateral direction ≥ 10 Hz
(2) Longitudinal direction ≥ 30 Hz

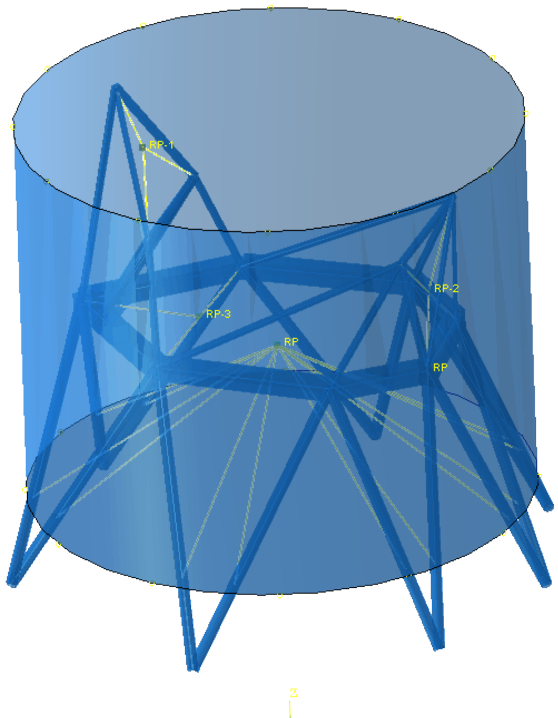
If the spacecraft does not satisfy above conditions, SCO should discuss loads, environmental conditions and usable volume, etc., with LSP using a result of Coupled Loads Analysis (CLA) at the technical interchange meetings, and confirm that there are no problems.

Overall stiffness, lateral level :16 Hz (15% margins and √2 →S/C to PLM load increase level)

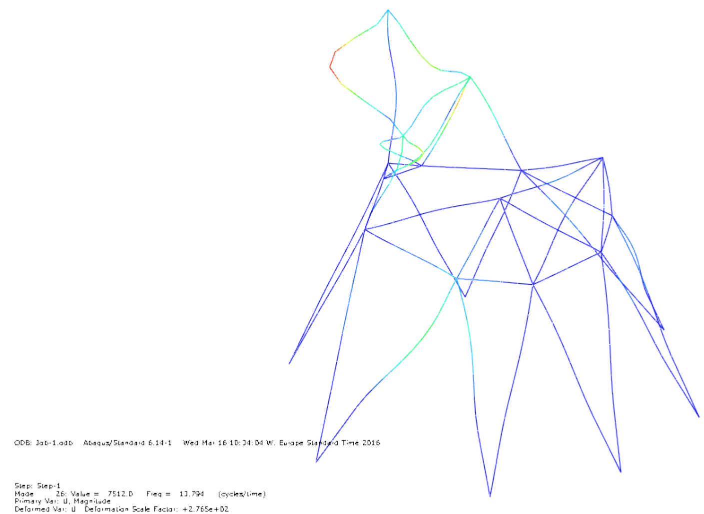
First assessment stiffness

Preliminary FEM model

Based on homogeneous CFRP properties



- Mass computed vs mass estimated OK!
- Extra mass (+30%) assumed for NSM



- First global lateral mode: 14Hz → right trend

Conclusions

- First structural configuration is proposed
- Mass are preliminarily allocated
- Preliminary stiffness (simplified modal FEA) shows good trends

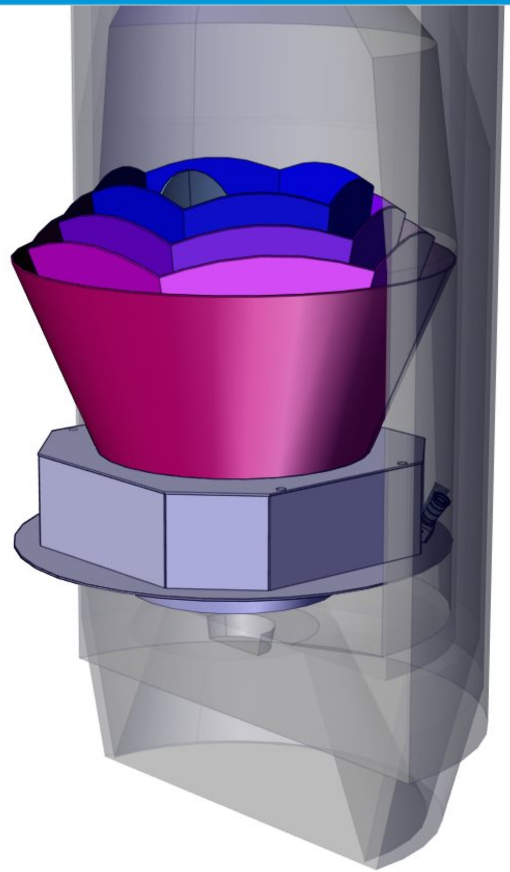
- Structural connection of the cryo-structure must be further investigated
- Balancing of the whole PLM not considered in the preliminary structural design → more accurate position of CoG needed

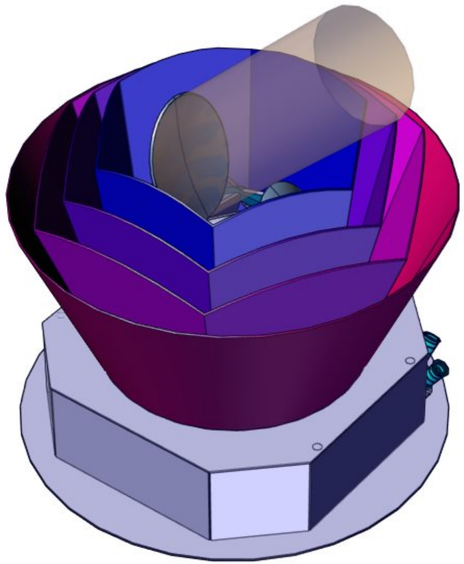
CMB Polarisation Mission

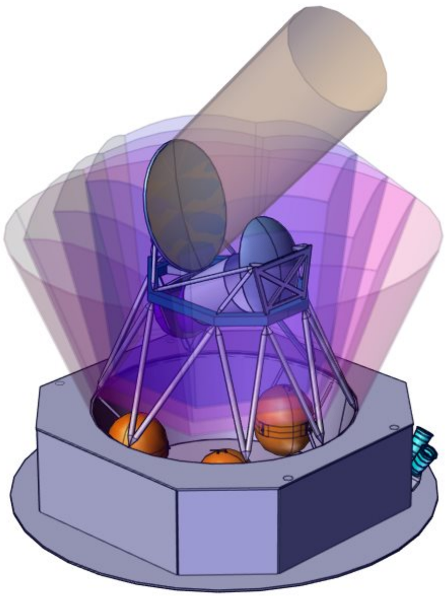
Configuration

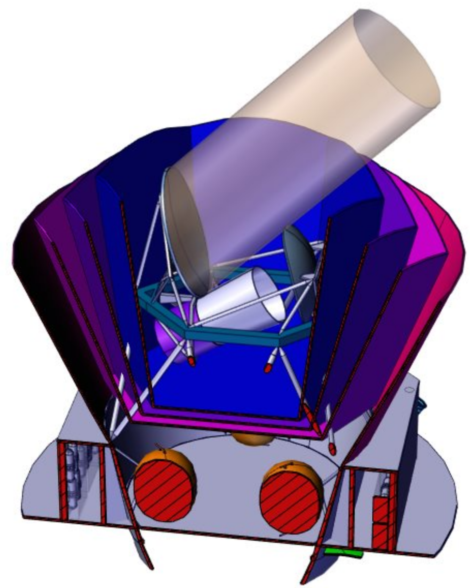
Prepared by the CDF* Team

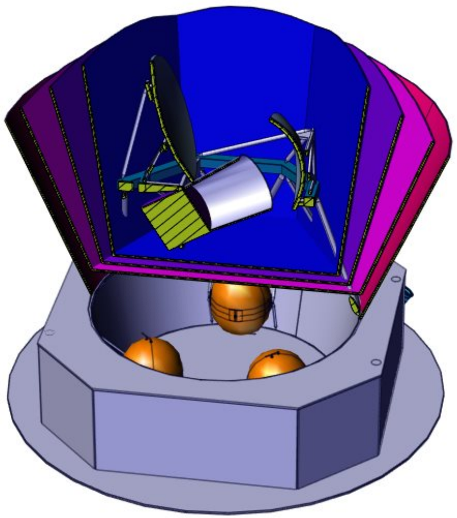
(*) ESTEC Concurrent Design Facility

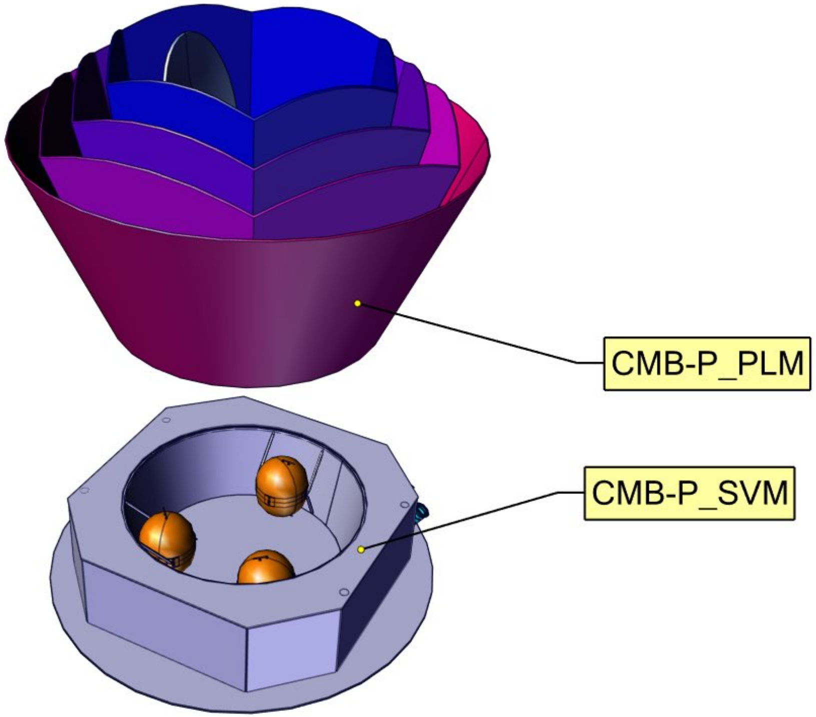


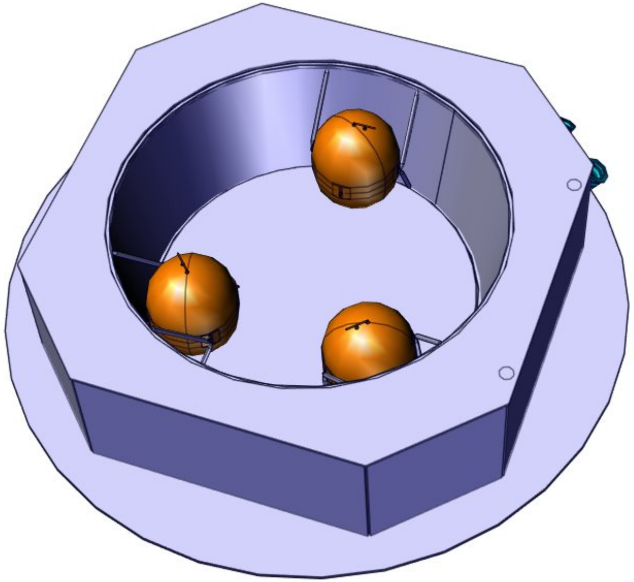


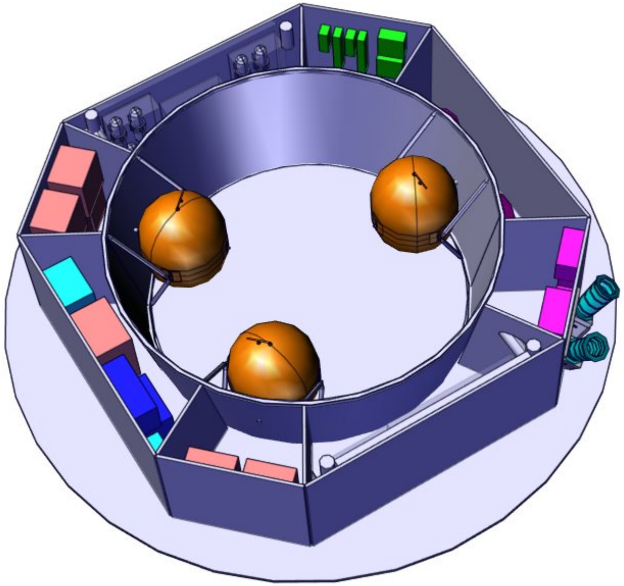


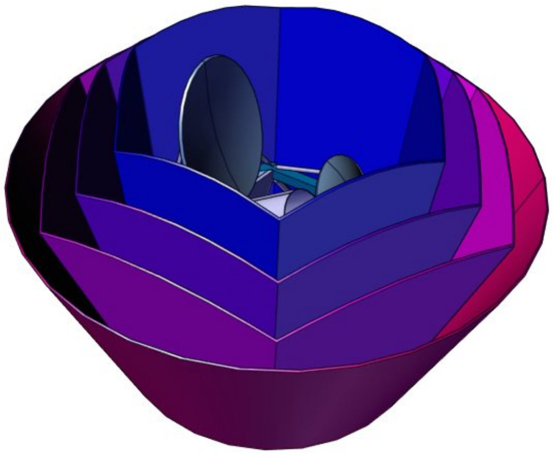


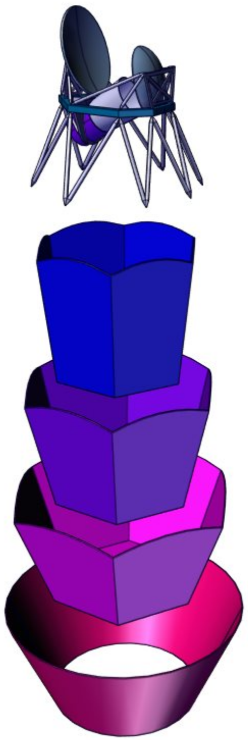


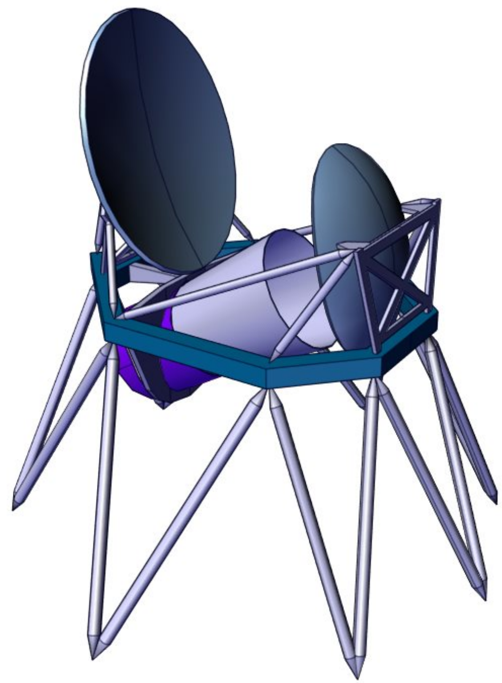

CMB-P_PLM
CMB-P_SVM

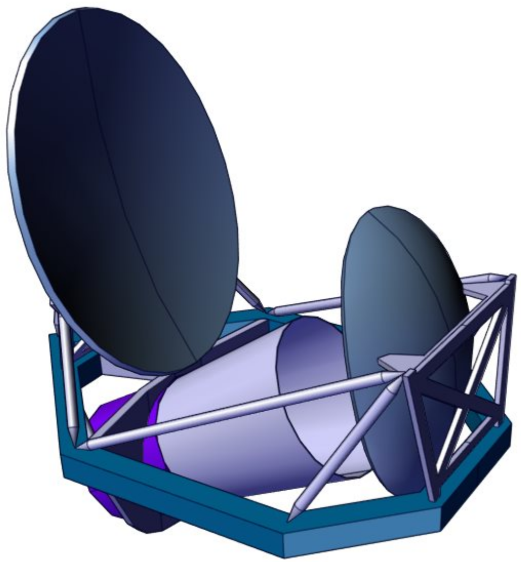


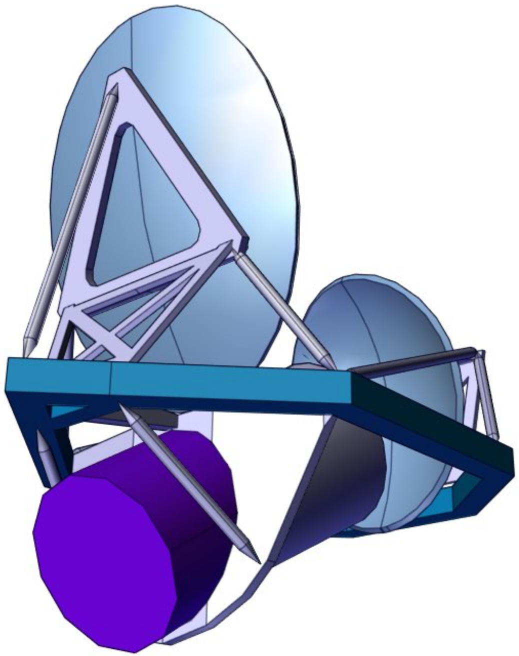












CMB Polarisation Mission

Programmatics and AIV

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Requirements and design drivers

Req. Id	Requirement
	Launch either on a Japanese H-II / H-III or on a European Ariane 62
	The nominal lifetime shall include 3 years observation time
	Launch in 2027/2028 in case of ESA-only mission, goal for JAXA 2025
	The ESA contribution shall be in the scope of an ESA M-class mission
	The Payload consists of a 1.2m aperture telescope below 60K and a Focal Plane Unit at 100mK

Assumptions & trade-offs

- a 50cm diameter Focal Plane Array should be sufficient, enabling the use of Japanese/European detectors, not relying on US technology only
- 4.5 K baffle will be mounted in front of the FPA
- Lower temperature baffles will then be part of the FPA
- Instrument Budget allocations
  - Size FPA+sub-K cooler: Ø 500mm, length 500mm
  - Mass FPA+sub-K cooler+ sub-K baffle: 50kg
  - Warm electronics: 100kg, 200W electrical power at 20°C, located in the SVM
- TRL 6 to be achieved before the implementation phase (B2/C/D or C/D)

- Planck mission and NGCryo study are used as reference models

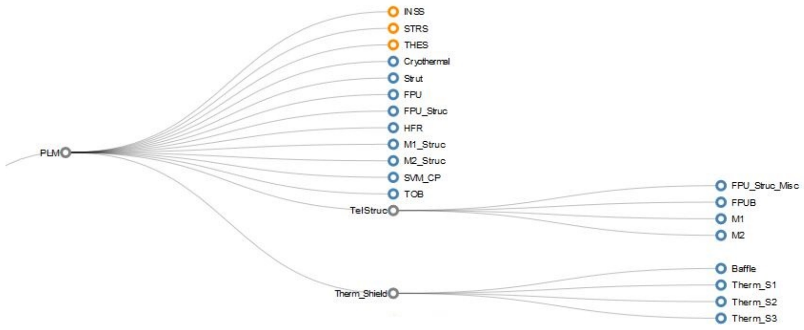
Options

- Not applicable

Product Tree / technology readiness level

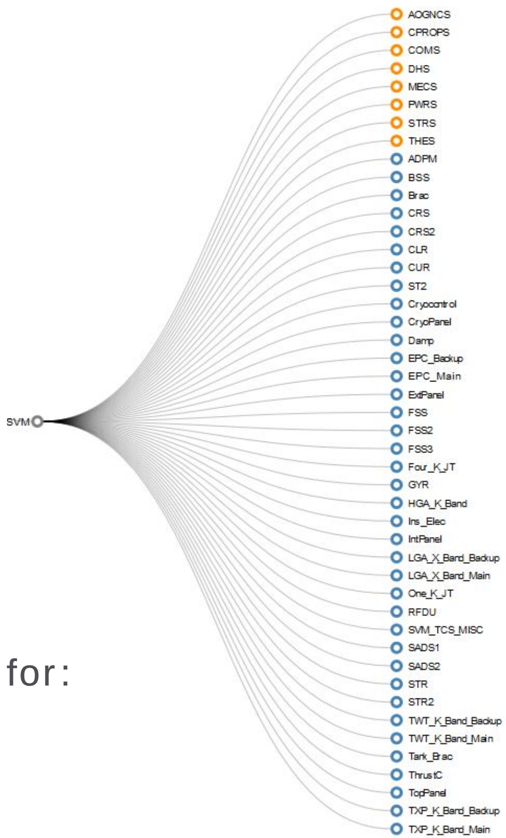
- The product tree in this presentation is taken from the OCDT model. It summarizes the equipment and instruments per subsystem and the associated Technology Readiness Level (TRL), if available, but without identifying subassemblies.
- For any item with a TRL below 6 development plan should identify the resources and time needed to reach TRL 6.
  - The lowest TRL identified for equipment on the PLM is 5!
  - No TRL is to be identified for structural and thermal parts because these items are build according to specifications and no new developments are needed for them.
  - TRL for instruments not considered
- Star tracker (2x): Technology not available off the shelf for operation at 12 deg/s with required accuracy - thus need of dedicated technology development
- TRL 6 shall be achieved before starting the implementation phase.
- Nevertheless, the TRL status appears not to be critical for equipment, considering that the anticipated launch date is not within the next 8 years.

PLM product tree from OCDT



Equipent	TRL	Equipment	TRL
ADPM	6	RFDU	5
EPC	8	SADM	9
HCA K Band	6	TWT K Band	9
LGA X Band	9	Transponder K Band	8

- Developments are to still be identified, e.g. for:
  - Star trackers



TRL scale

TRL	ISO Definition	Associated Model
1	Basic principles observed and reported	Not applicable
2	Technology concept and/or application formulated	Not applicable
3	Analytical and experimental critical function and/or characteristic proof-of concept	Mathematical models, supported e.g. by sample tests
4	Component and/or breadboard validation in laboratory environment	Breadboard
5	Component and/or breadboard critical function verification in a relevant environment	Scaled EM for the critical functions
6	Model demonstrating the critical functions of the element in a relevant environment	Full scale EM, representative for critical functions
7	Model demonstrating the element performance for the operational environment	QM
8	Actual system completed and “flight qualified” through test and demonstration	FM acceptance tested, integrated in the final system
9	Actual system completed and accepted for flight (“flight qualified”)	FM, flight proven

Model Philosophy

- Structural Model
- Cryogenic Qualification Model (CQM)
  - P/L QM, with a full structure (as for Planck), SVM dummy with fittings for the PLM coolers and "PLM warm units“, to be used for the cryogenic test qualifying the chain of cryo stages
- SVM Avionics Model (AVM)
- Protoflight Model (PFM)
  - New, no refurbishment from other models
- RFQM (refurbished CQM), tbd. depending on achievement of optical verification

- Mirror models:
  - QM, SM and FM: QM for the CQM and then the RFQM
- Flight spares

Integration and verification approach

- Based on Planck approach
- Cryogenic tests in CSL
- Optical test in CSL
  - As telescope configuration is different, the feasibility (required space) is still to be determined
- Videogrammetry test with PFM PLM and QM mirrors (tbc)
- Spin test in LSS
- PFM TB/TB

Thermal test

- New shrouds to be developed
- “hot part” of the chamber with nitrogen loops
- “cold part” with He cooling
- Fine tuning of facility needed
- Instrument test under cryogenic condition by stimulation

- Telescope optical verification
  - Test set-up to be developed

Thermal test facilities

- The baseline at CSL is to develop a dedicated test set-up according to a given specification.
- The highest dimensions so far are the ones used for Herschel in Focal 6.5 (vertical configuration) and for Planck S/W in Focal 5 (Horizontal configuration).
- 4m-4.5m as useful diameter is a first ROM value.
- The shrouds are generally cooled down to below 20K…but not 4K. This cannot be answered in general. We need the size, heat load, mini temp etc.….
- Both facilities are available. We made some (very) preliminary analyses in the past. The horizontal configuration (Focal5) was the best option, but the size could be a bit too limited.
- The vertical chamber will be more comfortable even if an additional collar is potentially required.
- The test set-up for the envisaged optical tests is still to be defined and its feasibility needs to be confirmed.

Test matrix

Test Description	SM	CQM	AVM	PFM
Mech. Interface	R, T			R, T
Mass Property	A, T			A, T
Electr. Performance		T	T	T
Functional Test		T	T	T
Propulsion Test			T	T
Thruster Lifetime Test				
Deployment Test	A, T			A, T
Telecom. Link			T	A, T
Alignment	A, T	T		T
Strength / Load	A, T			T
Shock / Seperation	T			T
Sine Vibration	A, T			T
Modal Survey	A			
Acoustic	T			T
Outgassing		A, I		I (T)
Thermal Balance		T		A, T
Thermal Vacuum		T		T
Micro Vibration		T		
Optical Verification		T 1)		
Videogrammetyry test				T 2)
Grounding / Bonding				R, T
Radiation Testing				A
EMC Conductive Interf.		(T)		T
EMC Radiative Interf.				T
DC Magnetic Testing				
RF Testing		T 3)		T

Abbreviations: I: Inspection, A: Analysis, R: Review, T: Test

1) in thermal chamber
2) on PFM with QM telescope (tbc)
3) after refurbishment to RQM

Schedule considerations

A possible schedule is shown in the next two slides, the second one identifies the critical path.

- Phase A start has been arbitrarily put at 2nd January 2017
- Phase A, B1, B2 durations and the preparation time between B1 and B2 are typical for these kind of projects; note that B1 and B2 include the time for SRR and PDR respectively.
- The Implementation phase is 6 years
- SM, SVM AVM and CQM procurement are started in a staggered way. Therefore the SM and SVM AVM do not appear on the critical path, but the SM test results will become available during the CQM manufacturing.
- The cryogenic test facility preparation should start to be implemented directly after the detailed s/c design. This allows for ample time and prevents that the facility readiness could become a bottleneck.
- SVM PFM procurement is started directly after SM test and SVM AVM procurement
- PLM PFM procurement is only started after the CQM test campaign and is therefore on the critical path.
- The mirror modules are procured in a staggered way and are not on the critical path because the polishing needed for this mission is less extensive than e.g. for the Herschel telescope.

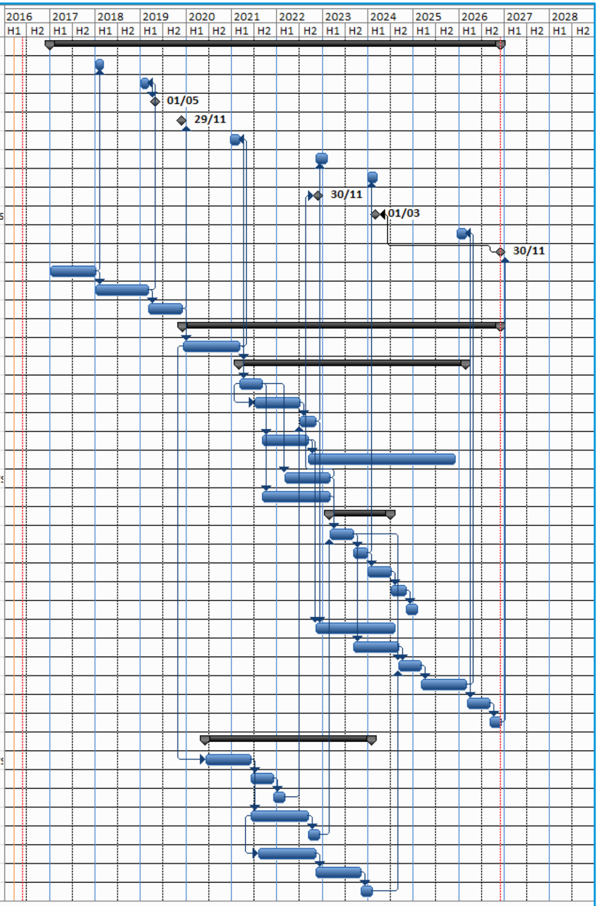
Schedule considerations continued

- The instrument EM need date, it needs to be integrated into the CQM, has been set 3 month before the completion of the CQM procurement. It happened to be in the s/c CDR time frame which is considered reasonable.
- The instrument FM need date, it needs to be integrated into the PLM PFM, has been set 33 month before launch. It happened to be in the s/c QR time frame and in the middle of the PLM PFM procurement, which both are considered reasonable.
- The optical QM test results, if needed (like in Planck) would be available in time for the telescope FM integration into the PLM PFM.

➔ **The presented schedule is therefore considered consistent and feasible.**

Master Schedule

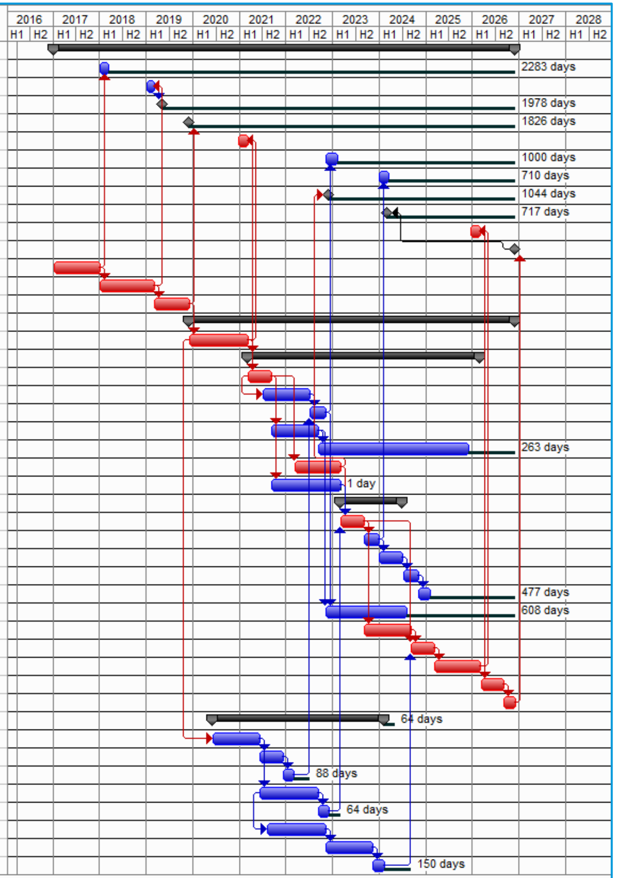
ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		**CMB Polarisation**	**2586 days**	**Mon 02/01/17**	**Mon 30/11/26**	
2		PRR (2 month)	43 days	Mon 01/01/18	Wed 28/02/18	13
3		SRR (2 month)	44 days	Mon 31/12/18	Thu 28/02/19	14FF
4		Mission adoption	0 days	Wed 01/05/19	Wed 01/05/19	3FS+44 days
5		Instrument TRL6 reached	0 days	Fri 29/11/19	Fri 29/11/19	15
6		PDR (2.5 month)	55 days	Mon 14/12/20	Fri 26/02/21	17FF
7		CDR (3 month)	65 days	Tue 01/11/22	Mon 30/01/23	21
8		QR (2.5 month)	53 days	Thu 28/12/23	Mon 11/03/24	28
9		Instrument EM need date	0 days	Wed 30/11/22	Wed 30/11/22	24FS-65 days
10		Instrument FM need date	0 days	Fri 01/03/24	Fri 01/03/24	12SF-717 days
11		AR (2.5 month)	55 days	Mon 15/12/25	Fri 27/02/26	35FF
12		Launch	0 days	Mon 30/11/26	Mon 30/11/26	37
13		Phase A (12 month)	260 days	Mon 02/01/17	Fri 29/12/17	
14		Phase B1 (14 month) incl. SRR	304 days	Mon 01/01/18	Thu 28/02/19	13
15		Intermediate phase (9 month)	196 days	Fri 01/03/19	Fri 29/11/19	14
16		**Implementation phase**	**1826 days**	**Mon 02/12/19**	**Mon 30/11/26**	
17		Phase B2 (15 month) incl. PDR	325 days	Mon 02/12/19	Fri 26/02/21	15
18		**Phase C/D (48 month)**	**1305 days**	**Mon 01/03/21**	**Fri 27/02/26**	6
19		Detailed design (6 month)	132 days	Mon 01/03/21	Tue 31/08/21	17
20		SM procurement (12 month)	261 days	Thu 01/07/21	Thu 30/06/22	19SS+88 days
21		SM test (4 month)	87 days	Fri 01/07/22	Mon 31/10/22	20,41
22		SVM AVM procurement (12 month)	261 days	Wed 01/09/21	Wed 31/08/22	19
23		SVM AVM utilisation (until AR / launch)	845 days	Thu 01/09/22	Wed 26/11/25	22
24		CQM procurement (12 month)	260 days	Wed 02/03/22	Tue 28/02/23	19FS+130 day
25		Cryogenic facility preparation	389 days	Wed 01/09/21	Mon 27/02/23	19
26		**CQM test campaign**	**348 days**	**Wed 01/03/23**	**Fri 28/06/24**	
27		Cryogenic verification (6 month nominal)	130 days	Wed 01/03/23	Tue 29/08/23	43,24,25
28		Optical verification (4 month nominal)	86 days	Wed 30/08/23	Wed 27/12/23	27
29		CQM test contingency	132 days	Thu 28/12/23	Fri 28/06/24	28
30		CQM refurbishment to RFQM (4 month)	88 days	Mon 01/07/24	Wed 30/10/24	29
31		RFQM test campaign (3 month)	66 days	Thu 31/10/24	Thu 30/01/25	30
32		SVM PFM procurement (21 month)	457 days	Tue 01/11/22	Wed 31/07/24	22,21
33		PLM PFM procurement (12 month)	261 days	Wed 30/08/23	Wed 28/08/24	27
34		SVM + PLM PFM integration (6 month)	132 days	Thu 29/08/24	Fri 28/02/25	27,33,46
35		PFM test campaign incl. AR (12 month)	260 days	Mon 03/03/25	Fri 27/02/26	34
36		ESA Contingency (6 month)	131 days	Mon 02/03/26	Mon 31/08/26	11
37		Phase E1 (3 month)	65 days	Tue 01/09/26	Mon 30/11/26	36
38		**Telescope schedule**	**958 days**	**Mon 01/06/20**	**Wed 31/01/24**	
39		Mirror design (12 month)	261 days	Mon 01/06/20	Mon 31/05/21	17SS+130 day:
40		Mirror SM manufacturing	131 days	Tue 01/06/21	Tue 30/11/21	39
41		Telescope SM integration	64 days	Wed 01/12/21	Mon 28/02/22	40
42		Mirror QM manufacturing (15 month)	327 days	Tue 01/06/21	Wed 31/08/22	39
43		Telescope QM integration (3 month)	65 days	Thu 01/09/22	Wed 30/11/22	42
44		Mirror FM manufacturing (15 month)	326 days	Mon 02/08/21	Mon 31/10/22	42SS+44 days
45		Mirror FM polishing (12 month)	261 days	Tue 01/11/22	Tue 31/10/23	44
46		Telescope FM integration and alignment (3 n	66 days	Wed 01/11/23	Wed 31/01/24	45



concurrent design facility

Master Schedule – critical path

ID		Task Name	Duration	Start	Finish	Successors
1		CMB Polarisation	2586 days	Mon 02/01/17	Mon 30/11/26	
2		PRR (2 month)	43 days	Mon 01/01/18	Wed 28/02/18	
3		SRR (2 month)	44 days	Mon 31/12/18	Thu 28/02/19	4FS+44 days
4		Mission adoption	0 days	Wed 01/05/19	Wed 01/05/19	
5		Instrument TRL6 reached	0 days	Fri 29/11/19	Fri 29/11/19	
6		PDR (2.5 month)	55 days	Mon 14/12/20	Fri 26/02/21	18
7		CDR (3 month)	65 days	Tue 01/11/22	Mon 30/01/23	
8		QR (2.5 month)	53 days	Thu 28/12/23	Mon 11/03/24	
9		Instrument EM need date	0 days	Wed 30/11/22	Wed 30/11/22	
10		Instrument FM need date	0 days	Fri 01/03/24	Fri 01/03/24	
11		AR (2.5 month)	55 days	Mon 15/12/25	Fri 27/02/26	36
12		Launch	0 days	Mon 30/11/26	Mon 30/11/26	10SF-717 days
13		Phase A (12 month)	260 days	Mon 02/01/17	Fri 29/12/17	2,14
14		Phase B1 (14 month) incl. SRR	304 days	Mon 01/01/18	Thu 28/02/19	3FF,15
15		Intermediate phase (9 month)	196 days	Fri 01/03/19	Fri 29/11/19	17,5
16		Implementation phase	1826 days	Mon 02/12/19	Mon 30/11/26	
17		Phase B2 (15 month) incl. PDR	325 days	Mon 02/12/19	Fri 26/02/21	6FF,19,39SS+130 days
18		Phase C/D (48 month)	1305 days	Mon 01/03/21	Fri 27/02/26	
19		Detailed design (6 month)	132 days	Mon 01/03/21	Tue 31/08/21	20SS+88 days,22,25,24FS+130 days
20		SM procurement (12 month)	261 days	Thu 01/07/21	Thu 30/06/22	21
21		SM test (4 month)	87 days	Fri 01/07/22	Mon 31/10/22	7,32
22		SVM AVM procurement (12 month)	261 days	Wed 01/09/21	Wed 31/08/22	23,32
23		SVM AVM utilisation (until AR / launch)	845 days	Thu 01/09/22	Wed 26/11/25	
24		CQM procurement (12 month)	260 days	Wed 02/03/22	Tue 28/02/23	9FS-65 days,27
25		Cryogenic facility preparation	389 days	Wed 01/09/21	Mon 27/02/23	27
26		CQM test campaign	348 days	Wed 01/03/23	Fri 28/06/24	
27		Cryogenic verification (6 month nominal)	130 days	Wed 01/03/23	Tue 29/08/23	28,33,34
28		Optical verification (4 month nominal)	86 days	Wed 30/08/23	Wed 27/12/23	29,8
29		CQM test contingency	132 days	Thu 28/12/23	Fri 28/06/24	30
30		CQM refurbishment to RFQM (4 month)	88 days	Mon 01/07/24	Wed 30/10/24	31
31		RFQM test campaign (3 month)	66 days	Thu 31/10/24	Thu 30/01/25	
32		SVM PFM procurement (21 month)	457 days	Tue 01/11/22	Wed 31/07/24	
33		PLM PFM procurement (12 month)	261 days	Wed 30/08/23	Wed 28/08/24	34
34		SVM + PLM PFM integration (6 month)	132 days	Thu 29/08/24	Fri 28/02/25	35
35		PFM test campaign incl. AR (12 month)	260 days	Mon 03/03/25	Fri 27/02/26	11FF
36		ESA Contingency (6 month)	131 days	Mon 02/03/26	Mon 31/08/26	37
37		Phase E1 (3 month)	65 days	Tue 01/09/26	Mon 30/11/26	12
38		Telescope schedule	958 days	Mon 01/06/20	Wed 31/01/24	
39		Mirror design (12 month)	261 days	Mon 01/06/20	Mon 31/05/21	40,42
40		Mirror SM manufacturing	131 days	Tue 01/06/21	Tue 30/11/21	41
41		Telescope SM integration	64 days	Wed 01/12/21	Mon 28/02/22	21
42		Mirror QM manufacturing (15 month)	327 days	Tue 01/06/21	Wed 31/08/22	43,44SS+44 days
43		Telescope QM integration (3 month)	65 days	Thu 01/09/22	Wed 30/11/22	27
44		Mirror FM manufacturing (15 month)	326 days	Mon 02/08/21	Mon 31/10/22	45
45		Mirror FM polishing (12 month)	261 days	Tue 01/11/22	Tue 31/10/23	46
46		Telescope FM integration and alignment (3 month)	66 days	Wed 01/11/23	Wed 31/01/24	34



Schedule duration modification possibilities

- Adaptation of durations of Phase A, B1 and the preparation time for the Implementation Phase in line with programmatic constraints, e.g. Esa Council meetings.
- CQM procurement could be further advanced
- Alternatively the STM could be used to build the CQM. This would increase the time needed, but would reduce the development risk somewhat and makes the building of an SVM dummy with fittings for the CQM unnecessary.
- The SVM PFM procurement could be accelerated and the PLM PFM procurement could be advanced before the completion of the CQM test campaign.

➔ It appears that schedule reduction measures could allow to shorten the schedule in the order of about 6 month, but at increasing the schedule risk.

Summary and conclusions

- A Model philosophy has been identified.
- Suitable thermal test facilities exist, but require adaptation and tuning.
- Details of the verification approach, in particular for the optical verification, need still to be identified.
- A launch within 6.5 years after start of the Implementation Phase appears to be feasible, respecting the requirement of 6 month ESA contingency and allowing for a 3 month launch campaign.

Reference documents

RD[1] "Guidelines for the use of TRLs in ESA programmes", ESSB-HB-E-002, Issue 1, Revision 0, 21 August 2013.

CMB Polarisation Mission

Cost

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Cost Estimate Assumptions and Cost Scope

EXCLUDED from the Estimate

- Launch excluded from the current estimate (agreed with the customer)
- FPA excluded from the scope of the study

INCLUDED in the Estimate

- Telescope development and production
- Adapter still included (100% ESA Share), as per CDF NGCryo
- Cryo coolers included in the baseline estimate
- Industrial Set-Up assumed as `Heavy for all SVM Subsystems, assumed to be procured by a separate Contractor (than the Prime) `3-tier approach` similarly to M Class references, currently under Project implementation)

Scope of the Estimate

- 1 X Phase B2/CD/E1->Expected Industrial Price
- CMB Polarization SC Industrial Production and Development , down to the equipment level, if available in the CDF Model
- Project Office, MAIT, GSE, provisions at system level and subsystem
- Mission Science and Ops
- ESA Internal Cost
- Cost Risk (Industry and ESA Share)

Cost estimating Methodology

- SC HW/SW: Analogy wrt past missions, ESA Standard CERs, Benchmarking wrt NG Cryo.
- Telescope: ESA Standard CERs, Benchmarking wrt NG Cryo and GAIA when applicable
- Prime and SS PO, GSE, AIV/T: RACE and POCoMo cost models
- Cost Risk: `Opera` risk assessment , based on Monte Carlo-like computation
- Launch preparation and Launcher adapter: based on NG Cryo/ESA internal references
- GS and Ops: RACE cost model

General Cost Driving factors for Space System

Cost Driving factors generally are (and **cost saving actions should be associated to the these factors` optimization)**

Mass budget, size-> MAIT and Material, plus AIV/T - Facility

Complexity of the entire system-> Project Office, AIV/T, GSE, and MAIT

Model Philosophy at System Level

Model Philosophy at equipment level ->please indicate TRLs and Hardware Matrix

Schedule (strictly linked to manpower assumptions)

Risk Assessment

International Cooperation assumptions

Industrial Set Up and Procurement Approach

CMB Polarization-Identified Cost Driving Factors

The following main cost driving factors have been identified:

A) Cryo System, which affecting the cost at:

- Mission prime Level
- Cryo System activities and Hardware
- Cost Risk (Industry Share)

B) Heavy Procurement Approach and Industrial set Up

Preliminary conclusions

Compatibility wrt to the M Class Budget Cap can not be concluded yet. The CDF design process is still ongoing (CDF Model just frozen), the estimating process is still ongoing