THESEUS

CDF Study – Executive Summary

Prepared by ESA Study and CDF* Teams

(*) ESTEC Concurrent Design Facility

Introduction

THESEUS

- **Transient High Energy Sources and Early Universe Surveyor**
- Recommended by the Space Science Advisory Committee (SSAC) to enter an assessment and feasibility study (Phase 0/A/B1), starting with an ESA internal study followed by parallel industrial study activities
- M5 candidate mission of the Cosmic Vision programme
- Programmatic boundaries: 550 MEur (CaC, 2016), European Launcher, Launch 2032, TRL 6 by 2024
- Science goals:
  - Gamma Ray Burst (GRBs) survey
  - Transient X-ray events monitoring

- Three types of instruments:
  - X-Gamma rays Imaging Spectrometer (XGIS)
  - Soft X-ray Imager (SXI)
  - InfraRed Telescope (IRT)

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CDF study objectives

The CDF study shall serve the following purposes:

- Identify technical and cost drivers from science requirements
- Define the mission concept including suitable observation strategy and operation of the instruments
- Prepare a design to allow a feasibility assessment and identification of critical areas (preliminary design)
- Define a preliminary AIV approach and work share between ESA and the Instrument Consortia
- Consolidate Payload <> S/C interfaces
- Consolidate the requirements (SciRD, MRD)
- Identify any critical technologies, potentially requiring TDAs
- Perform a programmatic analysis (cost, risk and schedule)

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CDF study objectives

The CDF study achieved the following purposes:

- Identify technical and cost drivers from science requirements => Done
- Define the mission concept including suitable observation strategy and operation of the instruments => Done (enhancements were even proposed)
- Prepare a design to allow a feasibility assessment and identification of critical areas (preliminary design) => Done
- Define a preliminary AIV approach and work share between ESA and the Instrument Consortia => Done
- Consolidate Payload <> S/C interfaces => Done (more work needed on the IRT I/Fs)
- Consolidate the requirements (SciRD, MRD) => Done
- Identify any critical technologies, potentially requiring TDAs => Done
- Perform a programmatic analysis (cost, risk and schedule) => Done

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Design philosophy

- **Design for robustness**
  - Design able to accommodate the most driving elements identified (e.g. highest mass of IRT telescope assumed)
  - High TRL elements/units chosen always even when requiring higher resources (e.g. STR choice, DHS, COMMS)
  - Room to grow left whenever possible (e.g. radiator and SA areas with comfortable margins to grow even above all the margins)
  - Core science can be achieved even with simple survey observational strategy and strictest assumptions (e.g. no science observations during eclipse)
  - A lot of improvements have been identified to further simplify the system (e.g. TCS) or to potentially increase the observation efficiency (different observation strategy, observe during eclipse, etc…). However, none of these were assumed! Conservative!

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General design guidelines

- Maximise science return within programmatic boundaries
- Design for robustness!
- Risk mitigation measures to be followed as much as possible:
    - Select COTS/higher TRL equipment,
    - Avoid locking the design to specific technologies

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Payload

Overview

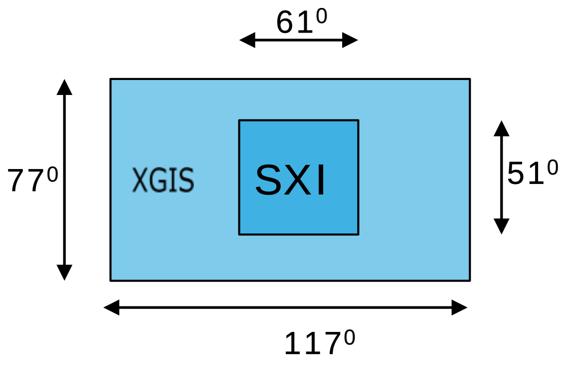
- Three 'coaligned' (2 have large FOV) instruments:

  IRT: Infra Red Telescope, 70 cm diameter, 0.7-1.8 µm

  SXI: Soft X-ray Imager. Lobster eye X-ray telescope 0.3-5 keV, 4 units

  XGIS: X- and Gamma Imaging Spectrometer, 2 keV – 20 MeV, 2 units

Instrument	Single Detector FoV	Overall FoV
SXI (4 DU)	26^0x31^0	51^0x61^0
XGIS (2DU – 40^0 offset)	77^0x77^0	77^0x117^0
IRT (max FoV)	10'x10'	10'x10'



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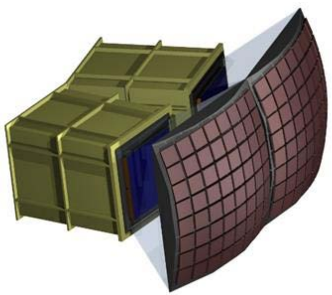
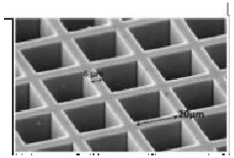
Instrument description (SXI)

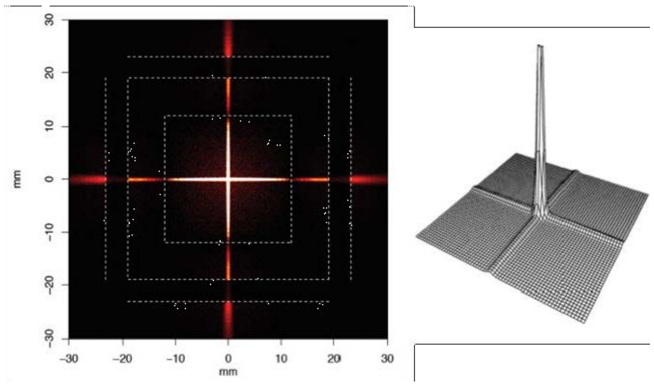
- SXI: Lobster Eye optics (MPO) which each unit 4 CCDs. Current baseline PLATO CCD 270 at -65°C. Other options (to be studied further): operating warmer (>-30°C) in IMO or CMOS (CIS I 20).
- Source location accuracy: <1-2 arc min



SXI Units



Close-up of MCP



PSF

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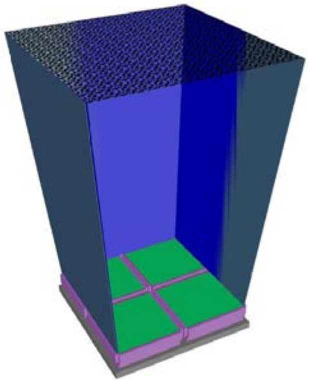
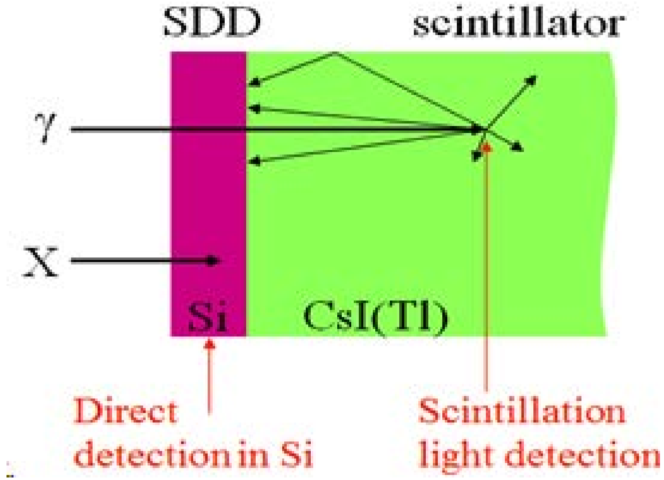
Instrument description (XGIS)

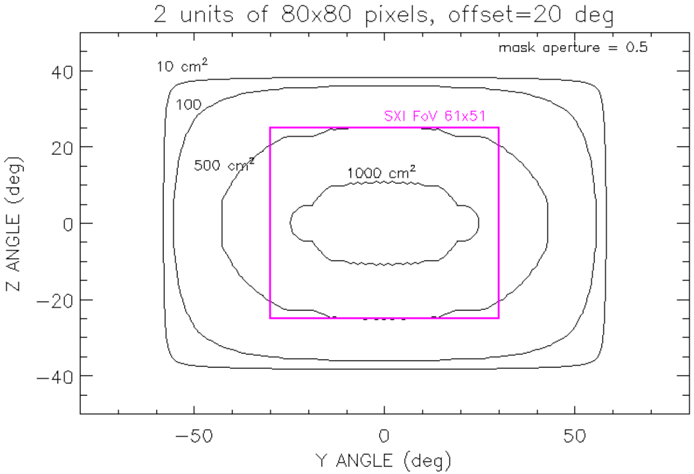
- XGIS: SDD+CsI(Tl) modules with coded mask (below 30 keV).
- Source location accuracy: ~5 arc min (in 2-30 keV band)



XGIS Unit



XGIS Detection principle



XGIS combined FoV

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Instrument description (IRT)

- IRT: 70 cm Korsch telescope (see IRT presentation) with IR detector. Baseline: European ALFA detector, 2048x2048 15µm pixels (Hawaii-2RG as alternative, 18µm).

- Each instrument has its own I-DHU (mechanically identical).

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Evolution during CDF (1)

Thanks to the active participation of the Consortium/Instrument teams a constructive evolution of the instruments has taken place during the CDF.

- SXI units were aligned to form combined rectangular view with large aspect ratio. Occultation (efficiency) considerations suggested that more square FOV was (slightly) more efficient. Alignment of units adapted (~square with 1^0 overlap). No changes to optical design of SXI itself.
- XGIS started as 3 units (8x8 modules each). Accommodation constraints drove the design to 2 units (8x12 modules each). Optimization with respect to almost square FoV of combined SXI resulted in 2 units of 10x10 modules each. Established relation between operating temperature, radiation damage and energy resolution.

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XGIS EoL performance

Assumption here: 2.5 10^9 p/cm^2 10 MeV equivalent, see radiation presentation for correct value.

Dependency of thresholds and energy resolution on temperature

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Evolution during CDF (2)

- Radiation monitor baseline not NGRM anymore but solution like BeppoSAX. Plastic scintillator + PMT, diameter 20mm, 5mm thickness (2mm Al scintillator cover). Mass 2.8 kg, power consumption 5 W. Electronic Box size: TBD

- TBU: size of antennas (2x) 10cm diameter x 50cm height, electronic box mass ~1-2kg, size 20cm cubed

- IRT: see IRT presentation. Baseline Korsch design.

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To be studied further

IRT	• Plate scale (optimizing SNR) • Open filter position • Cold stop (location) • Baffle design • Interface with camera • Detector selection • Finetuning operating temperatures (FEE, detector) • Wavelength range detector
SXI	• Detector / operating mode trade-off (impacting temperature) • Optics temperature (and stability requirements)
XGIS	• Optimization of offset angles • Energy resolution requirements

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Budgets: mass and power

Payload Element	CBE Mass (kg)	DMM (%)	Mass (kg)
IRT	-	20	-
SXI	143.6	20	172.32
XGIS	118.75	20	142.50
I-DHU IRT	4.8	20	5.76
I-DHU XGIS	4.8	20	5.76
I-DHU SXI	4.8	20	5.76
Radiation Monitor	2.8	20	3.36
TBU	2	20	2.40

Payload Element	CBE Power(W)	DMM (%)	Power (W)
IRT	-	20	-
SXI (total for 4 units)	115.00	20	138.00
XGIS (total for 3 units)	101.02	20	121.22
I-DHU IRT	15.67	20	18.80
I-DHU XGIS	15.67	20	18.80
I-DHU SXI	15.67	20	18.80
Radiation Monitor	5.00	20	6.00
TBU	2.00	20	2.40

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Budgets: volumes/sizes

Payload Element			
IRT (TBC)	Cylinder: ~0.80m diameter, TBD height		
SXI (x4)	0.38mx0.38m tapering to 0.20mx0.20m and then extended for another 0.20m (at 0.2x0.2m). Total height 0.50m		
XGIS (x2)	L: 0.63m	W: 0.63m	H:0.80m
TBU	L: 0.20m	W: 0.20m	H: 0.20m
TBU Antennas (2x)	Diameter:0.10m	Height:0.50m	
I-DHU IRT	L: 0.228m	W: 0.210m	H: 0.180m
I-DHU XGIS	L: 0.228m	W: 0.210m	H: 0.180m
I-DHU SXI	L: 0.228m	W: 0.210m	H: 0.180m
Radiation Monitor	L: TBD	W: TBD	H: TBD

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Budgets: telemetry

- Orbital period: 97 min for 600 km.

Payload element	Telemetry / orbit
XGIS	2.4 Gbit typical
IRT	2.2 Gbit typical
SXI	0.3 Gbit typical

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Telescope

Introduction

- IRT=telescope+imaging spectrometer.
- Design requirements
- Telescope trade off & selected baselinefor telescope and spectrometer example.
- The need for a field stop: problems & solutions.
- Preliminary tolerance analysis & need of focusing spectrometer.
- Conclusions.

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Telescope design requirements

- Entrance pupil: 700 mm diameter, central obstruction <230mm diameter
- Interface with instrument: imaging and spectroscopy (low and high resolution)
- Plate scale at detector: 0.3”/pixel, assume 18 µm pixel
- FoV: 10’x10’ for imaging and low resolution spectrometer
  5’x’5 for high resolution spectrometer
- Wavelength: 0.7 to 1.8 µm
- Working T: 240 K

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Telescope concepts: Cassegrain vs. Korsch

Option 1: Ritchey-Chretien. On axis.

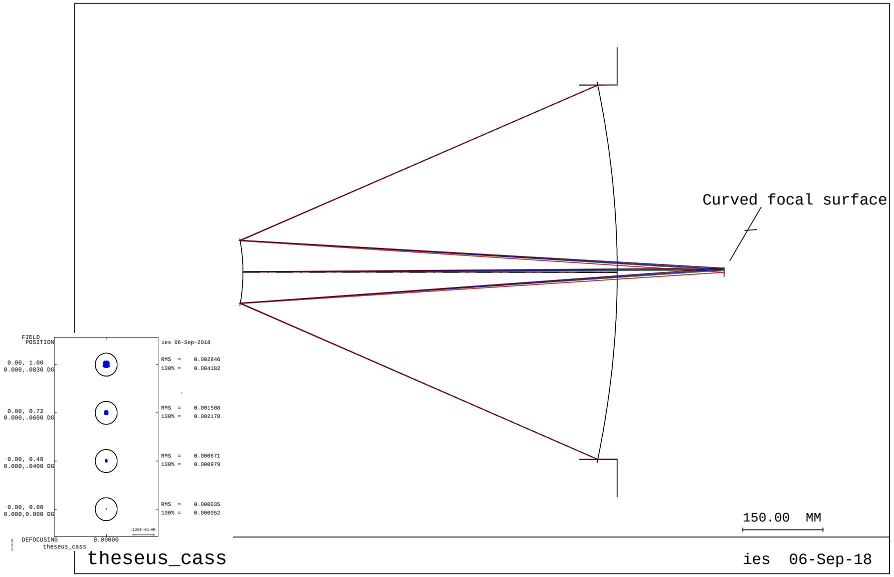
Interface at focus. EFL 5400mm.

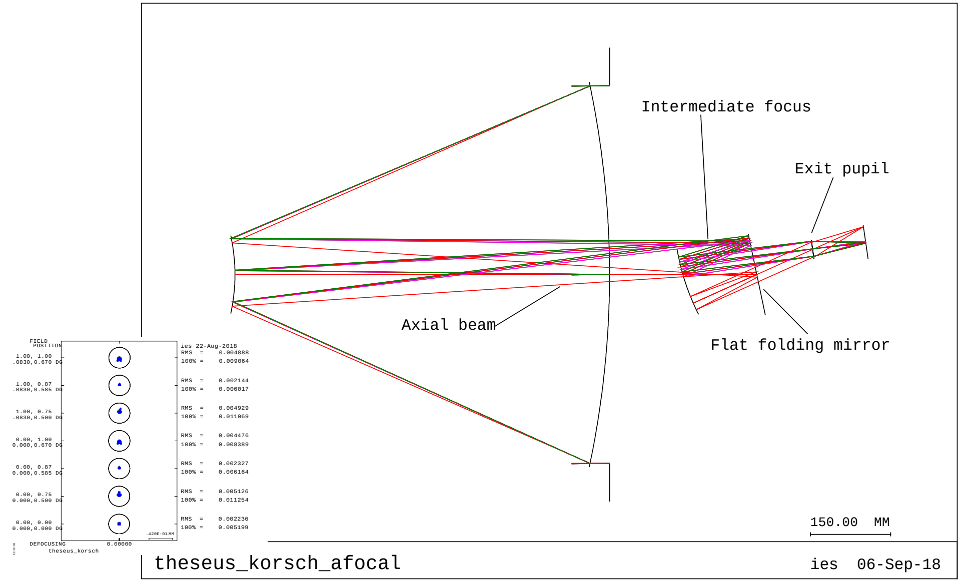
Diffraction limited (in curved focal surface).

Option 2: Korsch. FoV off axis.

Interface at exit pupil. Afocal.

Diffraction limited.





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Telescope: trade off, baseline

	Option1: Ritchey Chretien	Option 2: Korsch
Throughput	0 (2 mirrors)	0 (4 mirrors but spectrometer collimator no needed)
Manufacture	0	0
AIT	+	- (4 mirrors, off axis FoV)
Interfaces	0? Focus, curved image surface	0? Exit pupil, collimated beam
Instrument design	- aberrations of spectrometer collimator are added: if lenses => field curvature increases if mirrors => off axis system, self-corrected	+ image corrected up to exit pupil (no spectrometer collimator required)

Baseline: Korsch, easier instrument design

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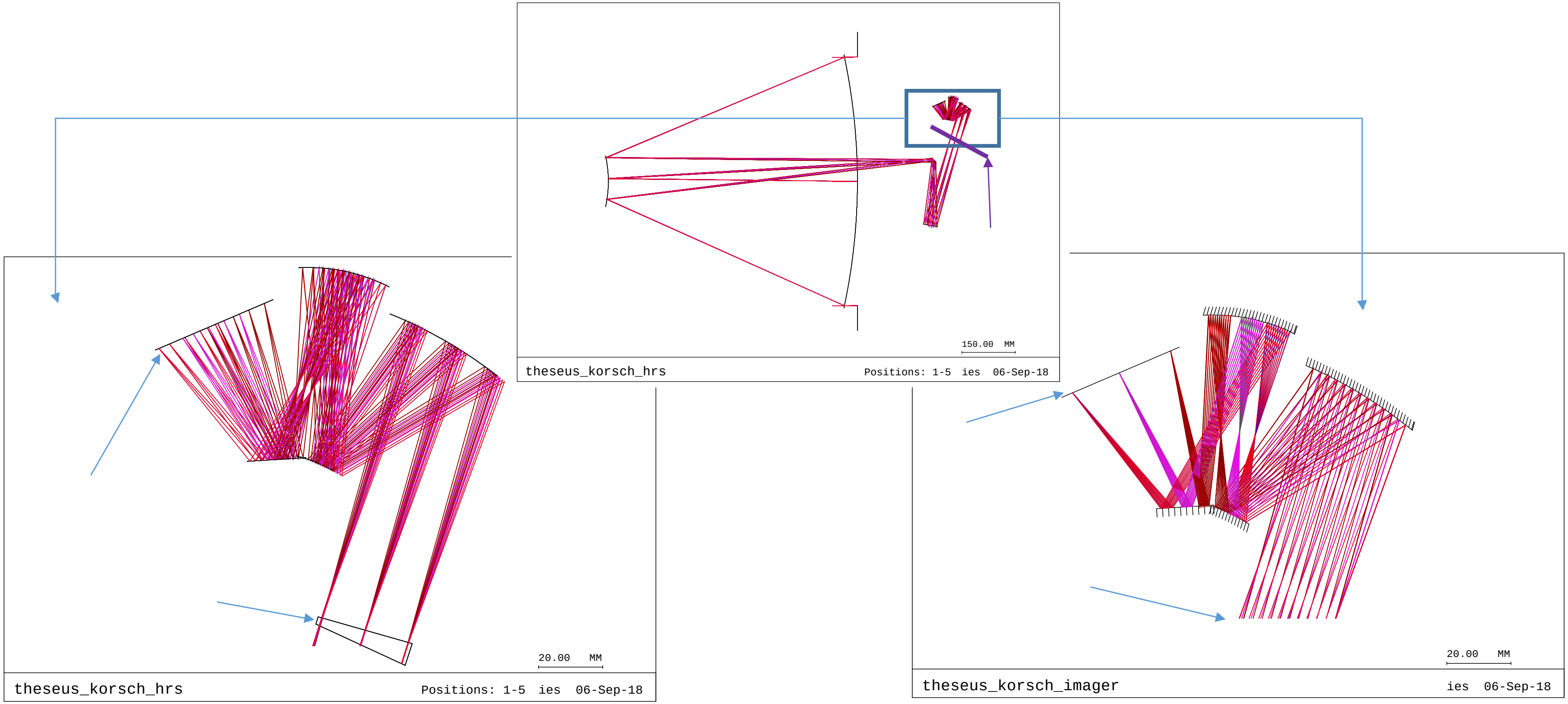
Telescope concept: spectrometer example



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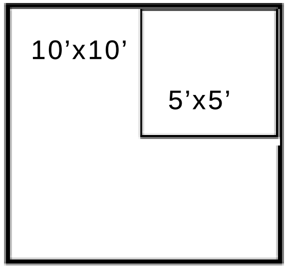
Field stops

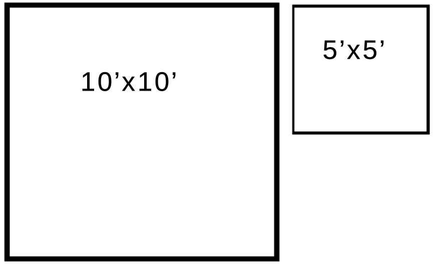
- Two field stops are required in spectrometer mode to prevent of stray light contamination:

A mechanism required to exchange them?: No, other solution suggested by instrument team

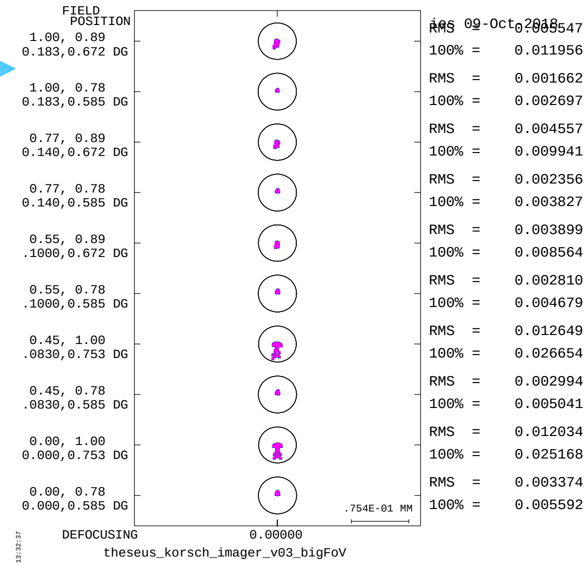
- Changes in design (analysed & feasible):
  - Telescope pointing outside imaging FoV of imager.
  - Device @ HRS deviating light towards detector area: near to grating.
  - Extended FoV of telescope.



Derived from proposal



Suggested by instrument team



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Preliminary tolerance analysis

- Tolerance criterion: RMS WFE for diffraction limit @1.8µm < 129 nm
- Performance budget:

Total RMS WFE = Design residual + Optics manufacture + Structure & AIT + Launch & in orbit

$$129 = [\ 42^2 + 43^2 + 80^2 + 80^2\ ]^{1/2}$$

- Compensation @ M2:

Focus, range ± 230 µm & Tip/tilt, range ± 0.2 mrad

No compensation

delta x	M1	**0.020**
delta y	M1	0.020
delta z	M1	0.20
tilt x	M1	0.00005
tilt y	M1	0.00005
delta x	M2	0.015
delta y	M2	0.015
delta z	M2	N/A.Compensator
tilt x	M2	N/A.Compensator
tilt y	M2	N/A.Compensator
delta x	Fold	N/A.Flat
delta y	Fold	N/A.Flat
delta z	Fold	0.200
tilt x	Fold	0.00025
tilt y	Fold	0.00025
delta x	M3	0.1
delta y	M3	0.1
delta z	M3	0.2
tilt x	M3	0.0015
tilt y	M3	0.0015
rotation z	M3	0.010

delta x	M1	0.010
delta y	M1	0.010
delta z	M1	0.0015
tilt x	M1	0.00001
tilt y	M1	0.00001
delta x	M2	0.0075
delta y	M2	0.0075
delta z	M2	0.0015
tilt x	M2	0.000025
tilt y	M2	0.000025
delta x	Fold	N/A.Flat
delta y	Fold	N/A.Flat
delta z	Fold	0.010
tilt x	Fold	0.00015
tilt y	Fold	0.00015
delta x	M3	0.05
delta y	M3	0.05
delta z	M3	0.005
tilt x	M3	0.00025
tilt y	M3	0.00025
rotation z	M3	0.0005

Units:
Lengths are mm.
Angles are rad.

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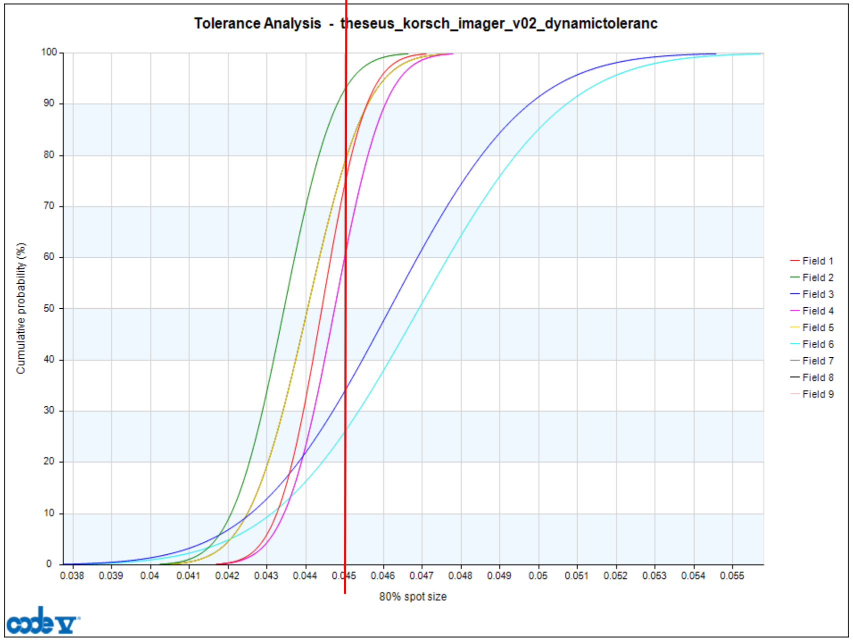
Tolerance analysis re-visited: 80 % EEC as criterion

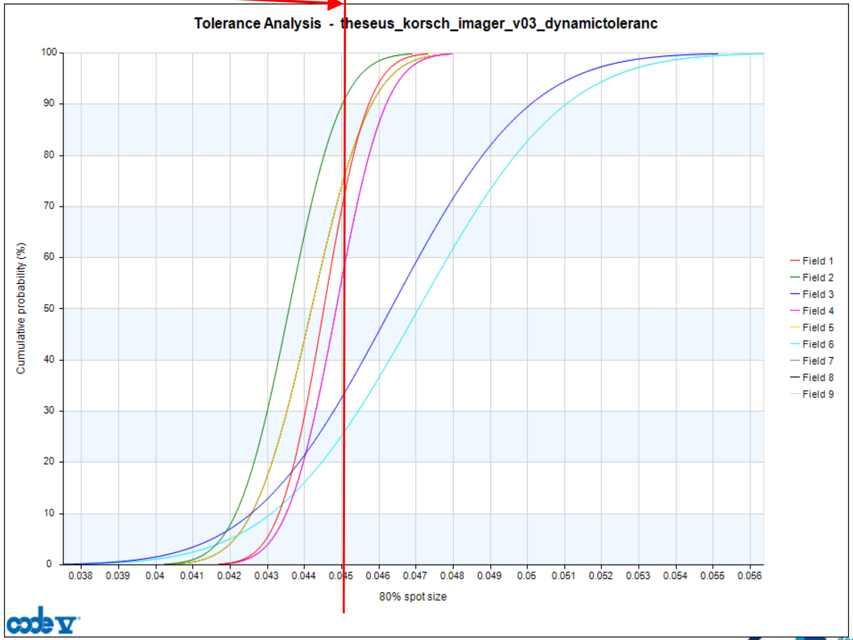
- Only contribution of Structure & AIT.
- 80% EEC does not change very rapidly in cumulative frequency plots: tolerances can be relaxed

Relaxed tolerances (only main offenders):

		Initial value	Relaxed value
delta x	M1	0.020	0.025
delta y	M1	0.020	0.025
delta x	M2	0.015	0.025
delta y	M2	0.015	0.025

80% EEC of telescope as designed





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Conclusions

- Baseline telescope meeting design requirements: Korsch
- Interface with instrument: exit pupil, collimated beam
- Field stops required for spectroscopy: two field stops implemented, changes required in pointing strategy, instrument optical design (grating of HRS) and telescope FoV
- Preliminary tolerance analysis:
  - Procedure:
    - Criterion RMS WFE, telescope diffraction limited as built and operating
    - Initial analysis shows tolerances too tight even integration with adjustment at M2
    - Re-visited analysis using criterion 80% EEC shows tolerances can be relaxed, though integration adjustments are still required.
  - Conclusions:
    - Analysis of launch & in orbit errors suggest a strict thermal environment.
    - An early AIT strategy will be required (integrate at room and check at working T?)

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Systems

Main Requirements and Design Approach

- Launch, orbit and lifetime
  - Launch in 2032
  - 3 years mission lifetime (launch to disposal) + 2 years of consumables
  - Low Earth Orbit minimizing radiation background noise
    - Baseline: Circular of 600 km altitude and 5.4° inclination
  - Launcher Vega C (more than 2 Ton to LEO, Ariane 62 as back-up option)
- Programmatic (cost, risk and schedule)
  - Compatibility with an M-size mission
  - TRL 6 by Mission Adoption
- Design approach
  - Design to robustness and cost (high TRL)
  - Mass has not been optimised

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Mission Drivers

- Target location accuracy (incl. AKE)
  - ~1' within a few seconds and ~1'' within a few minutes
- Trigger broadcasting
  - <1 kbit/event within 30 sec from detection, 70% of the time
- Slewing agility
  - Repointing from detection to target within 10min (i.e. ~6deg/min)
- Pointing stability
  - RPE < 1'' (3σ) over 10sec and PDE < 10'' (3σ) over 5min
- Infrared telescope
  - Mirror diameters (M1 = 70cm and M2 = 23cm)
- Accommodation of multi-head instruments and FoV blinding avoidance
- Instrument operation conditions at quasi-cryogenic temperatures
- Radiation susceptibility

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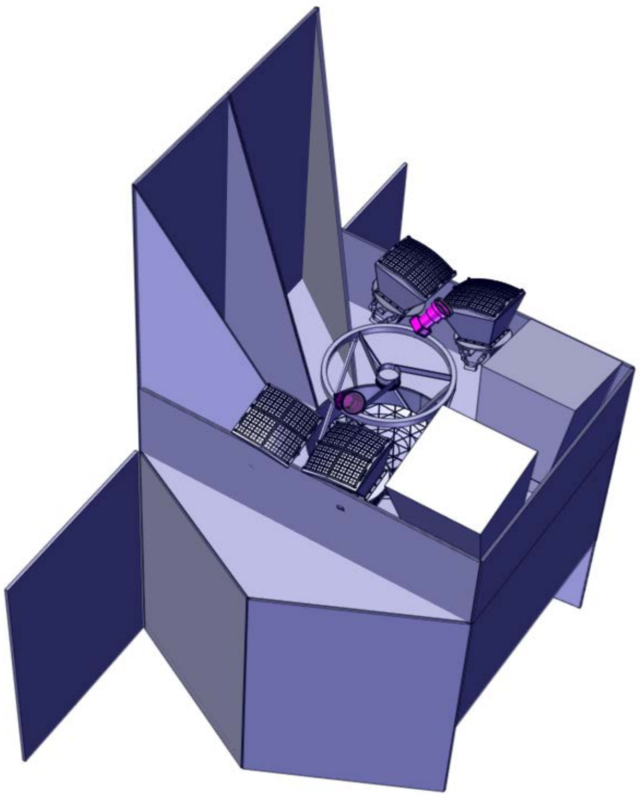
System Configuration and System Trade-offs



- Ritchey-Chretien on-axis vs. **Korsch FoV off-axis** Telescope
- Telescope of Zerodur/CFRP vs SiC
  - Budgets based on **worst cases** of each option
- **M2 focus mechanism** vs cold integration for IR Telescope
- Bipods vs **Spider** supporting structures for M2 assembly
- 3x vs **2x** XGIS units
- Rectangular vs **Squared** combined FoV for SXI
- Passive vs **Active** thermal control
  - HP vs **LHP**, and Ammonia vs **Propylene**
- **Coarse** vs High accuracy Star Trackers
- S-band vs X-band vs **S/X-band** communication system
- Un-controlled vs **Controlled** re-entry
  - **Chemical** vs dedicated Solid w/ thrust vector control

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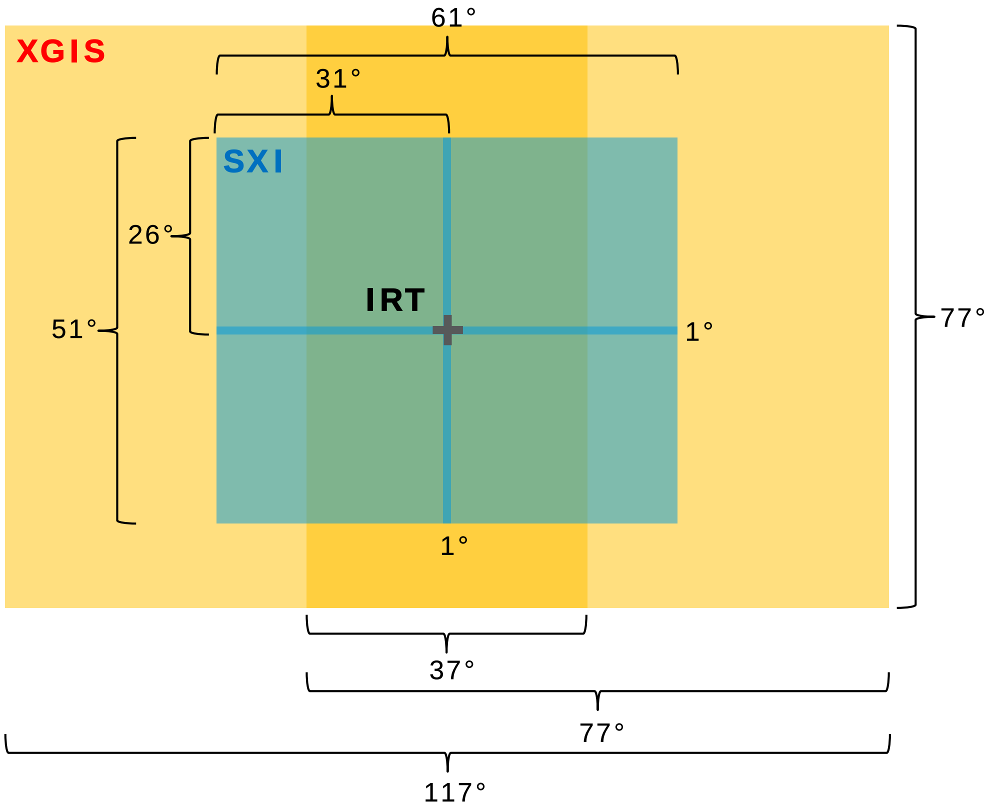
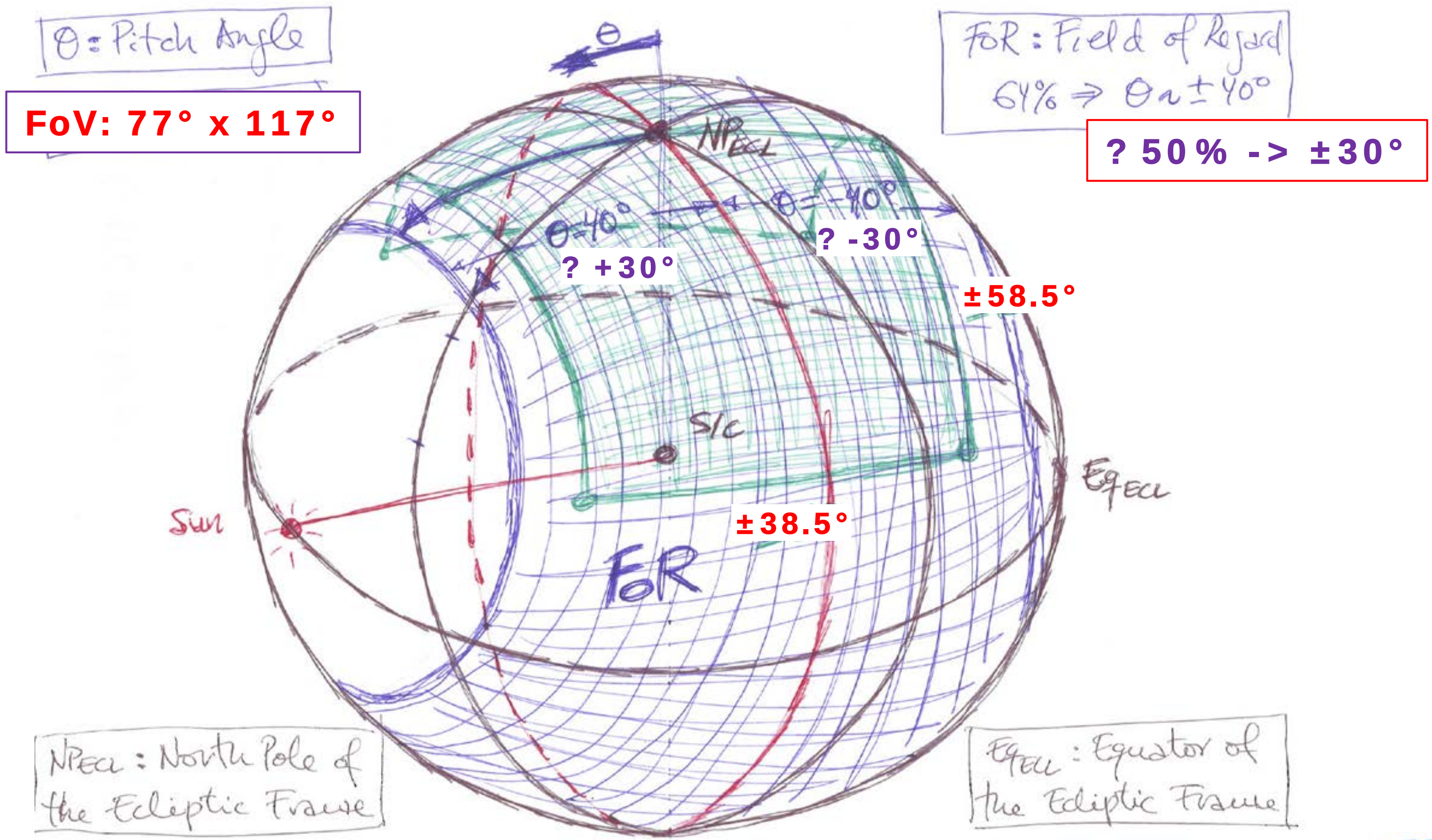
Instruments Combined Field of View



Mission Geometry: Field of Regard (FOR)



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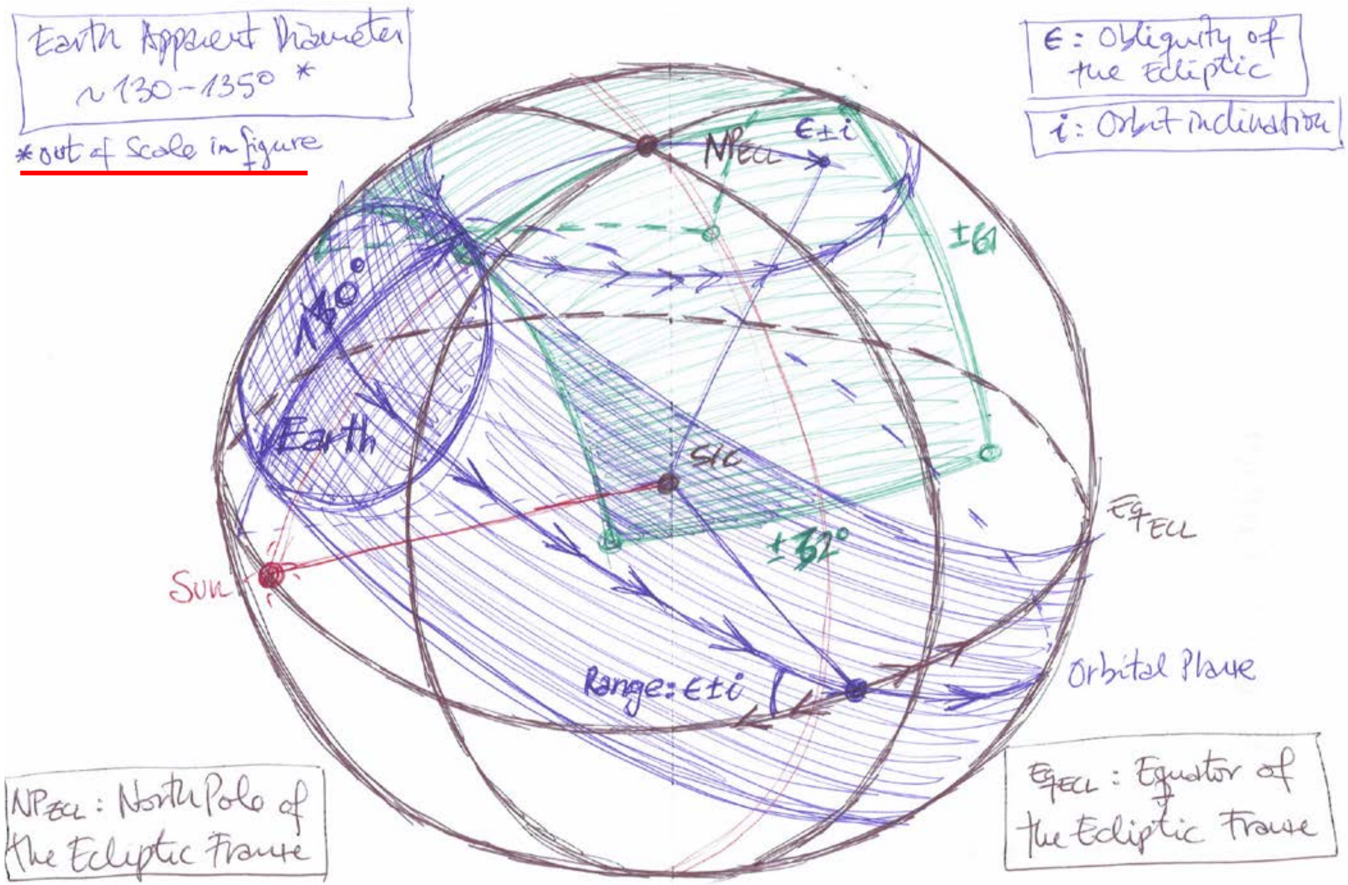
Mission Geometry: Occultation Free Zones (1 / 2)



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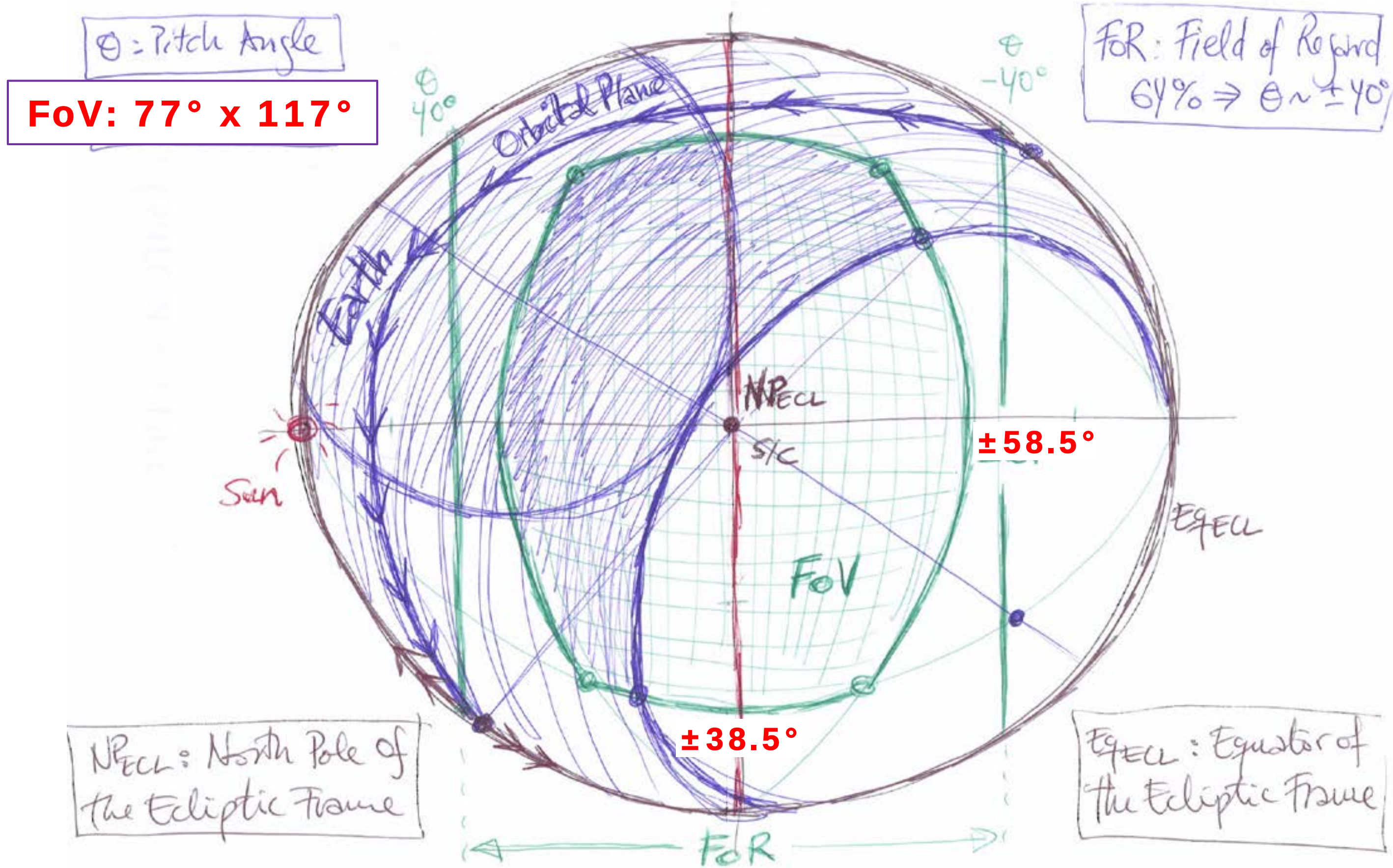
Mission Geometry: Occultation Free Zones (2 / 2)



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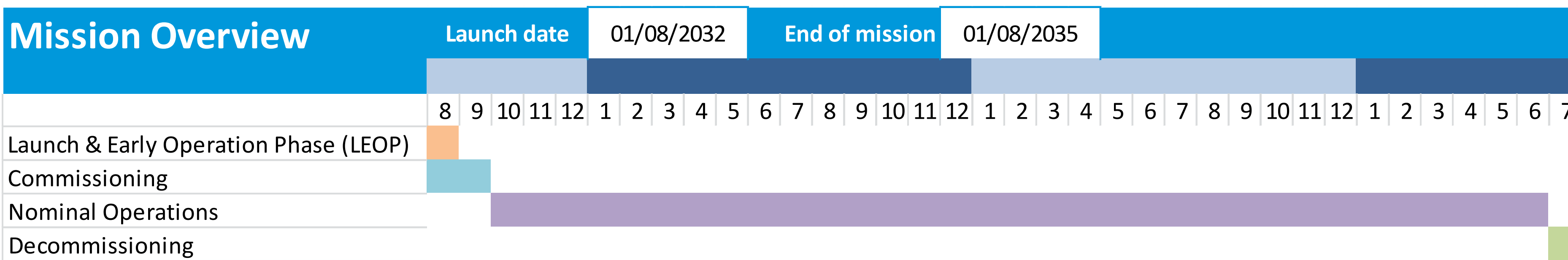
Mission Phases

Mission Phases

Phase	Start Day	End Day	Duration	Mode	Assumption
Launch & Early Operation Phase (LEOP)	0	2	2		Less than 1 day duration, max 2 days
Commissioning	2	90	88		3 months from launch (TBC)
Nominal Operations	90	1065	975		
Decommissioning	1065	1095	30		1 month (3-4 burns, ~1 week in between)



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System States

System States

Launch	From launcher umbilical separation to spacecraft separation. Launcher provided resources (i.e. power, comms... are TBD). All equipments are OFF except for essential equipment (by default assumed RTU, heaters and receiver). S/C powered by battery only (battery fully charged at start). Assumptions: Launch likely in eclipse to protect instruments from Sun illumination.
Sun Acquisition	From spacecraft separation to sun-pointing attitude. DHS units are ON. AOCS actuators/sensors are ON (coarse gyros and start trackers, attitude control on RCS). TT&C up- and down-link via S-band LGA. Instruments and rest of the platform equipments are OFF. Assumptions: No energy produced by the SA, S/C powered by battery only.
Safe	Attitude is Sun-pointing (maximum power generation). DHS units are ON, and minimum set of AOCS actuators/sensors are ON (attitude control on RCS). TT&C up- and down-link via S-band LGA. Cryocoolers are ON, Instruments are STAND-BY, and rest of platform equipments are OFF. Assumptions: Use of RW is preferred, as soon as possible, to minimise propellant consumption.
Science	Attitude assumes maximum pitch angle (sizing case: minimum power generation) AOCS actuators/sensors are ON. Cryocoolers are ON, and SXI, XGIS and IRT instruments are ON. Assumptions: No changes during eclipse. XGIS and SXI instruments during SAA crossings, and IRT during Survey Mode go to STAND-BY mode, i.e. they are ON but do not generate science data (just telemetry).
Science + Comms	Attitude assumes maximum pitch angle (sizing case: minimum power generation) AOCS actuators/sensors are ON. TT&C up- and down-link via S-band LGA + science data downlink via X-band LGA. Cryocoolers are ON, and SXI, XGIS and IRT instruments are ON. Assumptions: No changes during eclipse. XGIS and SXI instruments during SAA crossings, and IRT during Survey Mode go to STAND-BY mode, i.e. they are ON but do not generate science data (just telemetry).
Manouevres & Maintenance	• **Slew Manoeuvre (SLEW)**: For re-targeting and calibration purposes, etc. (attitude control on RW). • **Orbit Control Manoeuvre (OCM)**: Potential debris avoidance manoeuvres and de-orbiting (orbit control on RCS). • **Wheels Off-Loading (WOL)**: Non-nominal momentum build-up (attitude control on RCS).

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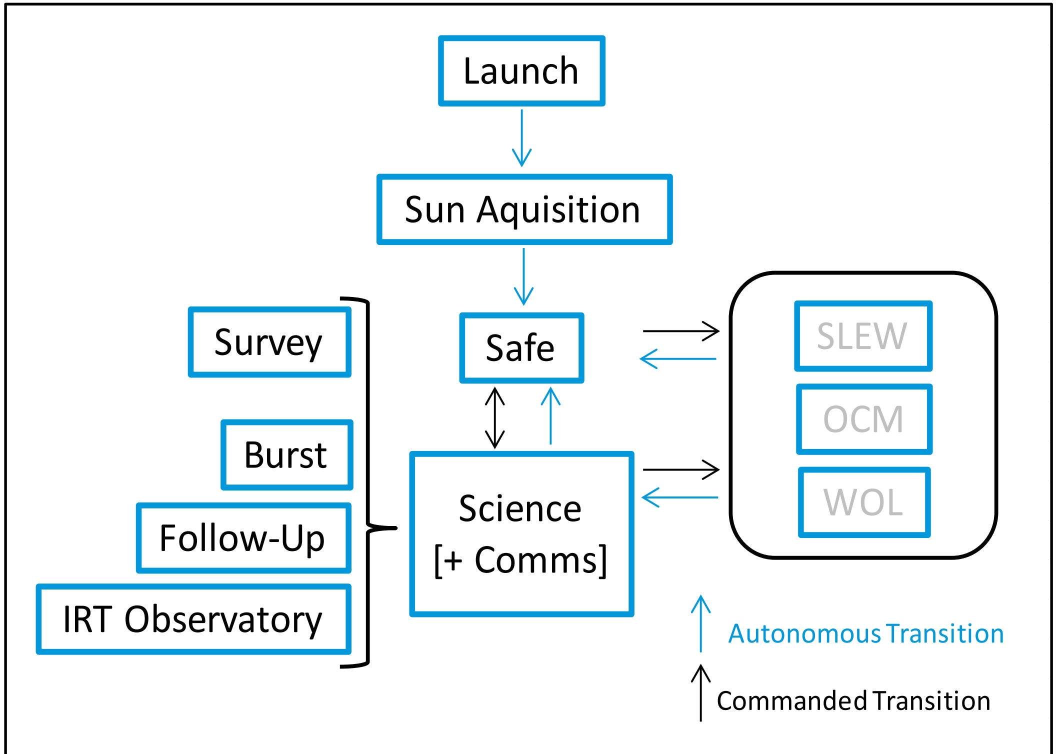
System State Transitions



- Transition from Launch to first Safe stand-by state fully autonomous up to start of platform commissioning
- Transition between Science and Science+Comms modes corresponds to switching transmitters ON/OFF
- Transition between Survey, Burst, Follow-up or IRT Observatory observation modes corresponds to SLEW when re-targeting is needed and changes to instrument modes
- Transition to OCM only required for debris avoidance and final de-orbiting
- Transition to Wheel Off-Loading only required in case of excessive momentum build-up (e.g. re-entry, TBC)

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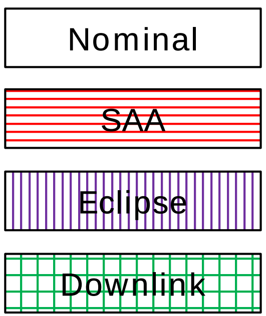
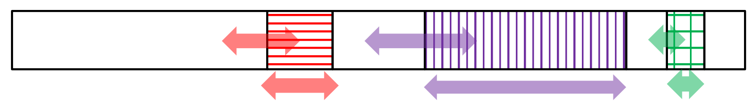
Orbit Sequence





Small variation length throughout the year

Variable position throughout the year

Overlaps occurring

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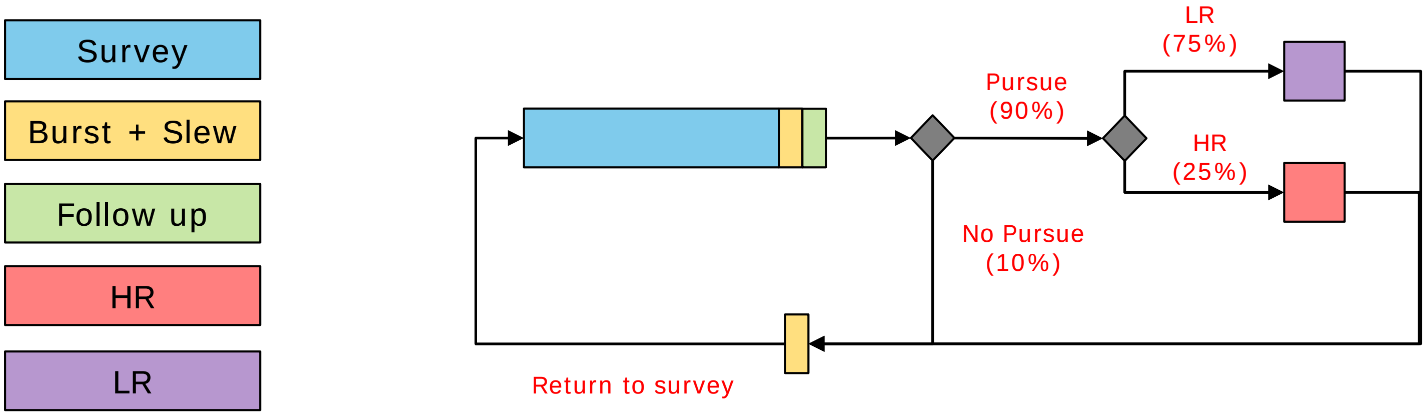
Observation Sequence



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Duration Assumptions

Durations (min)	
Survey duration	RANDBETWEEN(0,22*60)
Burst + slew duration	RANDBETWEEN(0,10)
Follow up duration	8
LR mode duration	60
HR mode duration	60

Uniform distribution [0,22] hours
Average 11 hours (consistent with 2 triggers/day)

Uniform distribution [0,10] min
Average 5 min

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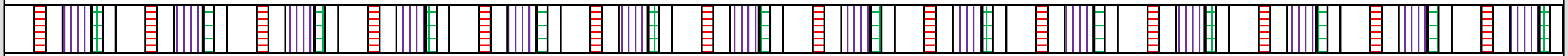
Mock Sequence (1 day example)

Orbit (14.9 orbits/day)



Observation / SC

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Science Data Generation Rate Assumptions

Data rates (kbits/sec)					
	XGIS	SXI	IRT	Total without compression	Total with compression
Survey	608.33	43.35	X	651.68	434.46
Burst + Slew	2250.83	43.35	0.00	2294.18	1529.46
Follow up	1095.00	43.35	416.67	1555.02	1106.12
LR mode	1095.00	36.85	2555.56	3687.40	2884.19
HR mode	1095.00	36.85	638.89	1770.74	1286.97
SAA	0.00	0.00	0.00	0.00	0.00
Occultation	N/A	N/A	0.00	N/A	N/A

Variable – Maximise!

- # units XGIS = 2
- “New XGIS unit FoV” = 1.52*”Proposal XGIS unit FoV” (Option 3 proposed by XGIS team with 10x10 modules – Total 12800 vs. 12288 pixels)
- Compression ratio (XGIS, SXI, IRT) = (1.5, 1.5, 1.2)
- Survey data rate of SXI assuming average %FoV occultation of 16.3% (results from Mission Analysis presentation –> square FoV)
- No effect of occultation on XGIS data rate
- XGIS and SXI “on” during LR and HR modes (SXI with additional average 15% more occultation – TBC)
- 30 % margin

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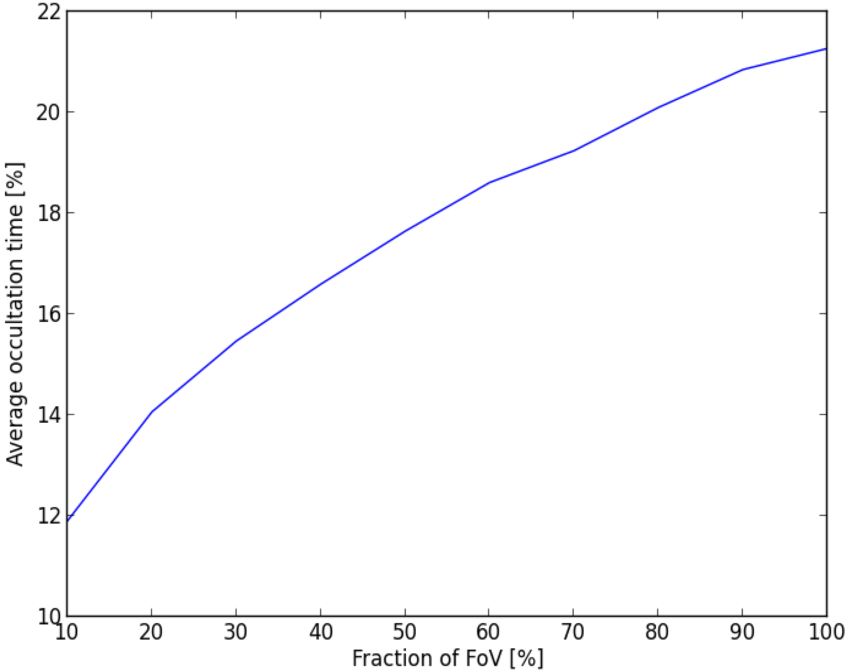
Model assumptions

- Simulation running for 4 representative cases around solstices and equinoxes
- 14 days simulations
- Radiation data used to define SAA
- Using actual propagation of the orbit to assess where downlinks occur
- New assumption on cumulative distribution function for the occultation
- Still 8.3 Mbps downlink (Malindi only)



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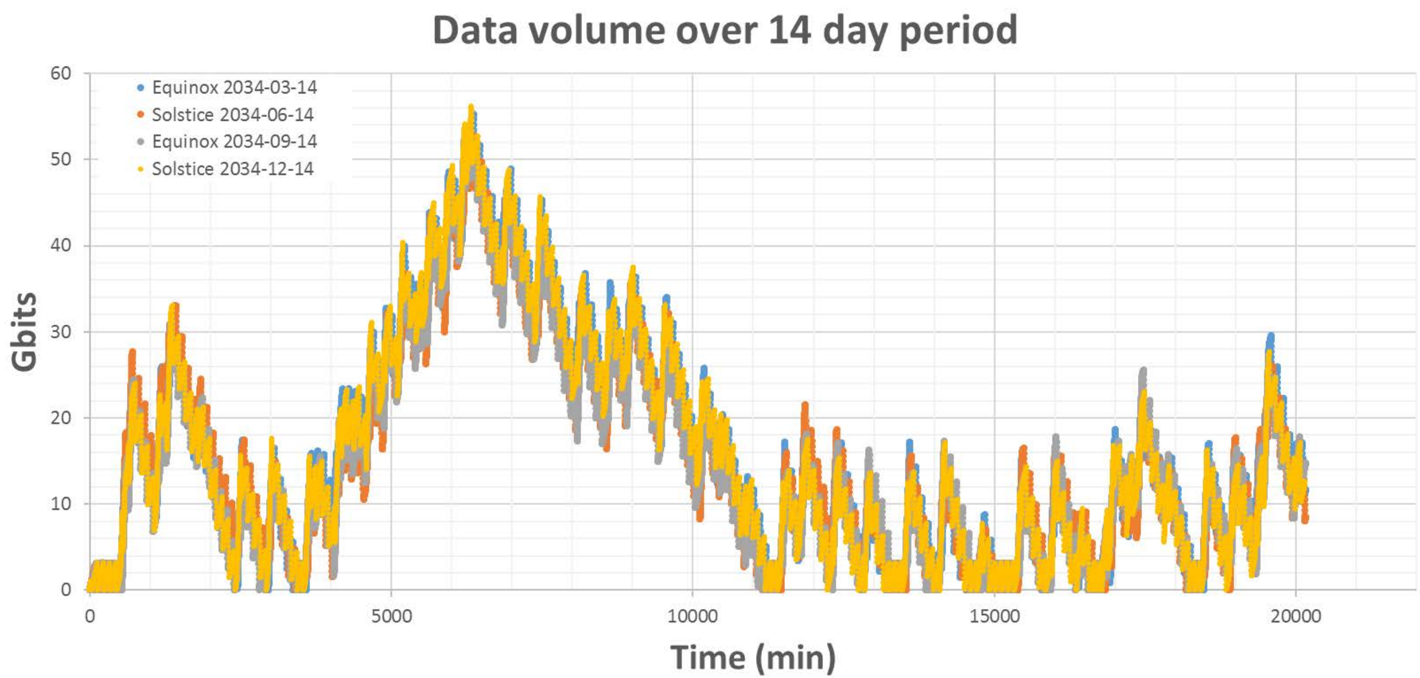
Example of results: No IRT data during survey

- Data volume (Gbits) vs time for 1 ground station (Malindi)
- Converging! = Good
- Max aggregated data volume < 60 Gbit



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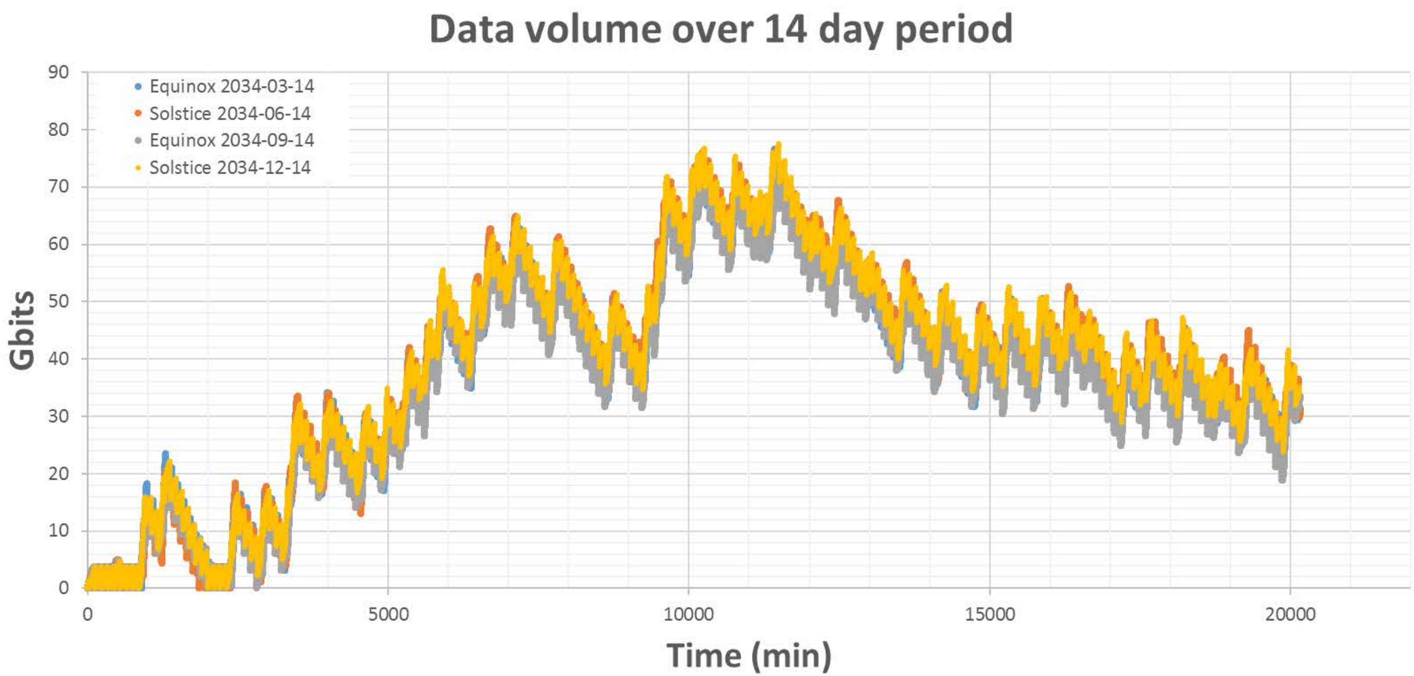
Example of results: 100 kbps IRT data during survey

- Data volume (Gbits) vs time for 1 ground station (Malindi)
- Converging! = Still good but on the limit => not in line with delay on science downlink requirement (2 days)
- Max aggregated data volume < 80 Gbit



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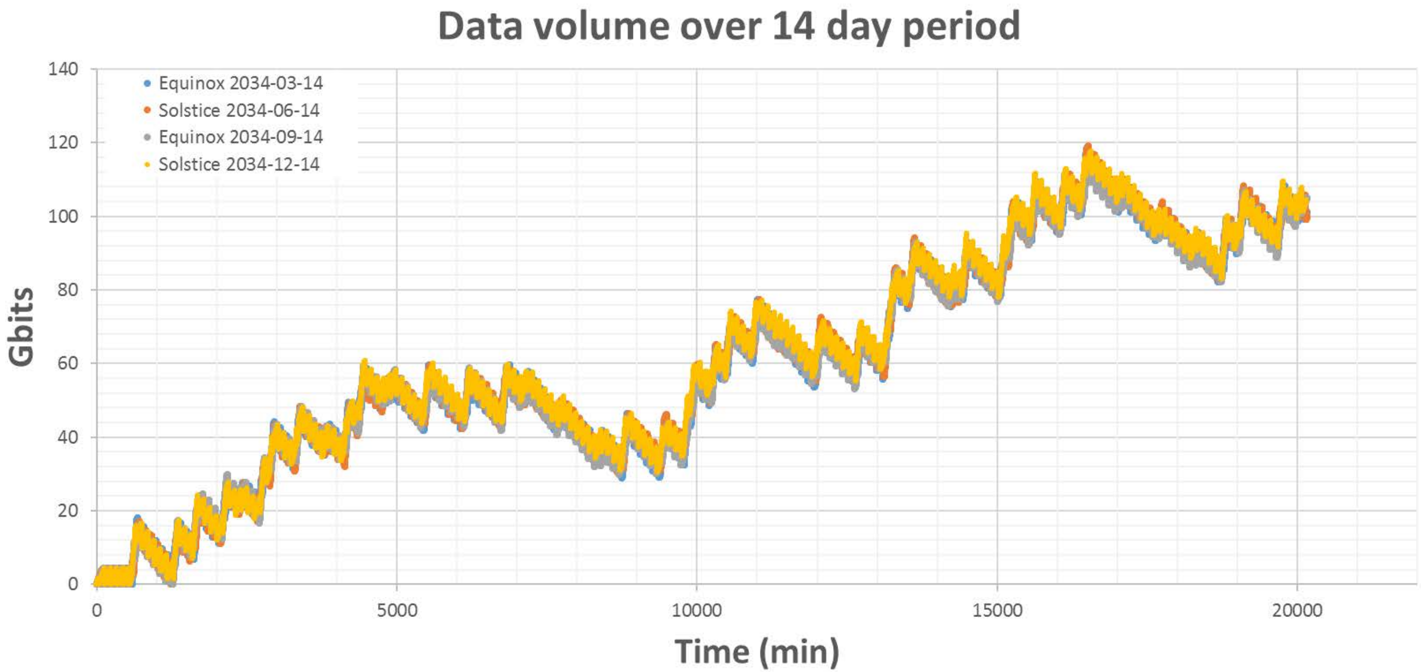
Example of results: 200 kbps IRT data during survey

- Data volume (Gbits) vs time for 1 ground station (Malindi)
- Not longer converging! = Would not work with one ground station
- Limit is somewhere between 100 and 200 kbps



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Observation efficiency

- % of total time
- Point estimate (no statistics yet)
- Missing safe modes and transient losses (e.g. transitions into an out of eclipse)

	Operational efficiency [%]			
	Downtime: only Slew	Downtime: Slew and occultation	Downtime: Slew, SAA and occultation	Downtime: Slew, SAA, occultation and eclipse
Survey	79.2%	79.2%	66.8%	42.28%
Follow up	2.1%	2.1%	1.8%	1.01%
HR	4.0%	3.6%	3.0%	1.74%
LR	12.5%	11.0%	9.3%	6.12%
Downtime	2.2%	4.1%	19.2%	48.85%

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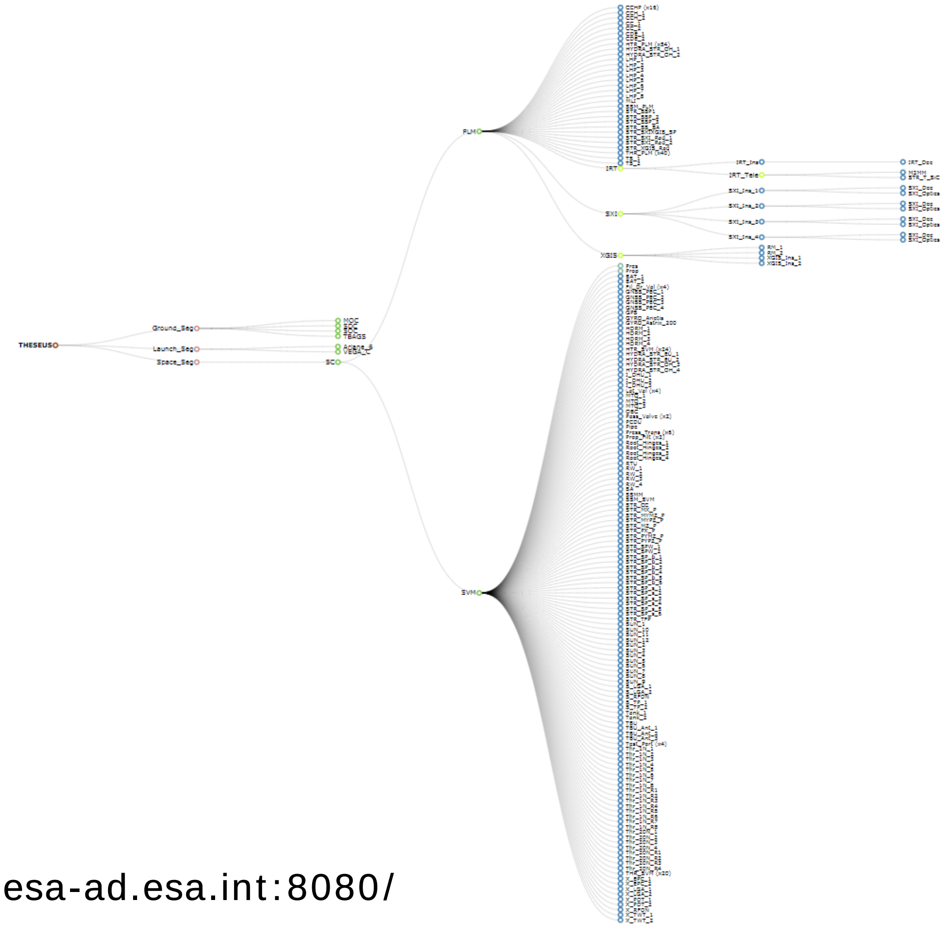
Product Tree



Synoptics Tool:
http://cdf-ocdt2.esa-ad.esa.int:8080/

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System Mass Budget

SVM (Service Module)		
AOGNC		68.38
COM		23.07
CPROP		58.12
DH		36.41
INS		23.28
INS Margin	10%	2.33
MEC		1.48
PWR		111.35
STR		230.81
TC		1.59
Harness	10%	55.68
DRY Mass SVM		**612.48**

PLM (Payload Module)		
AOGNC		2.94
INS		342.48
INS Margin	10%	34.25
MEC		3.60
STR		139.03
TC		88.30
Harness	5%	30.53
DRY Mass PLM		**641.12**

Spacecraft		
DRY mass PLM		641.12
DRY Mass SVM		612.48
Dry Mass		**1253.60**
System Margin	20%	250.72
Dry Mass incl. System Margin		**1504.32**
CPROP Fuel Mass		190.47
CCPROP Fuel Margin	2%	3.81
CPROP Pressurant Mass		2.96
CPROP Pressurant Margin	2%	0.06
Total Wet Mass		**1701.62**
Launch Adapter		95.00
Wet Mass + Adapter		**1796.62**

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System Power Budget

		LAU	SUN	SAFE	SCI	SCI_COM
PLM		273	274	560	570	570
SVM		248	339	411	352	412
Total		520	613	971	922	982
Losses	7%	36	43	68	65	69
Total w/ Losses		557	656	1039	987	1051
Margin	30%	167	197	312	296	315
Total w/ Margin		724	852	1350	1283	1366

NOTES:

- Losses margin per mode is 7% of power consumption
- System margin is 30% of total power consumption incl. losses
- No need to change system state during eclipse (all instruments always ON)
- Additional heating power in case of instrument failure can be sustained at least in Safe Mode

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Mission Baseline

Launch vehicle	VEGA-C (backup Ariane62)
Launch date	2032 (night launch)
Lifetime	Nominal 3 years (consumables for 2 more years)
Orbit	Circular LEO
Altitude	600 km
Inclination	5.4°
Ground stations	Malindi (backup Kourou) VHF SVOM network
Delta-V	225.8 m/s
Re-entry	Controlled re-entry (4 burns)
Mass	Dry mass w/ margin 1504 kg Wet mass 1702 kg Total (wet + adapter) 1697 kg
Dimensions	Launch conf.: 4.23 m x 3.02 m x 2.35 m Deployed conf.: 4.23 m x 4.40 m x 2.35 m
Payload	1x InfraRed Telescope (IRT) 2x X-Gamma-rays Imaging Spectrometer (XGIS) 4x Soft X-ray Imager (SXI) 2x Radiation monitors
Data Handling	OBC, RTU, SSMM (1 Tbit), GNSS

AOCS	4x star trackers 2x gyros (1x coarse / 1x high accuracy) 3x magnetorquers 4x reaction wheels 12x sun sensors
Communications	S-band for TM/TC (128 kbps/4 kbps) - 2x LGA X-band for science data (8.3 Mbps) - 2x LGA VHF for TBU - 3x VHF antenna
Chemical Propulsion	Monopropellant (Hydrazine) blow-down system 8(+8)x 1N thruster 4(+4)x 20N thruster 2x 148 l tanks
Mechanisms	M2 Mirror Focus Mechanism 4x Solar Panel HDRM 4x Solar Panel deployment hinges
Power	Sun-shield + body mounted and 2 deploy. panels (11.07 m² used from max. available 12.61 m²) MPPT and 28V regulated bus 2x Battery modules 6s16p
Structures	Thrust cone, shear and side panels, bottom- and top-panels, and Sun shield on composite sandwich (aluminium honeycomb and CFRP skins)
Thermal Control	Cryocoolers, LHP and heaters active TCS

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Mission Analysis

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Operational orbit requirements and characteristics

Low background radiation → low altitude to minimise South Atlantic anomaly effect

Ground station coverage for alert system → close to equatorial orbit

used for all simulations

Orbital Parameter	Reference value	Possible domain
Altitude (km)	600	535 – 640
Eccentricity (--)	0 (circular)	
Inclination (°)	5.4	0.0 – 6.0
RAAN (°)	Free	

Fine tuning of optimal altitude and inclination to best satisfy mission requirements was not done in the frame of CDF study and it **is left for next study phases**.

Additional Data for Reference Operational Orbit	
Orbital period (min)	96.7
Eclipse duration (min)	33.7 – 35.7
Precession period RAAN (days)	~ 50

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Launcher

Requirements:

- baseline launcher → **Vega-C** (backup → Ariane62)
- baseline **launch at night**

Vega-C data:

- first estimate of performance to reference orbit is ~2400 kg (net payload mass, 20% margin as by Arianespace)
- standard adapter for single launch: 95-120 kg
- launch in 0 deg inclination is TBC by launcher; performance penalty for 550 km altitude circular orbit is considerable (that is why reference orbit is 5.4 deg inclination):
  - 6 deg inclination → 3300 kg net payload
  - 0 deg inclination → 2000 kg net payload

(20% margin to be added)

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Ground stations Coverage

- baseline stations considered for TT&C and science data:
  - Kourou and Malindi
- additional stations for the alert system:
  - same as SVOM mission, but less stations (around 15) actually required due to low inclination of THESEUS operational orbit

Contact times (reference orbit, 5 deg min elevation)	Kourou	Malindi
Minimum communication window [min]	9.1	9.8
Average communication window [min]	10.4	10.7
Average contact time per day [min]	144.9	149.0

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Station keeping

Orbit altitude maintenance strategy: keep the altitude in 540-640 km range with the least deltaV possible.

Available options:

A. let the altitude drift to lower limit and then raise it
B. keep the altitude in a band around the reference altitude (e.g. 590-600 km)
C. raise the initial altitude so that letting the spacecraft drift for 5 years would still result in final altitude within the domain 540-640 km.

Assumptions used:

- cross section for air drag = 11.9 m^2 (average tumbling cross-section with deployed arrays, since attitude is not fixed w.r.t. Earth)
- mission launched in second half of 2032 and lasts 5 years
- 95^{th} percentile of solar activity prediction (N.B.: time frame includes peak of predicted solar cycle)
- 3 sigma dispersion from launcher manual (+/- 15 km in semi-major axis) and launcher target at 600 km altitude

Results:

- least expensive is option A = **initial re-orbit followed by 5 years drift**
- minimum altitude to be able to drift in allowed domain for 5 years = **630 km**
- to raise the initial worst case altitude (585 km) to target altitude (630 km) costs **25 m/s**.

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Re-entry deltaV

Trade-off made with 3-4 burns strategy and 40-80 N thrust. Baseline selected to lower the losses as much as possible:

- 4 burns
- 80 N (BoL of blow down)

Assumptions:

- 1656.5 kg initial s/c mass
- initial orbit altitude at EoL = 630 km (worst case: initial altitude raised, followed by 5th percentile of solar activity, leading to negligible drag)
- inertially fix thrust direction
- simplified thrust and Isp reduction due to system nature (blow down)
- no margin applied on mission analysis side

Results:

- last pericentre altitude = 230 km (minimum possible for AOCS)
- total deltaV = 196.8 m/s (impulsive deltaV is 167.6 m/s)

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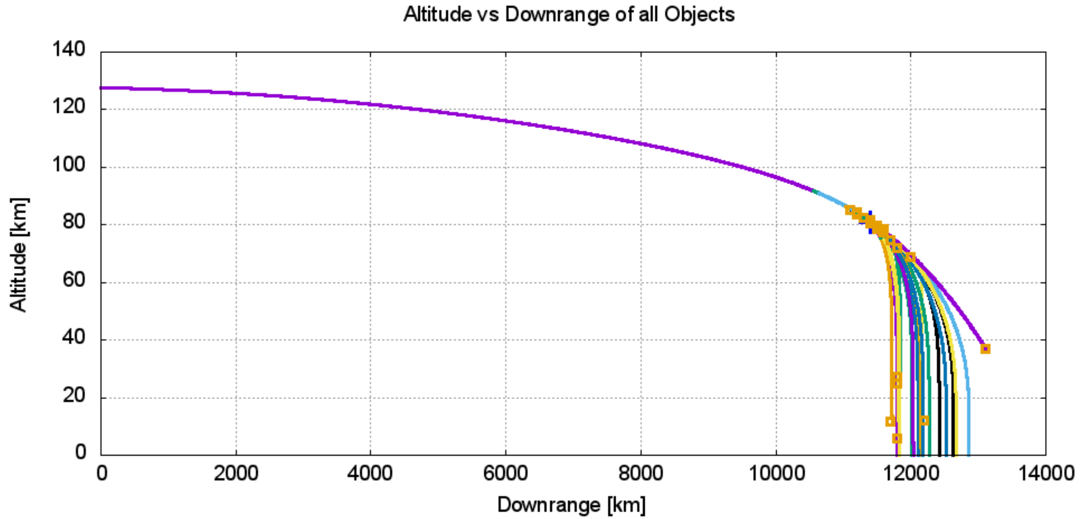
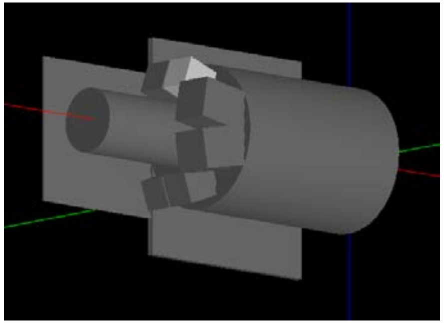
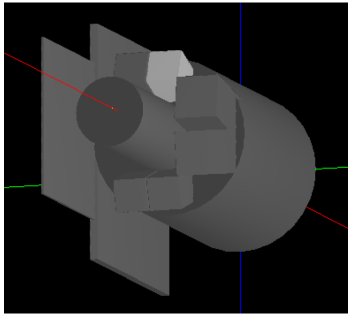
Risk assessment uncontrolled re-entry

- Re-entry 2037-01-01, inclination 5.4 degree, eccentricity 0.001
- Modern break-up scenario:
  - Thermal driven break-up
- Break-up around ~82 km
- 22.1 m^2 casualty area
- 2.6 10^{-4} casualty risk

→ controlled re-entry required







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Risk assessment and reduction options

- Critical payload elements: Optical benches, mirrors, optics.
  - Not all lenses behave equally from a demise point of view and carefully material selection can be considered
  - Benches based on carbon fibre solution are more demisable than SiC based
  - Lowering the amount of monolithic mirrors is a risk reduction
  - Ensuring that optical components remain attached to the instrument is a risk to be addressed later on (in case the reliability of the controlled re-entry would be low).

- Critical SVM components: reaction wheels, tanks.
  - Development of Al based tanks for spacecraft at TRL 3-4. Next phase to be started.
  - Development of demisable reaction wheels at TRL 2-3. Investigation for options without performance reduction is on-going.

- Assessment needs to be refined w.r.t. the maturation of the payloads.

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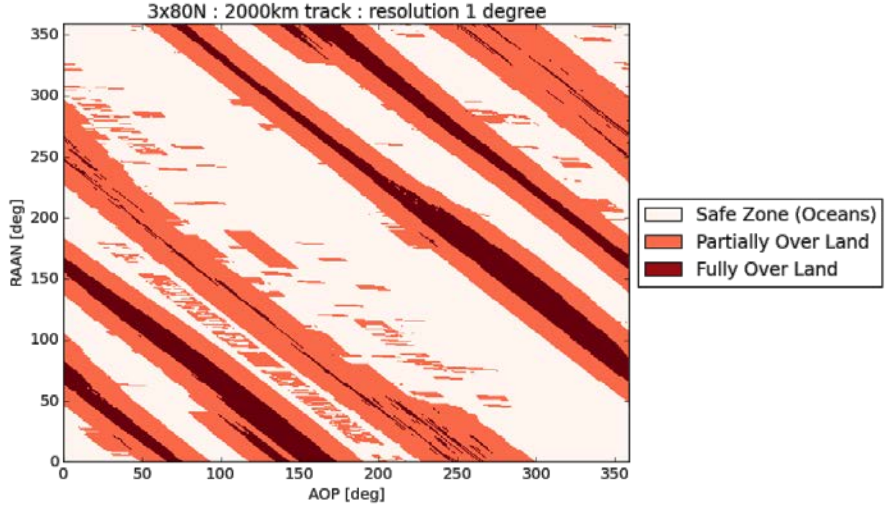
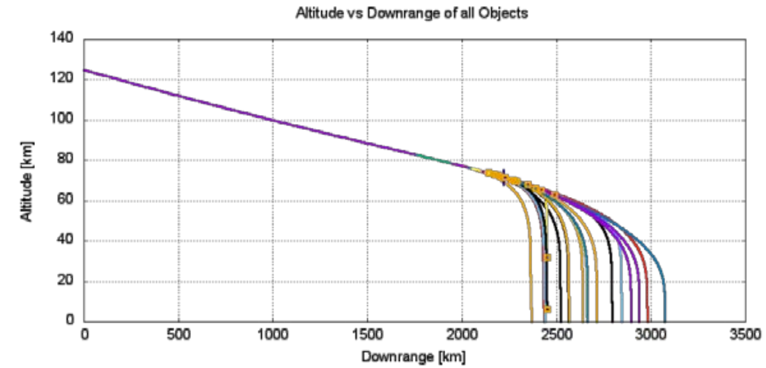
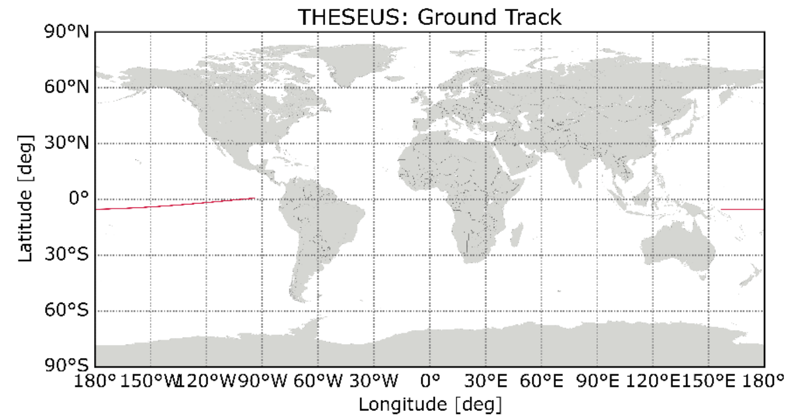
Controlled re-entry – safe footprint 2000km







- Avoiding land and economical exclusion zones

- Zones outside of the SPOUA can be found
- E.g. 'safe zone' of RAAN=3º ArgPer= 0-51º

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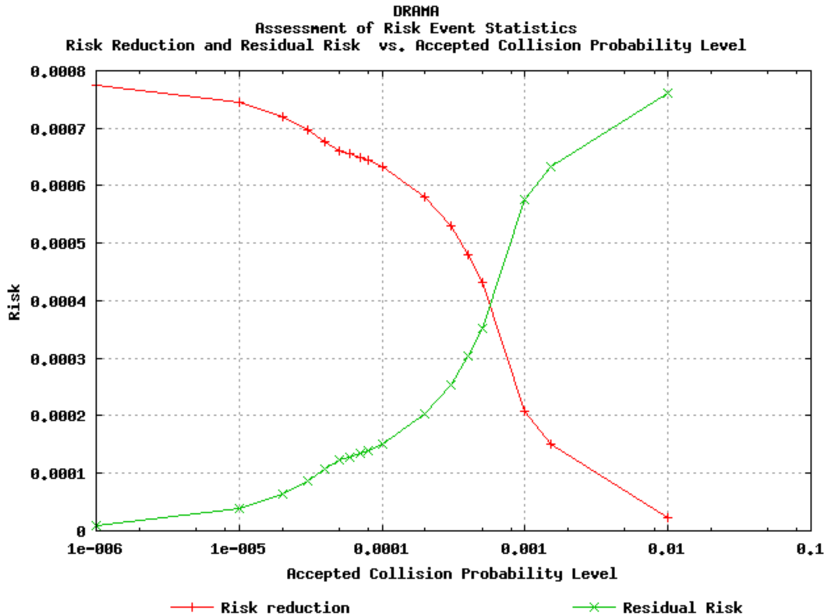
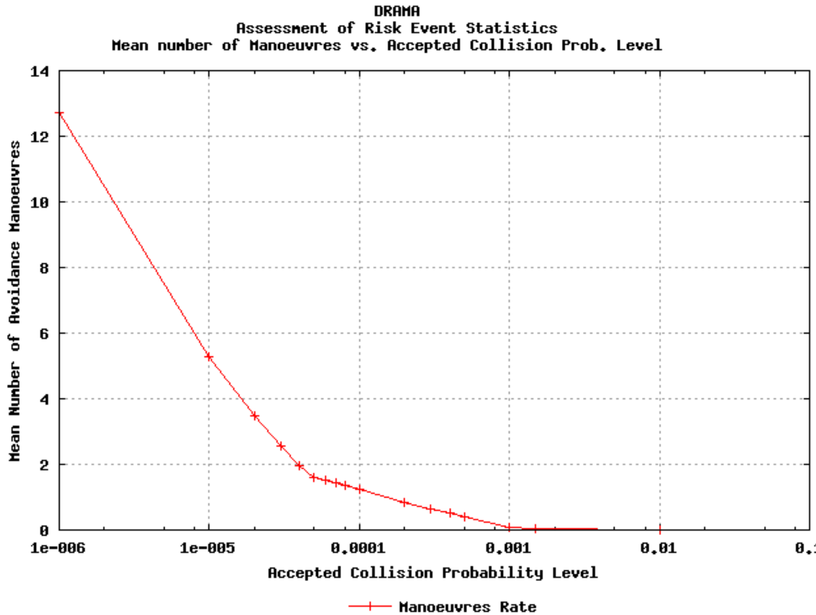
Assessment of collision avoidance deltaV

- In 2032, Annual Collision Probability (ACP) of $7.84*10^{-4}$
- To reduce >90% of risk, ACPL of $2*10^{-5}$ → 3.6 manoeuvres per year → 5.8m/s deltaV per year (risk reduction by 100)
- With available deltaV with current tanks → possible to reduce 83% of risk (ACPL of $6*10^{-5}$) → 1.5 manoeuvres per year → 0.64m/s delta V per year (risk reduction by 100)





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DeltaV budget

	DeltaV [m/s]	Margin [%] (to be applied applied)
Collision avoidance	4	0
Launcher dispersion correction	0	--
Orbit altitude maintenance	25	5
Re-entry	196.8	5
Total	225.8	--

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Survey mode boresight pointing

Requirements:

- maximise GRBs detectable with possibility of follow-up
- acceptable impact on spacecraft design

Analysed strategies (with 1 year simulations, covering all possible geometries of s/c, Earth, Sun):

- Ecliptic North pointing, best case from systems point of view (solar aspect angle between bounds with no periodic evolution)
- Earth poles pointing, best case from Earth occultations point of view (solar aspect angle kept in smaller domain with seasonal pole switching)

Trade-off results:

- **Ecliptic North pointing is baseline** (more beneficial for spacecraft)
- possibility to vary the survey mode pointing strategy to be assessed in next phases (how much spacecraft design can cope with? how much beneficial could different strategy be?)

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Observation inefficiencies (1)

Orbit related:

- s/c in **South Atlantic anomaly → 16.1 % of the time** (conservative assumptions for radiation level: flux for particles with energy >20MeV and threshold at 1 p+/cm2/s)
- s/c in **eclipse → 36.3 % of the time** (penumbra entry/exit considered)

Pointing related:

- Moon occultation → neglected (since no observation close to the ecliptic plane)
- Earth occultation (10 km limb) → presented as graph and table in next slides
- NOTE: the occultations are however not affecting the science in the same way across the FoV of XGIS. **XGIS is less sensitive closer to the edges of its FoV** (for the moment this aspect was however **neglected** for lack of detailed information)

Trade-off performed on instrument arrangement (to define overall FoV):

- adjusted XGIS and SXI modules with respect to proposal

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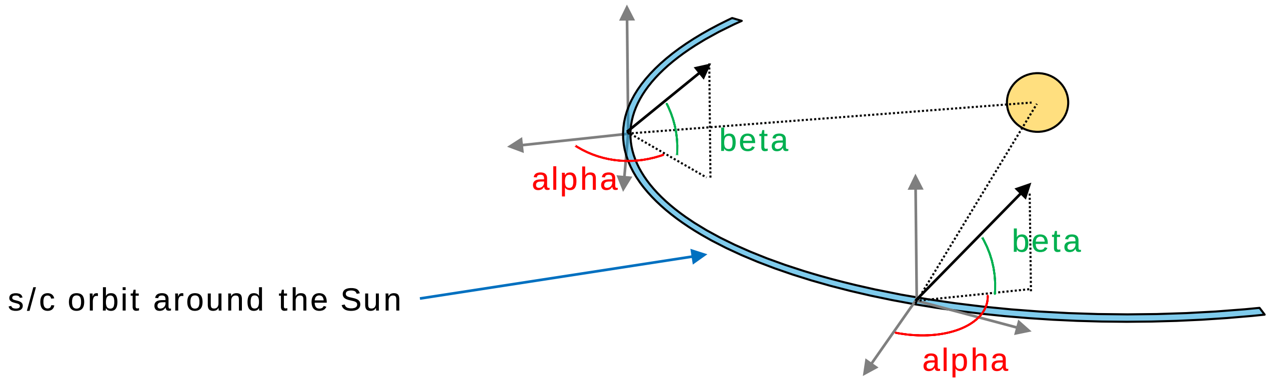
Rotating frame used

Rotating frame (with alpha and beta to define direction) so that
FoV is fixed in survey mode in this frame



alpha = 180, beta = 0 → Sun direction
alpha = 180 → 90 – beta = Pitch angle towards the Sun
alpha = 0 → 90 – beta = Pitch angle away from the Sun

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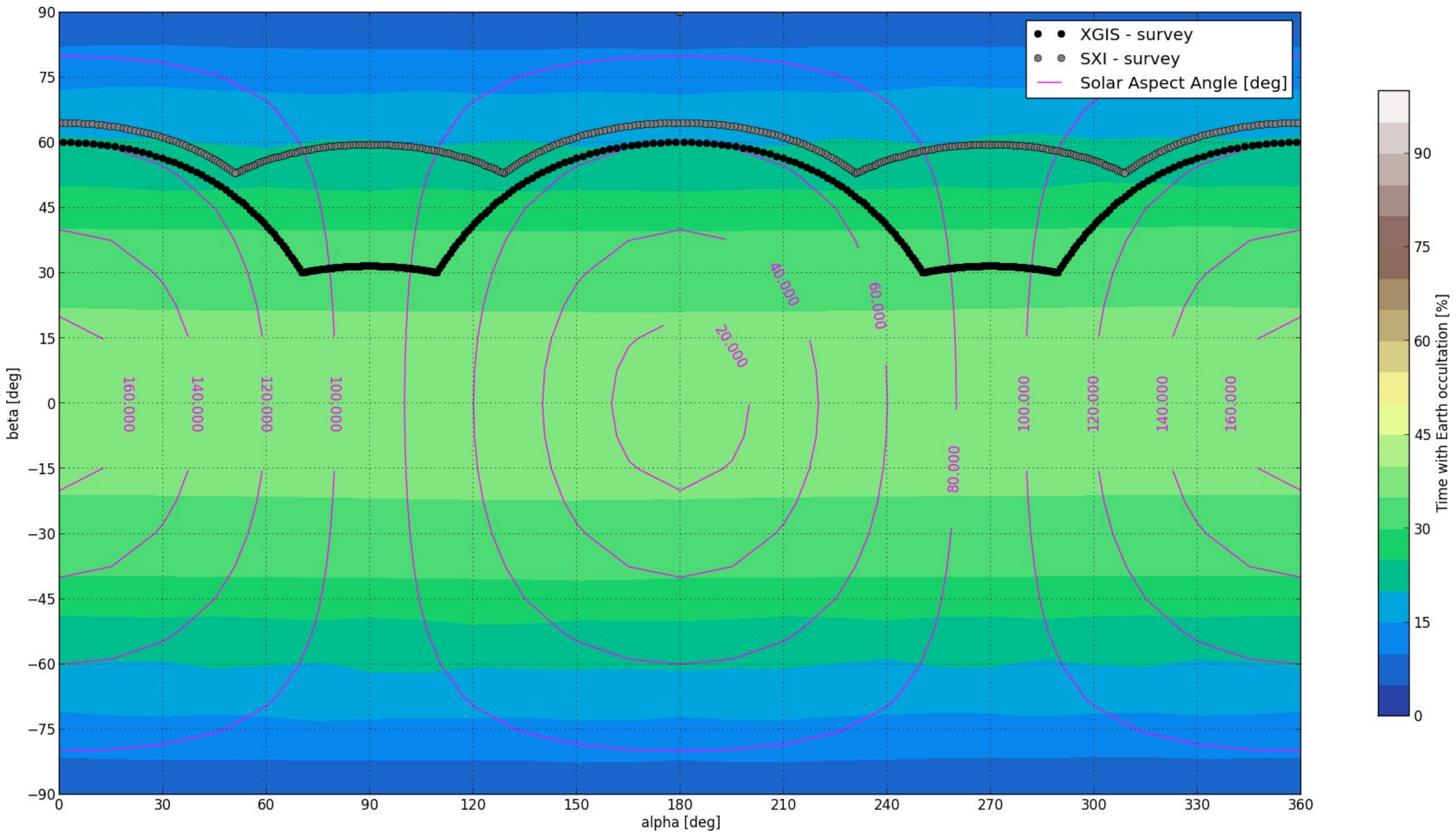
Observation inefficiencies (2)



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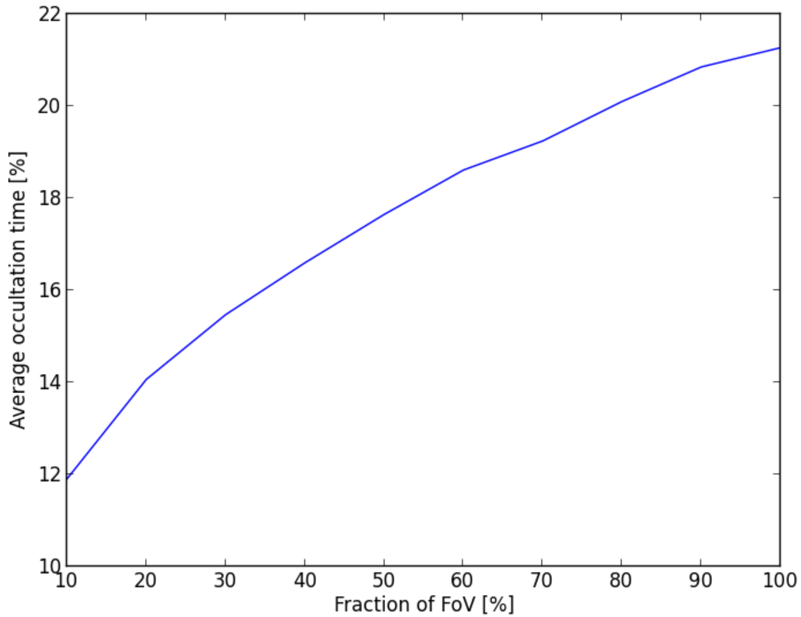
Observation inefficiencies (3)

Integrating the Earth occultation inefficiency over the FoVs

Instrument	XGIS	SXI
Average inefficiency in FoV during survey mode (due to Earth occultation) [%]	21.9	16.1



The trend is obtained reducing the FoV area of XGIS while keeping fixed its shape (rectangular).

Given a GRB located inside a certain fraction of the XGIS FoV, the figure provides the average probability that the GRB is occulted by the Earth.

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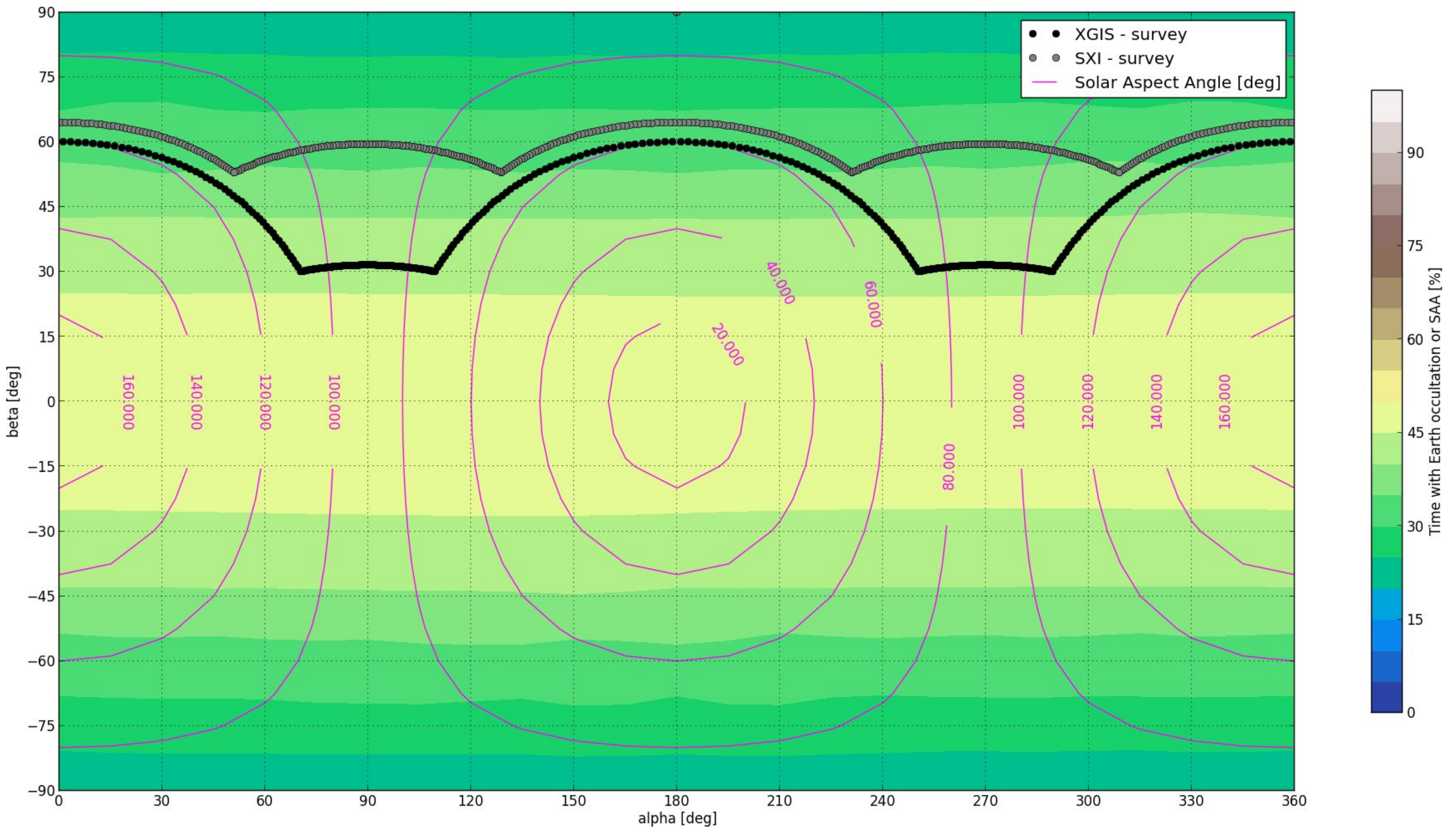
Observation inefficiencies overlapping (1)
SAA or Earth occultation



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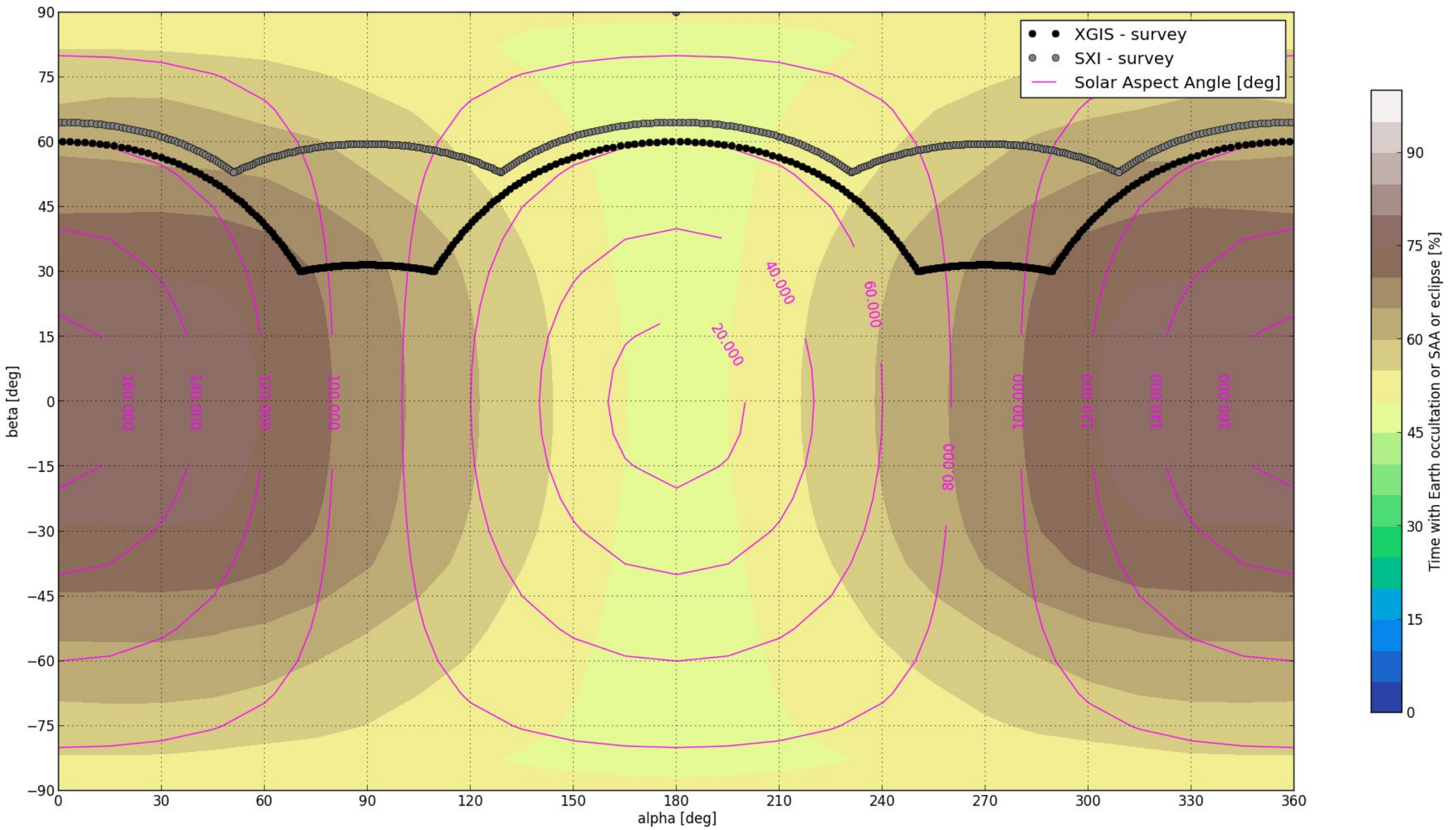
Observation inefficiencies overlapping (2)
SAA or eclipse or Earth occultation



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Observation inefficiencies overlapping (3)

Orbit related:

- SAA or eclipse = 46.6 % (SAA and eclipse = 5.8 %)

Overall:

Instrument	XGIS	SXI
Average inefficiency in FoV during survey mode (Earth occultation or SAA) [%]	34.3	29.4
Average inefficiency in FoV during survey mode (Earth occultation or SAA or eclipse) [%]	58.9	54.8

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Observation inefficiencies overlapping (4)

- The South Atlantic anomaly is not linked to the pointing directly and its effect is an homogenous decrease of the efficiency for all pointing directions
- The brown patches (~70% inefficiency) are appearing when eclipses are considered and are centred in 0 deg beta and 0 alpha, which corresponds to pointing in the anti-Sun direction: the closer the pointing is to the anti-Sun direction the more eclipses and Earth occultation are not overlapping, with worst case being full addition of the two effects to the overall inefficiency.

Room for further optimisation / trade-off in:

- pointing strategy
- orbit inclination and altitude selection (taking into account always the launcher performance)

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Radiation

Requirements

• The mission shall minimise the trapped proton exposure (in particular > 100 MeV)	Experience shows the detector to be primarily sensitive to noise induced by radiation
• Radiation sensitive instruments (XGIS) shall be equipped with a radiation monitor	The monitor provides feedback on the radiation environment to allow for mitigation of noise and detector damage.
• The radiation monitor shall reliably detect the flux of protons (including > 100 MeV)	To provide noise mitigation and on-board instrument protection
• The radiation monitor system shall have a wide solid angle coverage (omnidirectional)	The environment is highly anisotropic, requiring an almost isotropic radiation detection

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Design drivers

- *In terms of the Radiation Environment the main design drivers are:*
  - *Minimise trapped proton exposure (detector noise & degradation)*
    - *Orbit selection low inclination low altitude → skirting South Atlantic Anomaly*
    - *Radiation monitor for environment measurements*
  - *Minimise radiation dose*
    - *low inclination, low altitude is a very benign environment*
  - *Anisotropy of the environment*
    - *Trapped protons are mirroring and confined to travelling in directions normal to the local magnetic field*

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Assumptions and trade-offs

- *Assumptions:*
  - *The radiation belt models are accurate – this is not the case for these orbits. Data from other missions required to mitigate uncertainty and **RENELLA R&D outcome will support the models validation***
- *Trade-off between different orbits and radiation belt models:*
  - *Baseline: Inclination of 5.4 deg and Altitude of 600 km*
  - *Equatorial: Inclination of 0 deg and Altitude of 600 km*
  - *Low altitude: Inclination of 5.4 deg and Altitude of 535 km*
  - *High altitude: Inclination of 5.4 deg and Altitude of 640 km*

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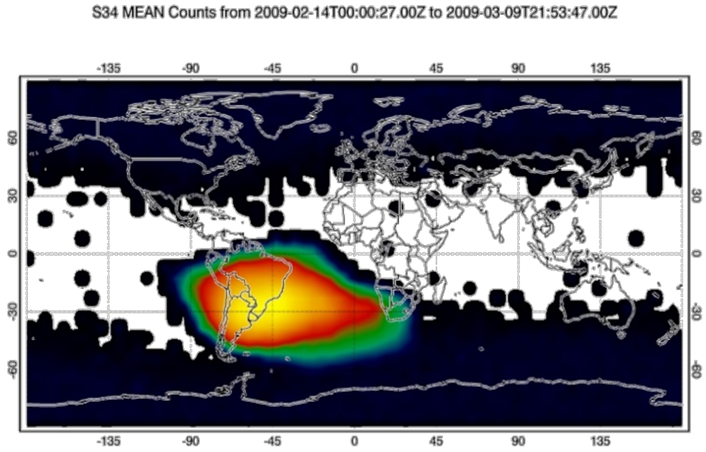
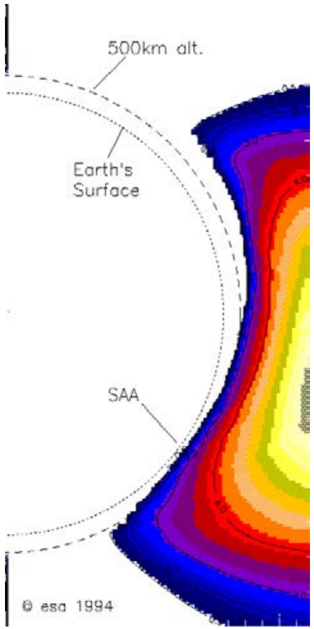
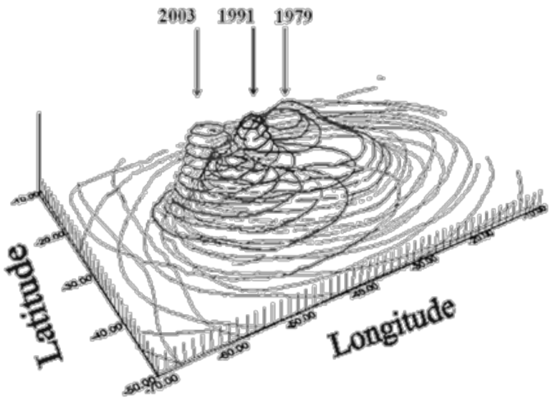
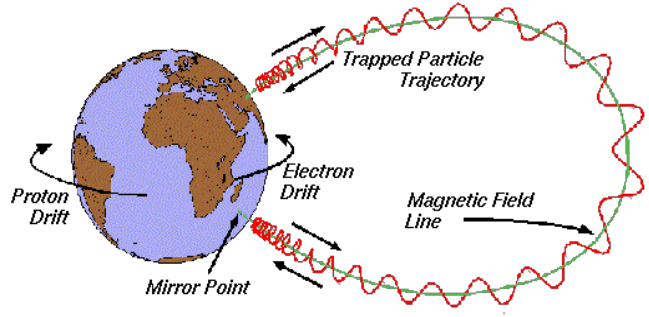
The South Atlantic Anomaly - Geography

- Origins: Offset & Tilt of magnetic field
- Protons up to 400 MeV
- Anisotropic distribution
- Evolution:
  - Solar cycle
  - Drift West & North









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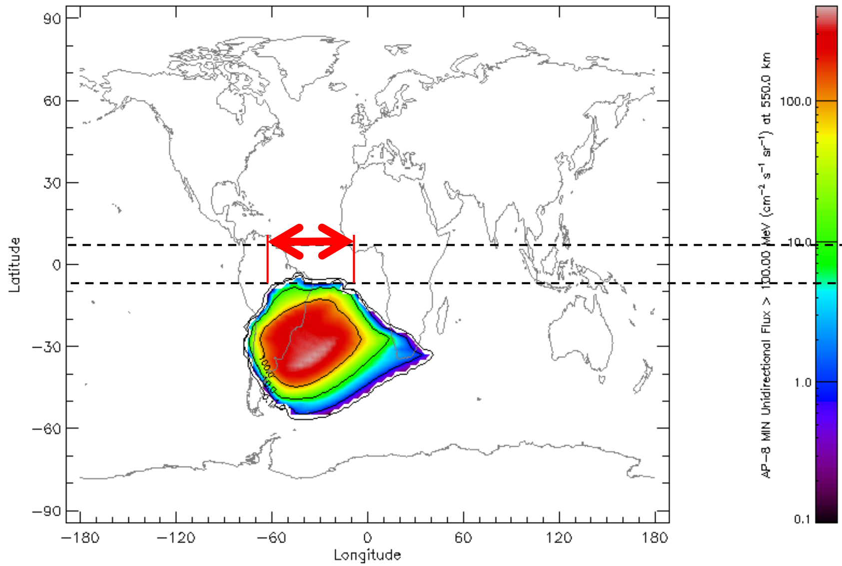
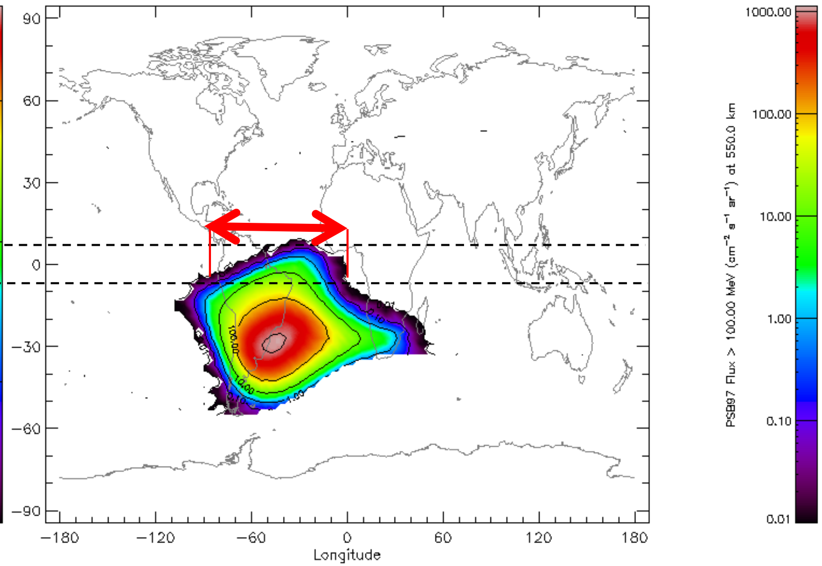
South Atlantic Anomaly - Models

AP-8 Model



SAMPEX '97 Model



Colour scales are (slightly) different

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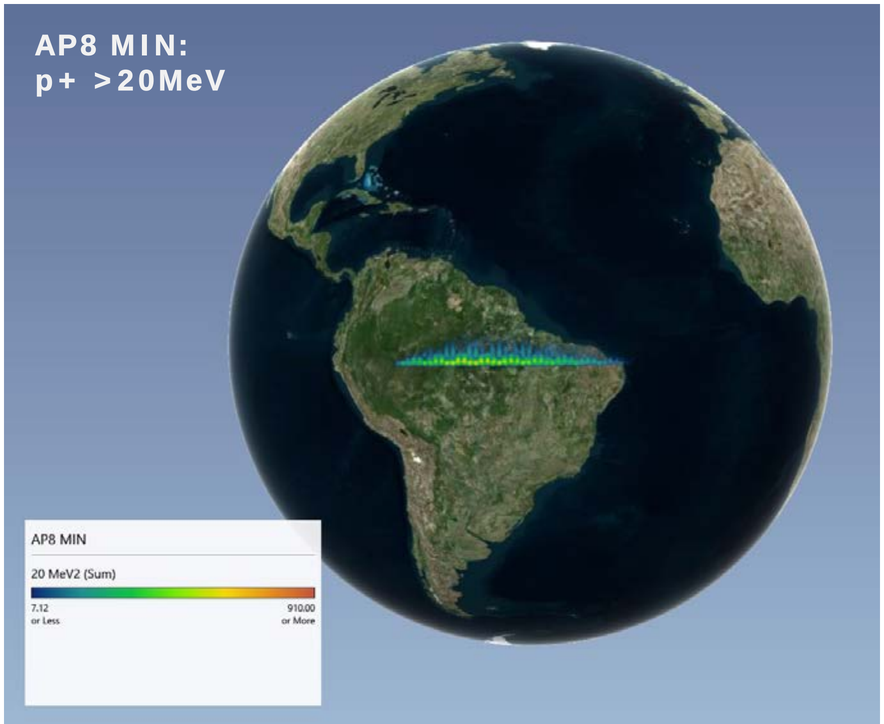
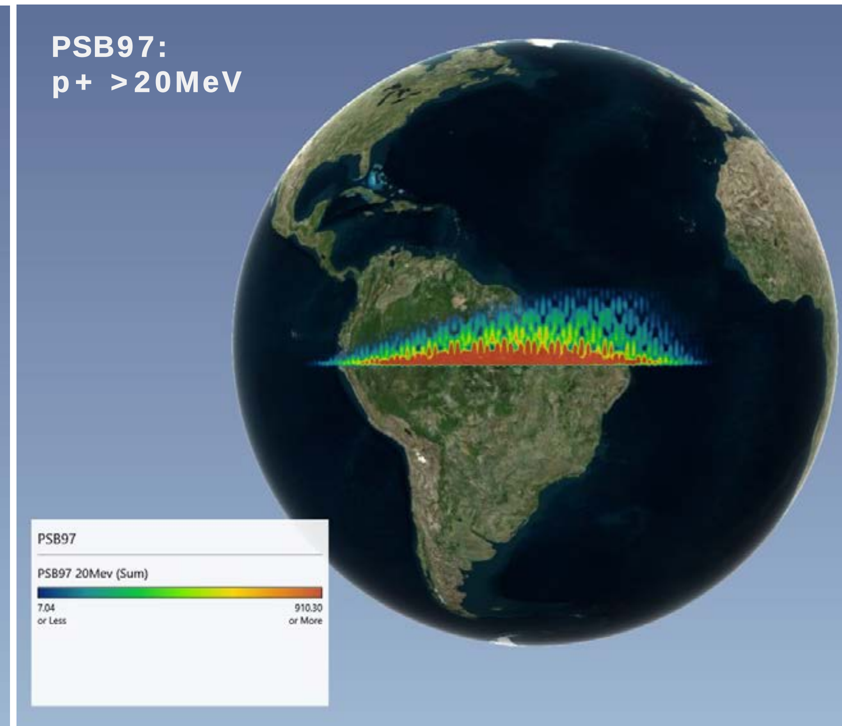
Flux along the orbit for the Baseline orbit





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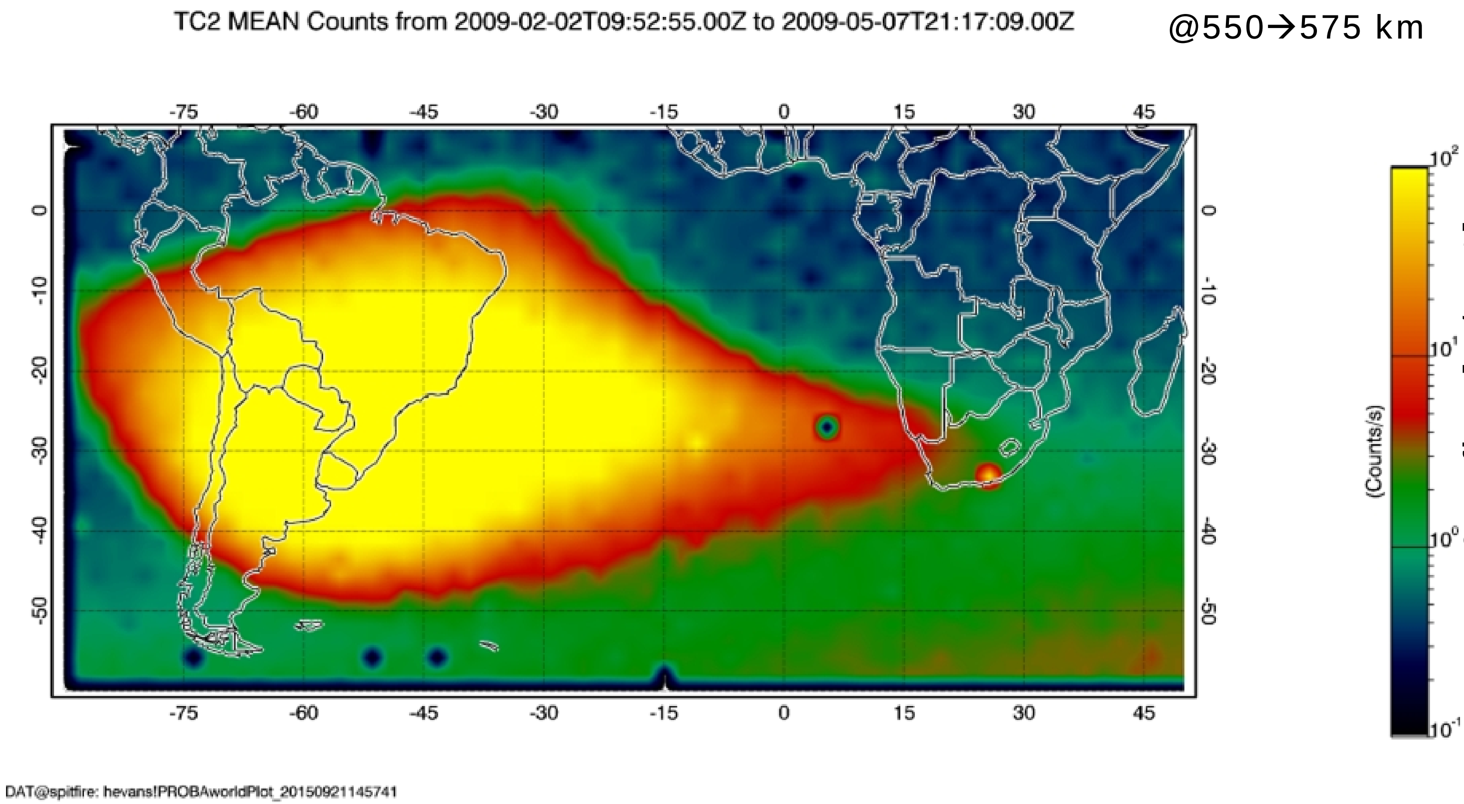
South Atlantic Anomaly – PROBA1 data

@550→575 km

~50 MeV p+
Pseudo Omnidirectional



×13 to flux [#/cm²]

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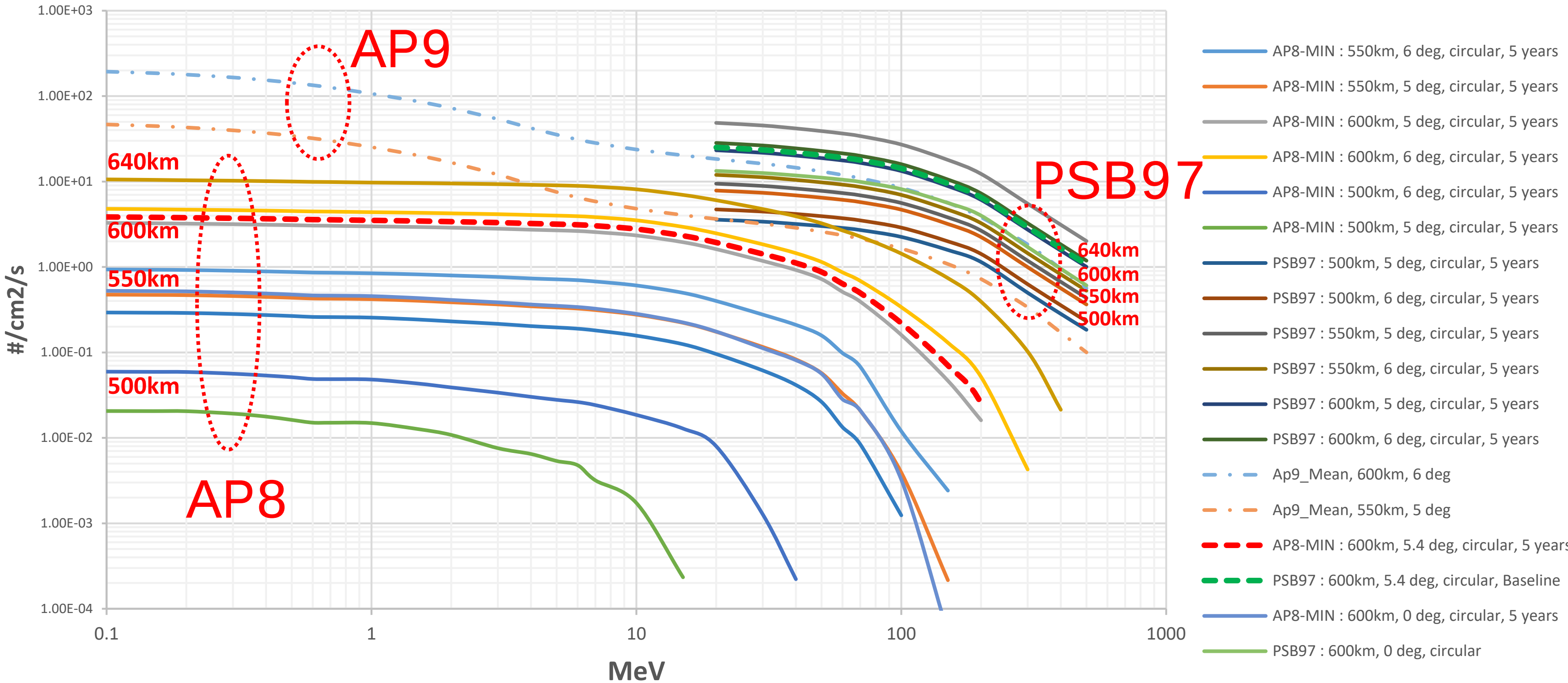
Environmental Models Comparison: Average Integral Flux



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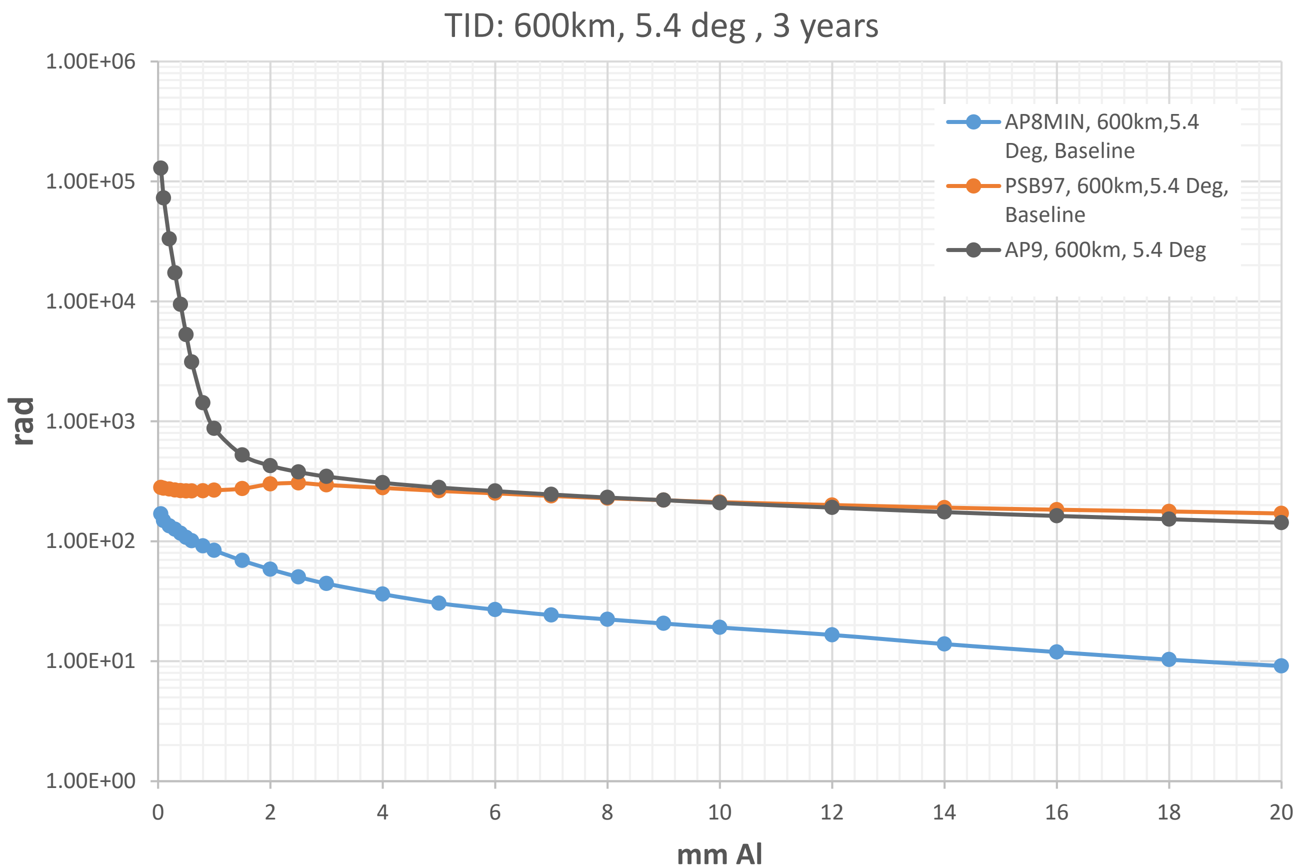
Environmental Models Comparison: TID Dose-Depth Curve



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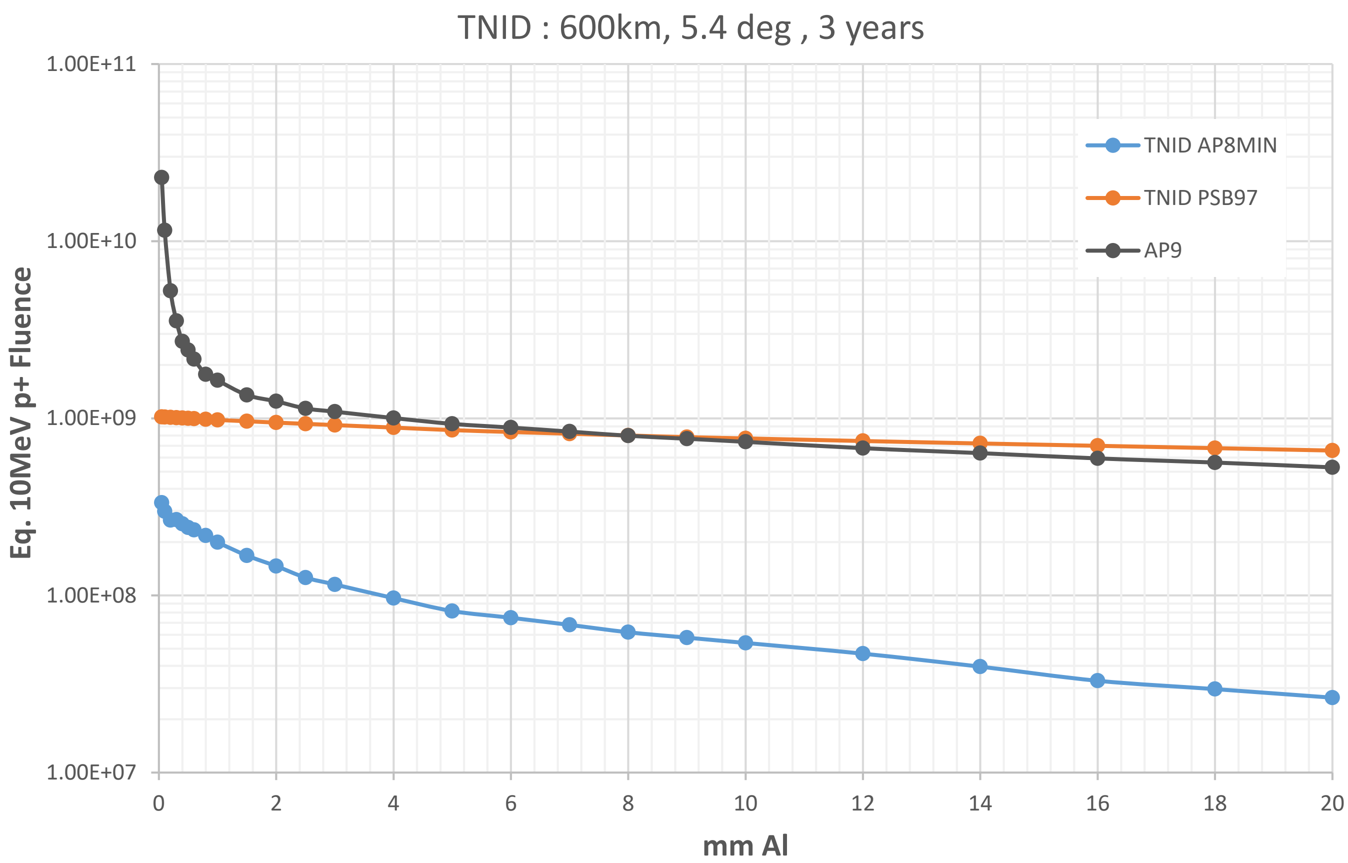
Environmental Models Comparison: TNID Dose-Depth Curve



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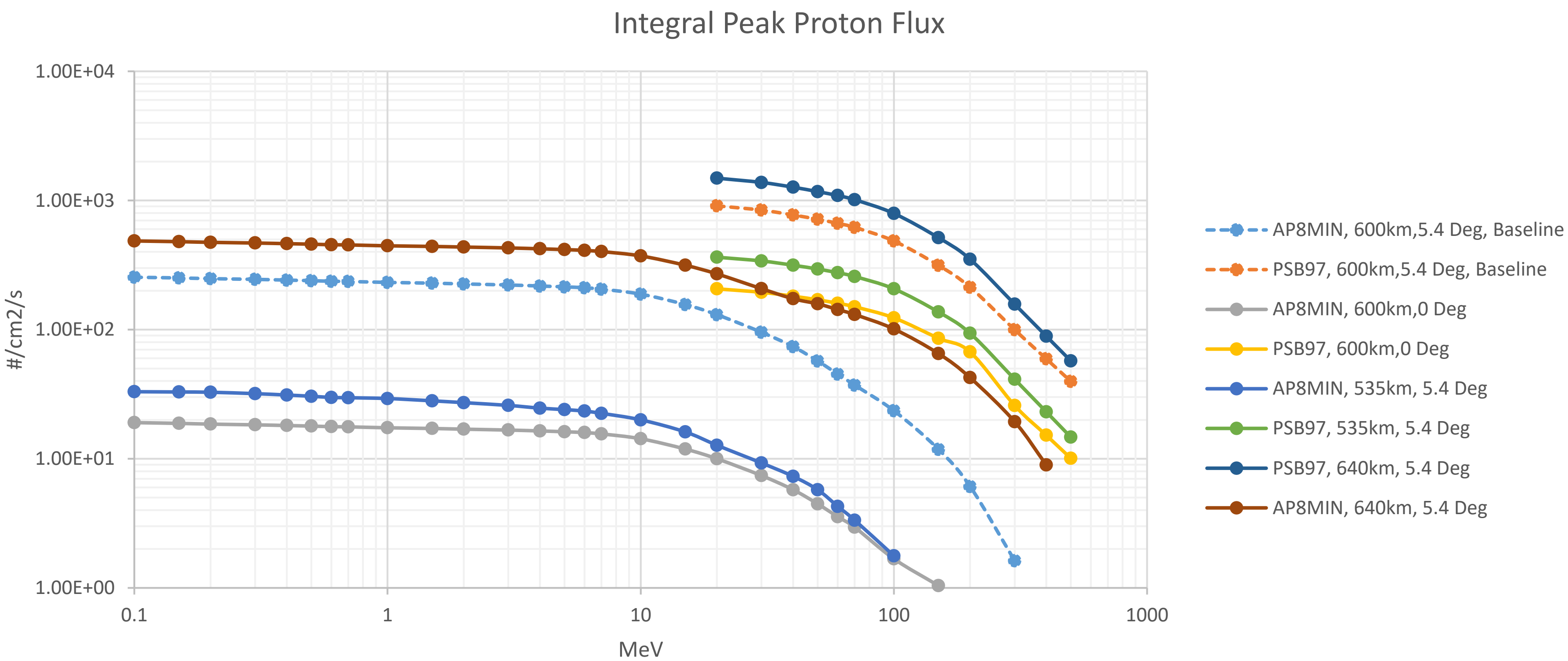
Environmental Models Comparison: Int. Peak Proton Flux



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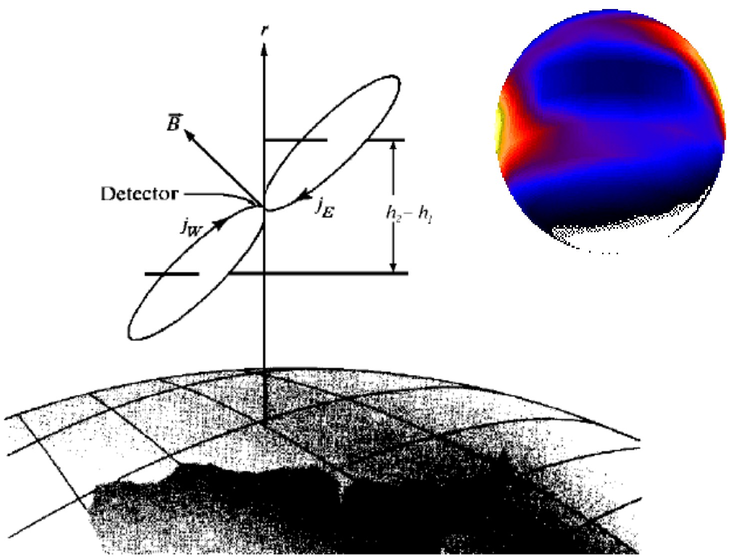
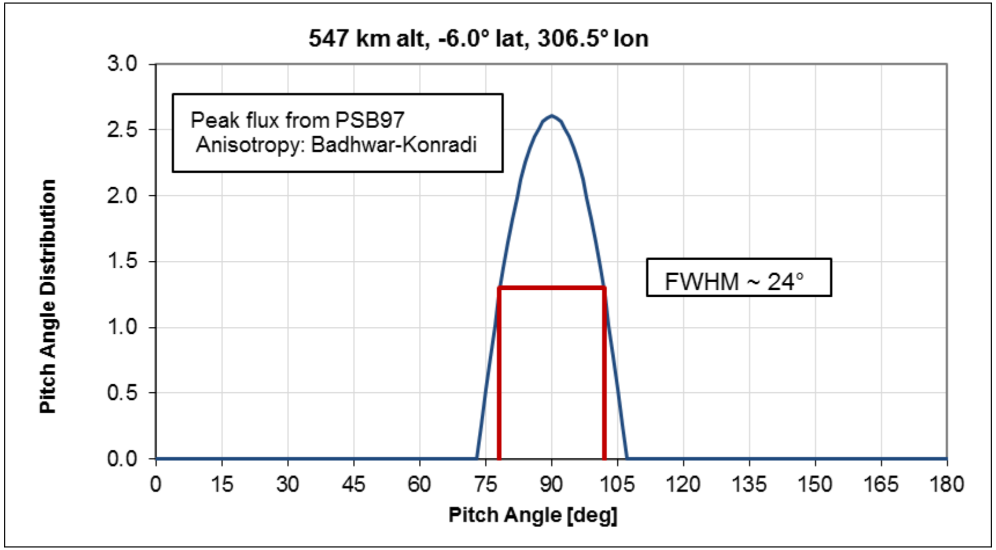
Anisotropy

1. Mirroring (pitch angle) distribution
2. East-West effect





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Exposure time for the Baseline orbit

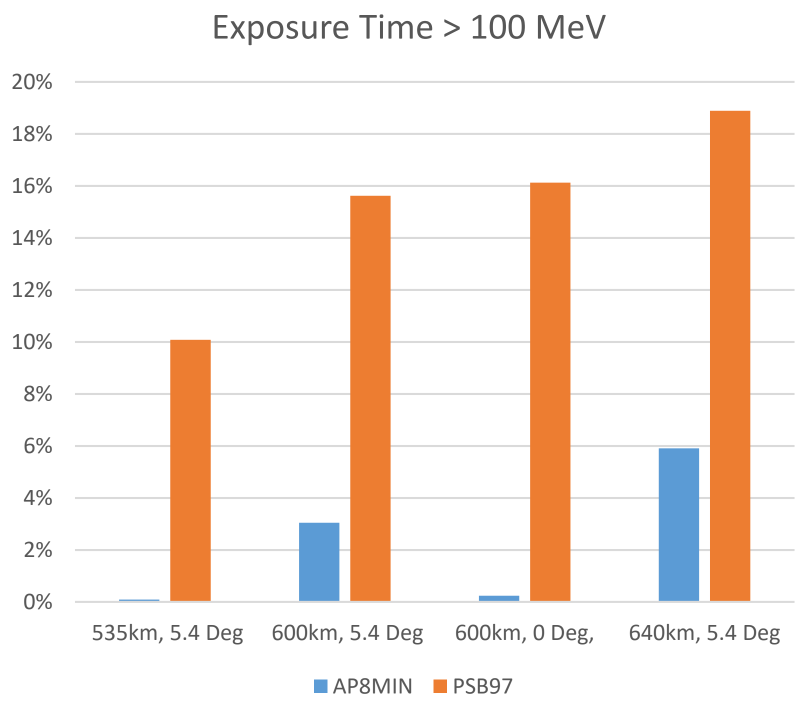
AP8MIN, 600km,5.4 Deg, Baseline

Energy (MeV)	Total exposure (hr)	Mission segment 1 Exposure time (hr)	Mission segment 1 Orbit fraction
0.1	2431.16	2431.16	0.0555
0.15	2431.16	2431.16	0.0555
0.2	2431.16	2431.16	0.0555
0.3	2424.64	2424.64	0.0554
0.4	2413.78	2413.78	0.0551
0.5	2400.74	2400.74	0.0548
0.6	2394.23	2394.23	0.0547
0.7	2394.23	2394.23	0.0547
1	2394.23	2394.23	0.0547
1.5	2379.02	2379.02	0.0543
2	2350.77	2350.77	0.0537
3	2313.84	2313.84	0.0528
4	2305.15	2305.15	0.0526
5	2281.25	2281.25	0.0521
6	2281.25	2281.25	0.0521
7	2270.39	2270.39	0.0518
10	2233.45	2233.45	0.051
15	2196.52	2196.52	0.0501
20	2142.2	2142.2	0.0489
30	2024.88	2024.88	0.0462
40	1979.26	1979.26	0.0452
50	1846.73	1846.73	0.0422
60	1757.65	1757.65	0.0401
70	1720.71	1720.71	0.0393
100	1333.99	1333.99	0.0305
150	736.52	736.52	0.0168
200	449.73	449.73	0.0103
300	36.93	36.93	0.0008
400	0	0	0

PSB97, 600km,5.4 Deg, Baseline

Energy (MeV)	Total exposure (hr)	Mission segment 1 Exposure time (hr)	Mission segment 1 Orbit fraction
20	7087.08	7087.08	0.1618
30	7058.84	7058.84	0.1612
40	7037.11	7037.11	0.1607
50	7006.7	7006.7	0.16
60	6991.49	6991.49	0.1596
70	6948.04	6948.04	0.1586
100	6841.58	6841.58	0.1562
150	6626.49	6626.49	0.1513
200	6441.82	6441.82	0.1471
300	5863.9	5863.9	0.1339
400	5433.72	5433.72	0.1241
500	4920.98	4920.98	0.1124

Threshold: 1 p+ / cm^2 / s



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Summary

- Strong **anisotropy** in the SAA at low altitudes →
  - Directions from which no radiation is expected
- Radiation belt **models not very accurate** in these regions
    - high flux gradients over small geographic distances →
- Exposure **increases** with altitude and with inclination;
- Doses to be expected are **low** enough for astronaut EVAs;
  - ISS has a harsher radiation environment

- Primary radiation concern is **detector noise**
- **RENELLA R&D** will provide a first validation of the models
- The **Radiation Monitor** needed because of the environment uncertainty (SAA)

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Thermal

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Requirements and Design Drivers

- **1 x IRT**: FPA and FEE dissipation of 0.6 W @ 95 K
  - Based on THESEUS ESA 13 Septembre 2018 HT DG SB Version140918 and internal discussion
- **4 x SXI**: 4 x CCDs total dissipation of 3.3 W (incl. parasitic) @ -65 °C
  - Based on THS-LU-SXI-TN-0002 SXI thermal calculations
- **2 x XGIS**: PCBs total dissipation of 45 W @ 10 °C
  - Based on XGIS power thermal considerations
- **Orbit and attitude**
  - Inclination: 5.4°
  - Altitude: 600 km

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Assumptions

- Temperature margin: 20 K
- Radiator coating: SSM Teflon silvered 5mil (EOL: eps = 0.81, alp = 0.15)
- Radiator efficiency: 0.9
- Radiator trimming margin: 25%

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Equipment list

Technology	Description	Image	TRL	Euro tech. (Y / N)
Kapton foil Heaters	Standard element: to apply electrical heat to actively control temperature of a component		9	Y
Thermistors	Standard element: to measure the temperature at temperature reference point of each component but also in other relevant positions.		9	Y
Paints and coatings	Standard element: to control of radiative heat exchange. E.g. black paints on electrical units or white paints on antennae.		9	Y / N
Washers	Standard element: thermal decoupling between units or units and structure.		9	Y
Thermal fillers	Standard element: to increase conductive heat transfer between units and structure.	 Source: SGL Group	9	Y

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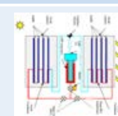
Equipment list

Technology	Description	Image	TRL	Euro tech. (Y / N)
MLI	(Multi-Layer Insulation) standard element: for thermal insulation.		9	Y / N
SSM	(Second-Surface Mirror) standard element: applied to dedicated radiator surfaces.		9	Y / N
Heat pipes	High heat transfer from heat source to heat sink. Different working fluids depending on temp. range.	 	9	Y
Thermal Straps	Aluminum, copper, graphite thermal straps available. Increased heat transfer from heat source to heat sink.	 	9	Y
Cryocooler	See dedicated slide		6	Y
East-West coupled radiators	See dedicated slide		6	Y

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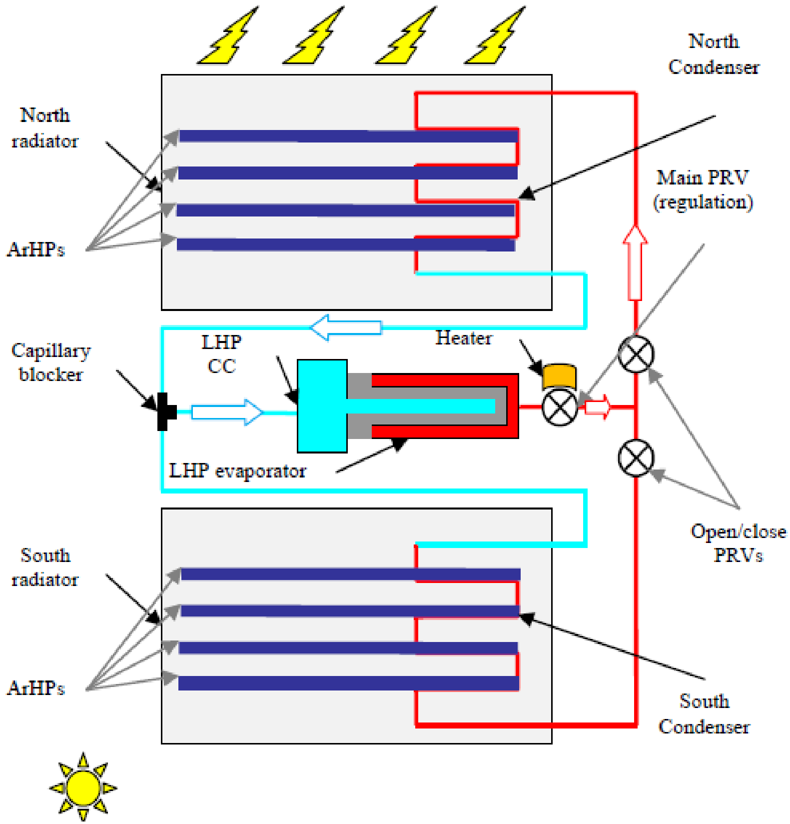
Equipment list

- **Coupled Radiators with LNA-LHP*:**
  - Efficiently reject heat according to the environment (i.e. view to cold space always available)
  - Heat collection: aluminium base plate
  - Heat transport: single propylene LHPs with pressure regulating valve (PRV)
  - Heat rejection: 2 radiators with embedded propylene Arterial Heat Pipes (ArHPs)
  - Developed by IberEspacio
  - Ground tested: TRL 6



* Prado-Montes et al. 2016

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Baseline Design: Overview

PLM

- **IRT:**
  - FPA+FEE and Optics cooled using double-stage cryocooler at 95 K and 160 K (embarked in PLM).
  - Cryocooler is connected to radiators (-Z-Y/-Z+Y) using 2 LHPs (ammonia).
  - Possible to decouple by switching-off the LHP.
- **SXI:**
  - Coupled radiators East-West.
  - Both radiators (-Y/+Y) are coupled with 2 LHPs (propylene).
  - Possible to use the most favourable radiator to reject heat.
- **XGIS:**
  - Connected to radiator (-Z) using 16 HPs directly mounted on the surface.

SVM

- Passive thermal design
- Use of heaters, thermal doublers or spreaders
- For P/L E-Units and SVM sub-systems, mounted on shear panels or directly on radiators (-Z-Y/-Z+Y).

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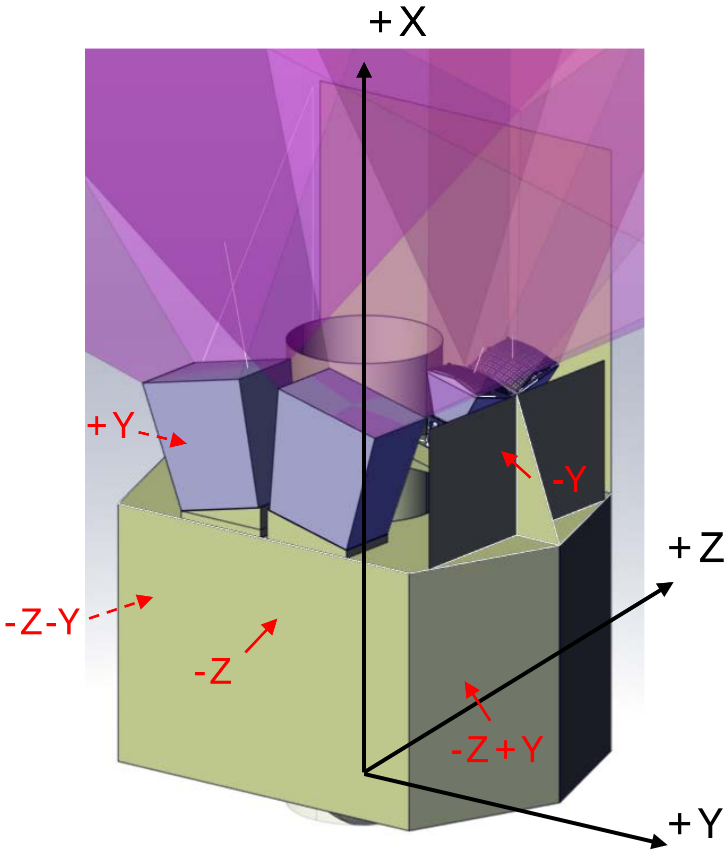
Baseline Design: Radiators

- Summary of the radiator surface:

Unit	Radiator	Area (m²)	Area with margins (m²)
IRT	-Z-Y/-Z+Y	1.8	2.3
SXI	-Y/+Y	1.6	2.0
XGIS	-Z	2.3	2.9
PLM		5.7	7.2
SVM	-Z-Y/-Z+Y	1.4	1.8
TOTAL		**7.2**	**9.0**



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Baseline Design: Heater power

- **LAU**: Launch Mode, all units are non-operating.
- **SUN**: Sun Acquisition Mode, all payload units are non-operating.
- **SAFE1**: Safe Mode 1, IRT fails, the rest is operating.
- **SAFE2**: Safe Mode 2, 1 out of 4 SXI fails, the rest is operating.
- **SAFE3**: Safe Mode 3, 1 out of 2 XGIS fails, the rest is operating.
- **SCI**: Science Mode, normal operating cold case.
- **SCI-COM**: Science Mode, normal operating cold case + data transmission.

Required heater power (W) (margin **20%**, not applied):

Unit	LAU	SUN	SAFE1	SAFE2	SAFE3	SCI	SCI-COM
IRT	7.3	7.3	7.3	0.0	0.0	0.0	0.0
SXI	26.8	26.8	0.0	6.7	0.0	0.0	0.0
XGIS	238.4	238.4	194.2	194.2	216.3	194.2	194.2
PLM	272.5	272.5	201.5	200.9	216.3	194.2	194.2
SVM	139.5	114.1	47.6	47.6	47.6	52.8	35.9
TOTAL	**412.1**	**386.6**	**249.2**	**248.6**	**264.0**	**247.1**	**230.1**

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Mass budget

Element	Mass (kg or kg/m²)	Quantity (items or m²)	Mass (kg)	Margin (%)	Total Mass (kg)
Cryo cooler	7.3	2	14.6	20%	17.5
Cryo cooler harness	1	2	2.0	20%	2.4
Cryo drive electronics	7	2	14.0	20%	16.8
SSM PLM	0.50	7.2	3.6	20%	4.3
SSM SVM	0.50	1.8	0.9	20%	1.1
Heaters PLM	0.01	54.0	0.8	20%	0.9
Heaters SVM	0.01	24.0	0.3	20%	0.4
Thermistors PLM	0.005	40	0.2	20%	0.2
Thermistors SVM	0.005	20	0.1	20%	0.1
MLI	0.4	19.4	7.7	20%	9.3
Thermal Strap	0.25	2	0.5	20%	0.60
Loop Heat Pipe	2.7	8	21.6	20%	25.9
Heat Pipe	0.54	16	8.6	20%	10.4
TOTAL MASS (kg)	**-**	**-**	**74.9**	**-**	**89.9**

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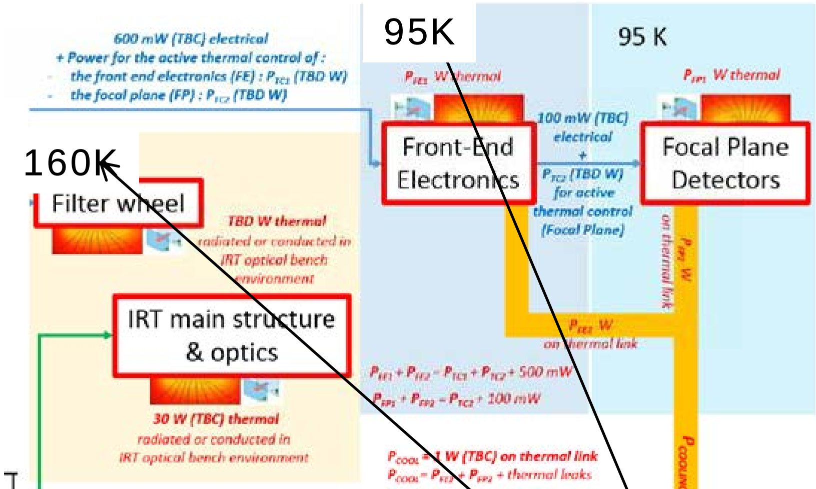
30-50K Double Stage Pulse-Tube Cooler

- 1W @62.5K and 3W@144K at 50W input power@20°C rejection – data provided by supplier
- Cooling power budget: +100% cryogenic systems margin at both stages with 100W input
- Cooler is oversized but is robust against changes in detector and optics
- Oversizing also allows longer thermal straps for a more flexible cryocooler accommodation.

- FEE at 120 K requires calibrated thermal shunt with closed loop temperature control. Current assumption is to have it at 95 K, same temperature as FPA.



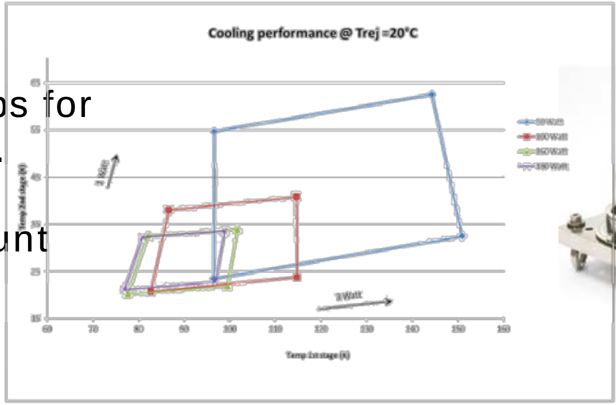
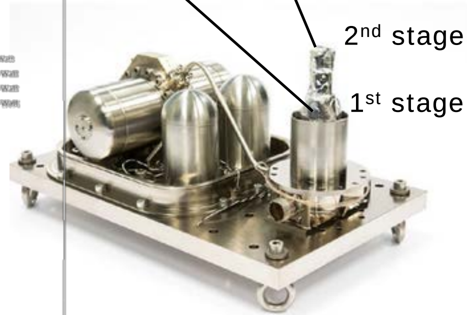


Figure 6 – Cooling performance results of SNR0001 for different input powers at 20°C rejection temperature and 58.5Hz driving frequency



THALES

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IRT Telescope Transient Response

Assumptions:

- 45 kg; SiC 690 J/kgK
- Polished surface ε0.1 α0.14
- Flat disk 0.7m diameter = $0.385m^2$
- Parasitic Coupling to PLM = 0.1 W/K
- PLM at constant +20C
- No view factor to deep space while exposed to Earth, due to baffling

- Steady-State Cases:

Hot Case (Total Earth Flux 18.5 W) = 206 C -> Transient conditions

Cold Case (PLM at -30C) = -68 C , Heater Power of 27 W to keep at -33C (240K), with no parasitic heat load from the PLM

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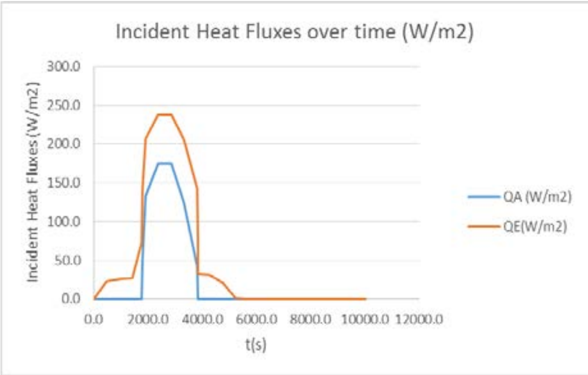
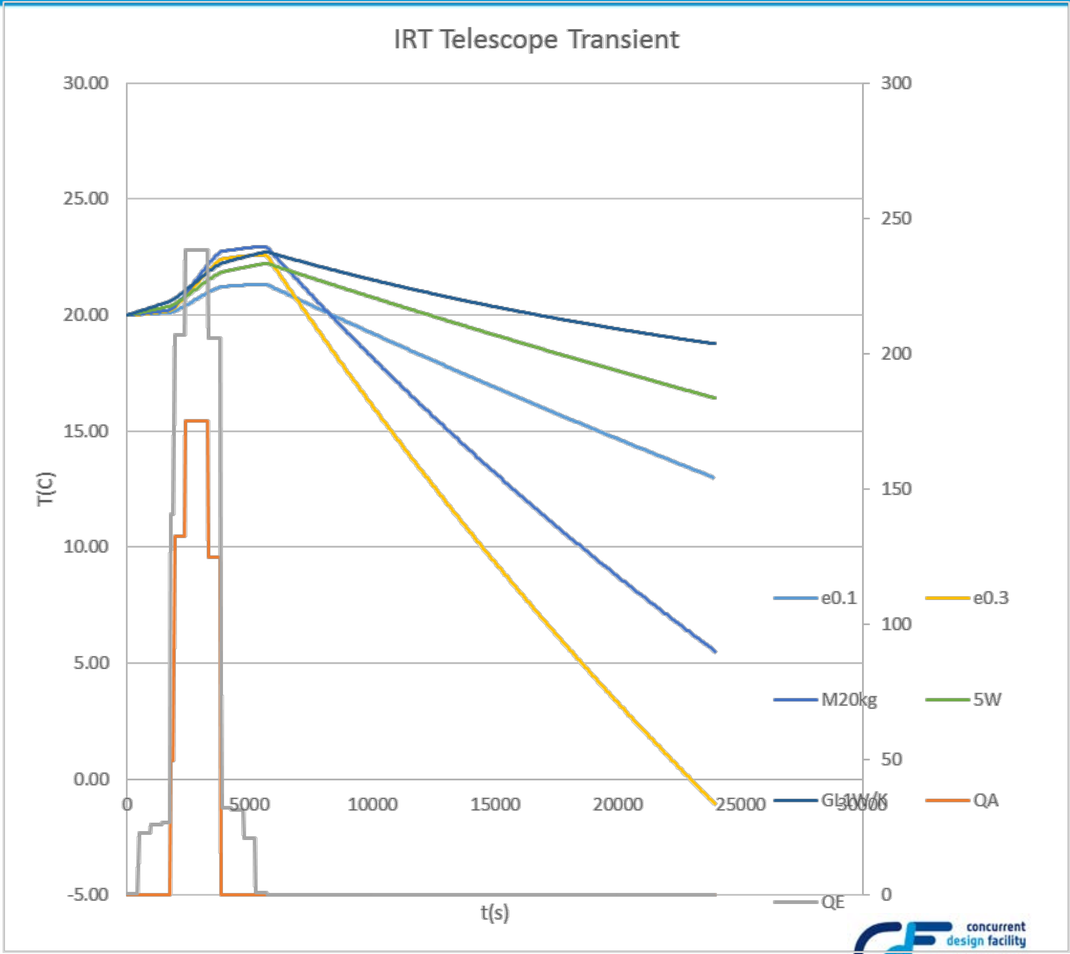
IRT Telescope Transient Response

- Heat Flux Profile considered



- Assumes the IRT telescope is fully occulted by the Earth
- Instant slew to deep space (VF=1) considered after earth transit
- Parameters varied:
  - Nominal case, M45kg, a0.14 e0.1, PLM coupling 0.1W/K, 0W dissipation
  - e0.3
  - 5 W dissipation (Star tracker)
  - Mass 20 kg
  - GL 1.0 W/K to PLM



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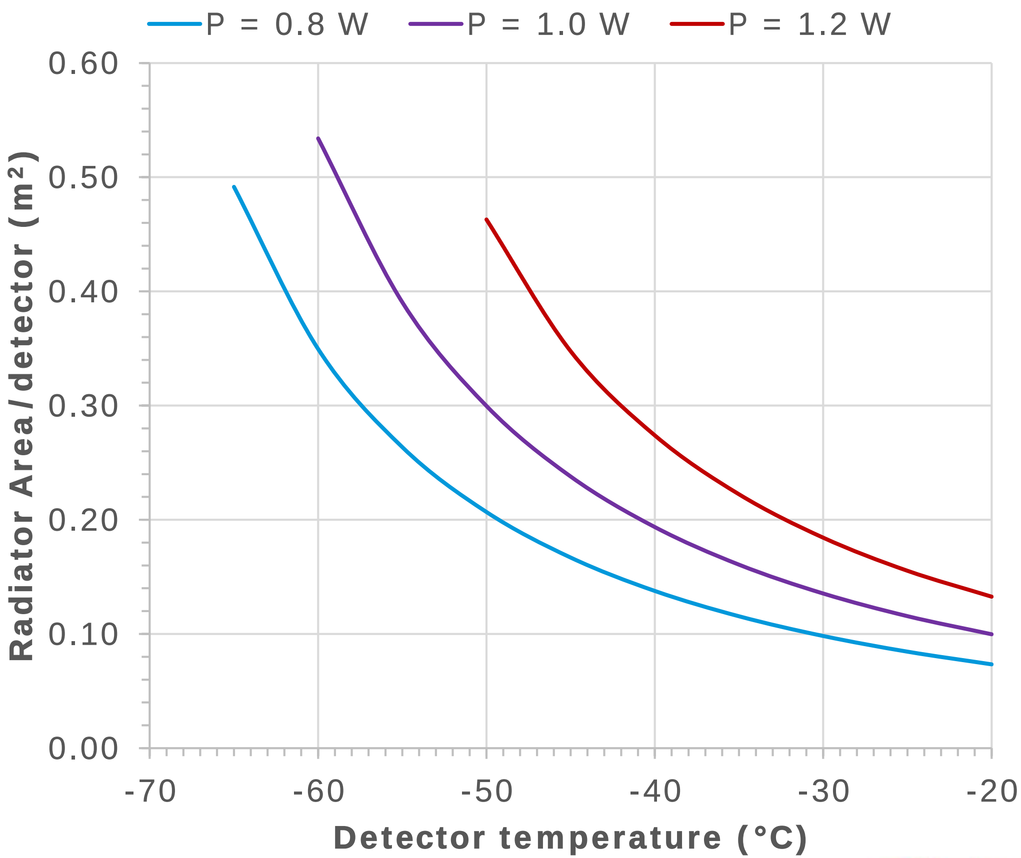
Option: Higher SXI detector temperature

- If the detector operating temperature was increased, the necessary radiator area could be significantly decreased.
- **Baseline**: -65 °C (4 x 0.8 W) -> Area: 2 m^2 (4 x 0.5 m^2)
- **Option**: -20 °C (4 x 0.8 W) -> Area: 0.36 m^2 (4 x 0.09 m^2)



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Structures

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Requirements and Design Drivers

- Telescope Target Mass < 60 Kg.

- Telescope and S/C Eigenfrequency requirements dictated by launcher:
  - Launcher either Ariane 6-2 or Vega C.
  - Eigenfrequencies >10 Hz (lateral), 20 Hz (longitudinal).

- Overall S/C Mass Requirement Not Defined.

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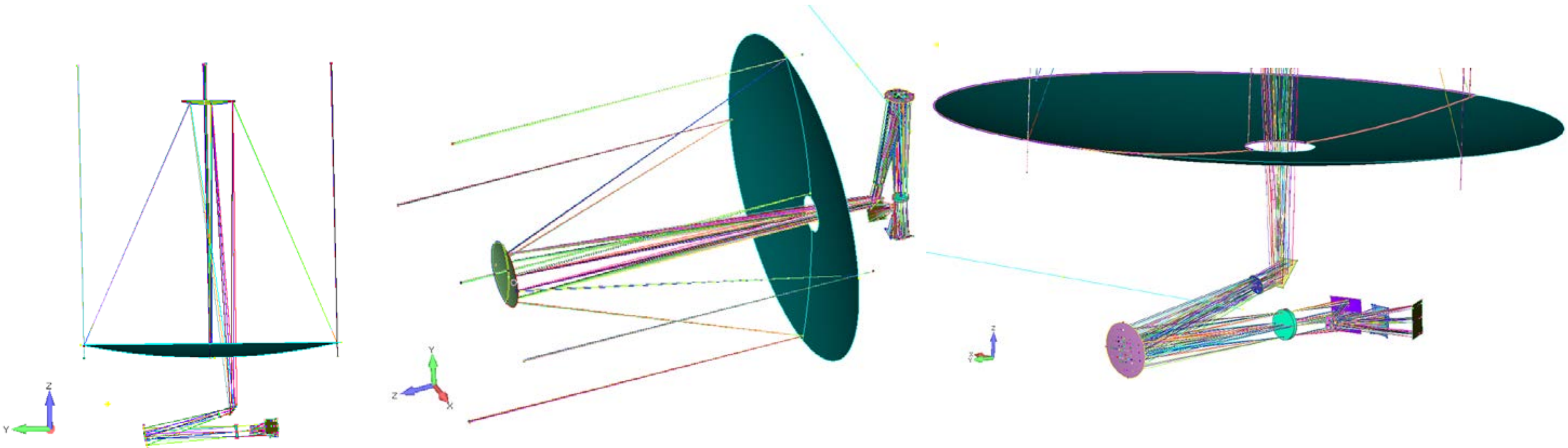
Telescope Optical Baseline

3 Mirror Off Axis Korsch Design Selected as Baseline (ref Isabel Escudero)



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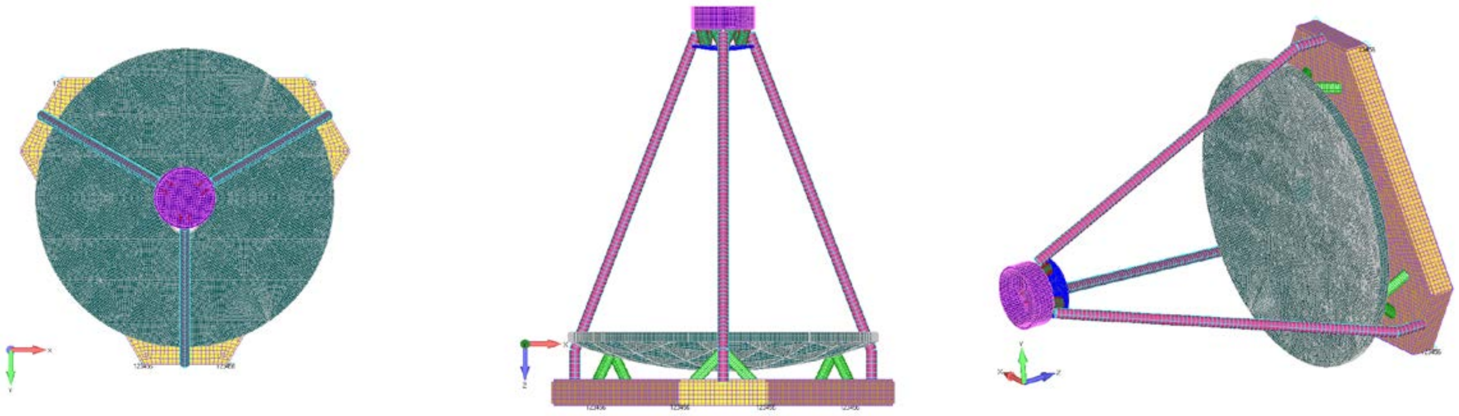
Telescope Concept: Option 1

Off Axis Korsch

Tripod Truss Configuration

SiC Optics and Structure

Mass 47 Kg (Excluding Spectrometer)



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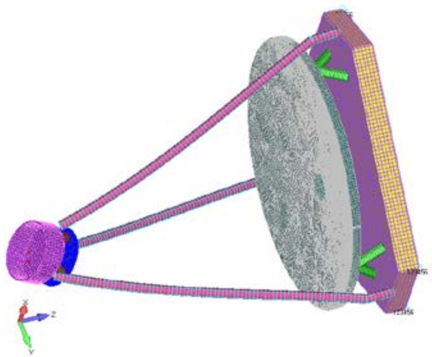
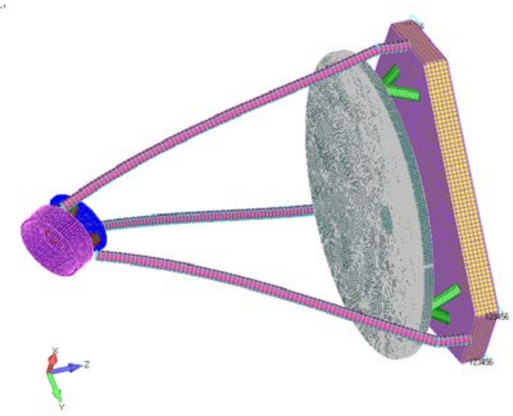
Telescope Concept: Option 1

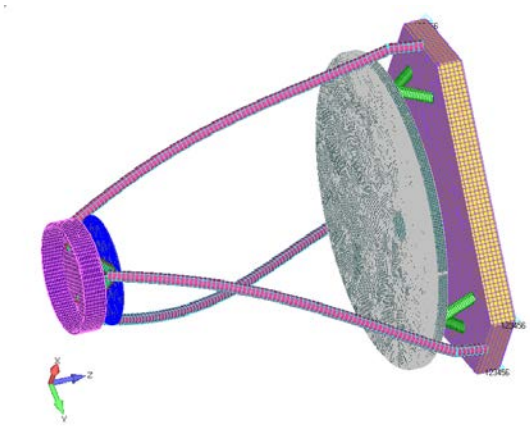
EigenModes



Mode 1 107 Hz



Mode 2 107 Hz



Mode 3 179 Hz

Eigenmodes dominated by bending and torsional response of Tripod Truss.
Telescope Option 1 compliant with design mass and eigenfrequency requirements.

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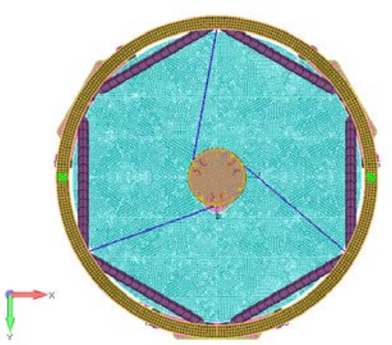
Telescope Concept: Option 2

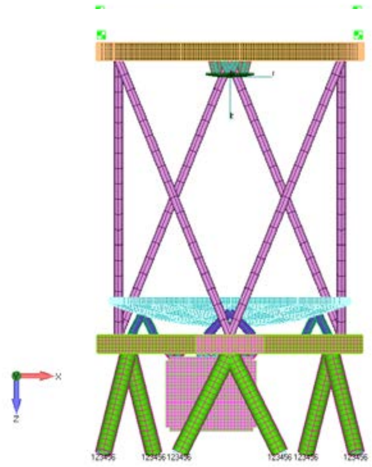
Off Axis Korsch

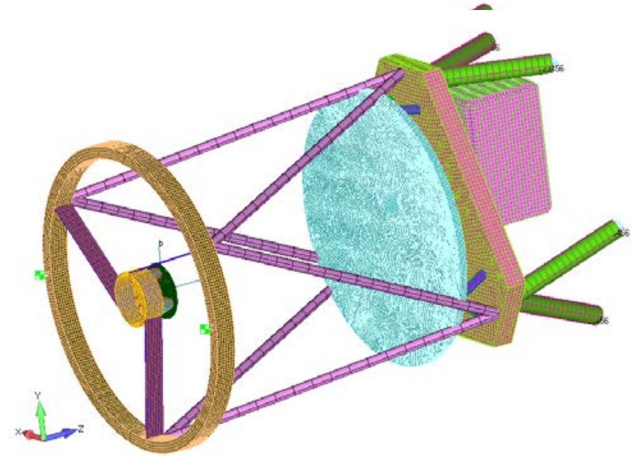
Half Serrurier Truss Configuration (Star Trackers Mounted On Telescope Upper Cage)

SiC Optics and Structure

Mass 50 Kg (excluding spectrometer)







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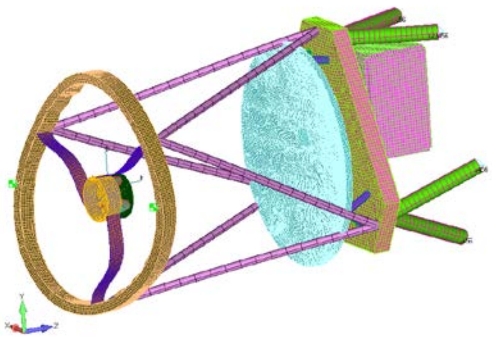
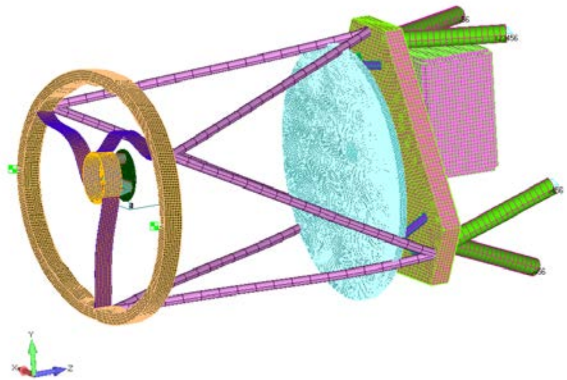
Telescope Concept: Option 2

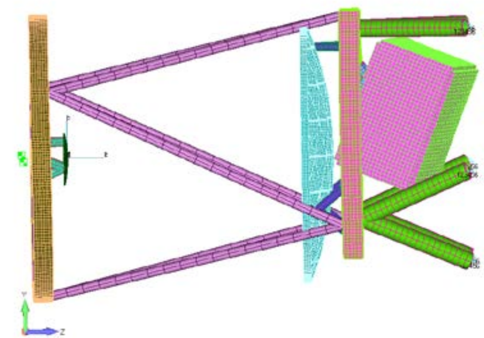
Eigenmodes



Mode 1 71 Hz



Mode 2 74 Hz



Mode 3 112 Hz

Eigenmodes 1 and 2 dominated by bending and torsional response of Upper Cage and M2 Spider.
Eigenmode 3 dominated by rocking modes of spectrometer.
Telescope Option 2 compliant with design mass and eigenfrequency requirements.

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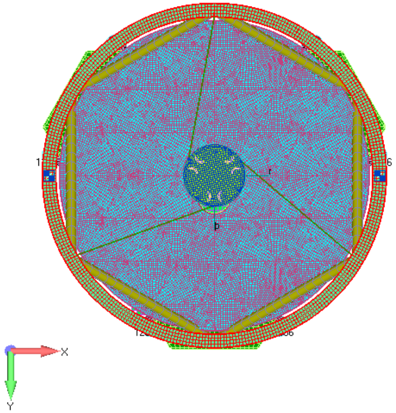
Telescope Concept: Option 3

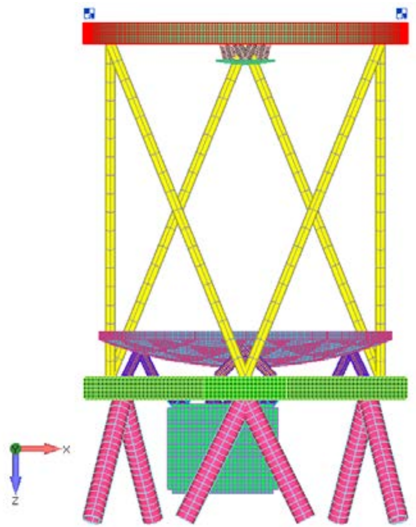
Off Axis Korsch

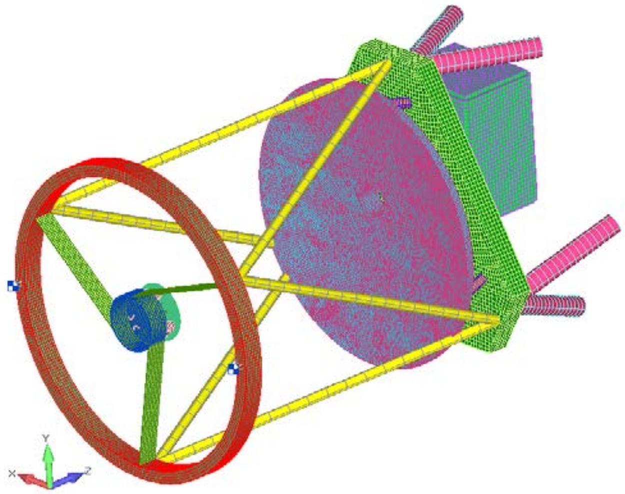
Half Serrurier Truss Configuration (Star Trackers Mounted On Telescope Upper Cage)

Zerodur Optics and CFRP Structure

Mass 30 Kg (excluding spectrometer)







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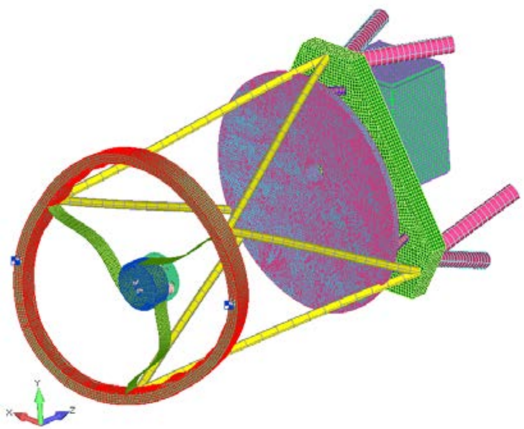
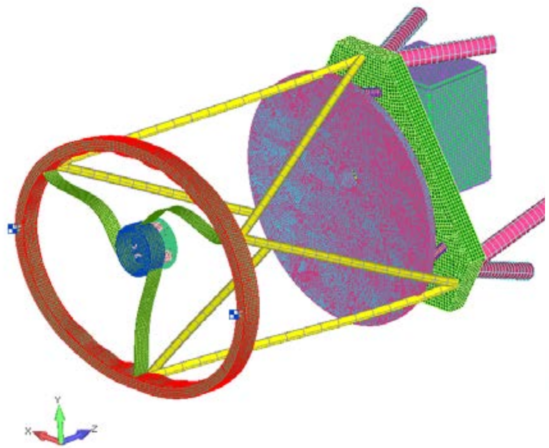
Telescope Concept: Option 3

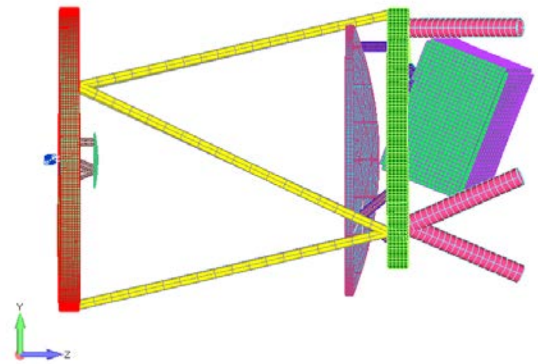
Eigenmodes



Mode 1 65 Hz



Mode 2 68 Hz



Mode 3 85 Hz

Eigenmodes 1 and 2 dominated by bending and torsional response of Upper Cage and M2 Spider.
Eigenmode 3 dominated by rocking modes of spectrometer.
Telescope Option 3 compliant with design mass and eigenfrequency requirements.

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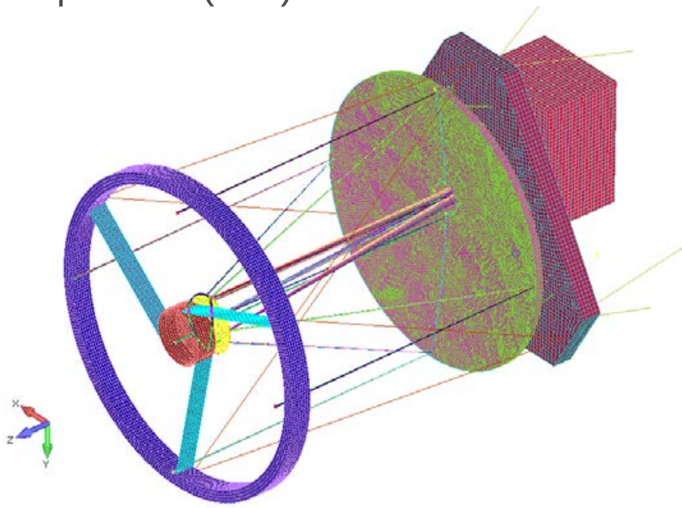
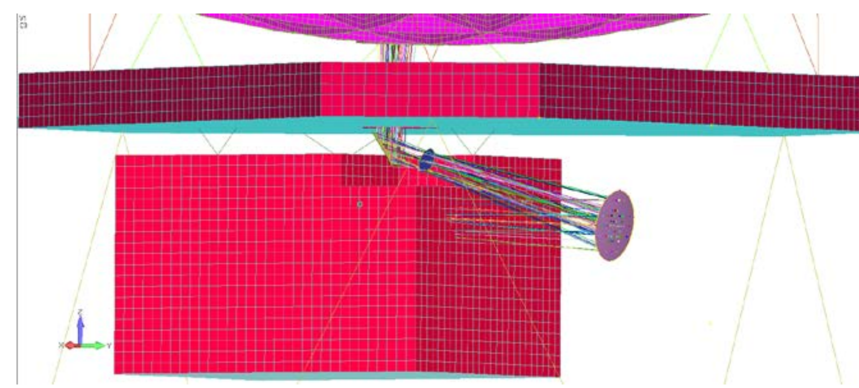
Telescope Concept Downselection

- All telescope options compatible with mass and eigenfrequency requirements.
- Options 2 & 3 preferred due to lower obscuration, ability to mount star trackers on M2 upper cage and ease of design/installation of telescope baffle (no need to perforate baffle to for tripod truss tubes).
- Option 2 (SiC) selected for further study due to worst mass assumption.





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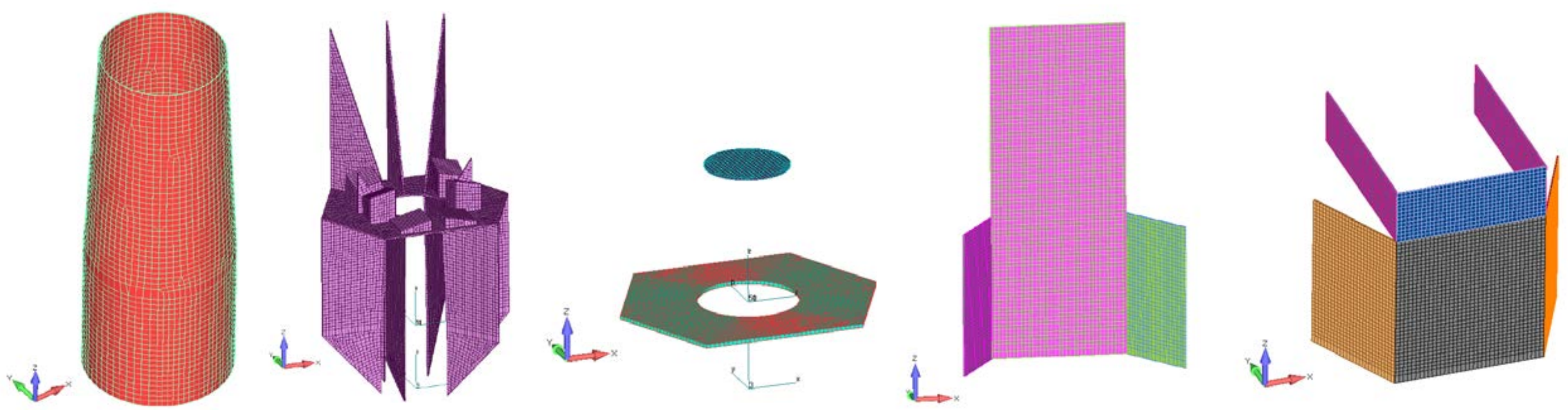
Structure Concept

Central Cone +	Shear Panels +	Floor Panels +	Solar Array Panels +	Radiator Panels
44 layers	0.8 mm CFRP +	0.8 mm CFRP+	0.8 mm CFRP +	0.4 mm Al facesheet+
0.0001 CFRP	20 mm Al Core	40 mm Al Core	20 mm Al Core	20 mm Al Core



Structure Mass (Central Cone + Panels) = 540 Kg

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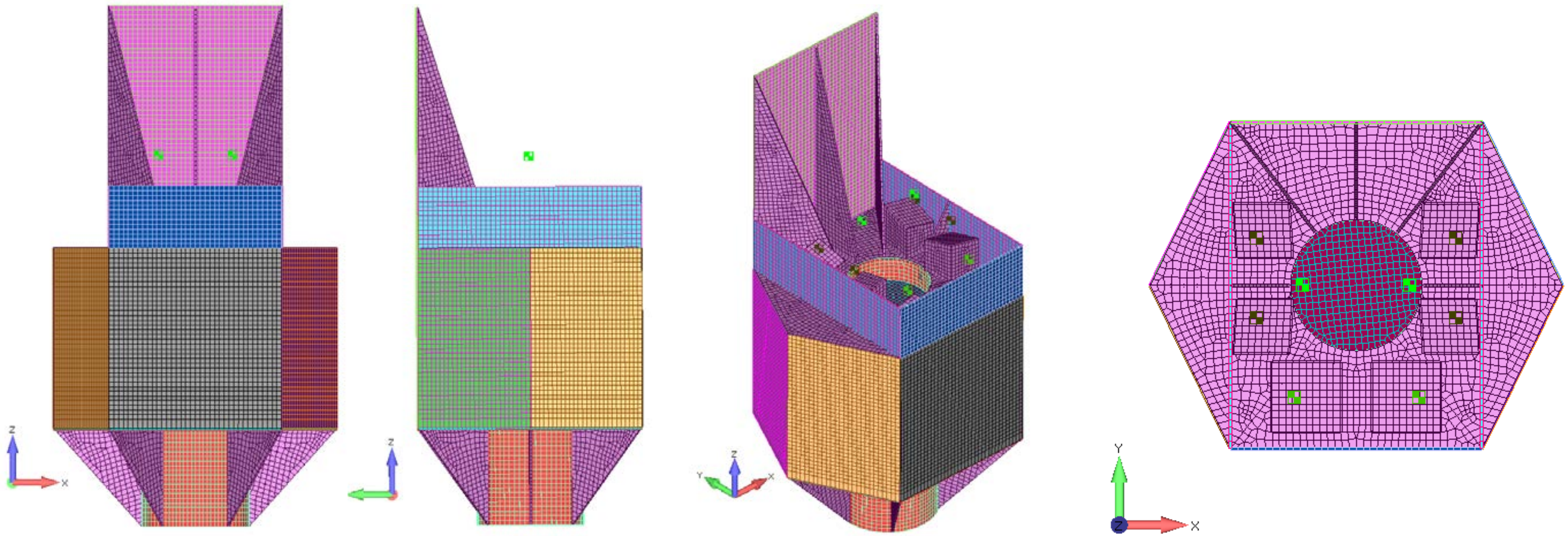
Structure Concept



Instruments (XGIS,SXI), Propellant Tanks, cryocoolers added as lumped masses = 530 Kg

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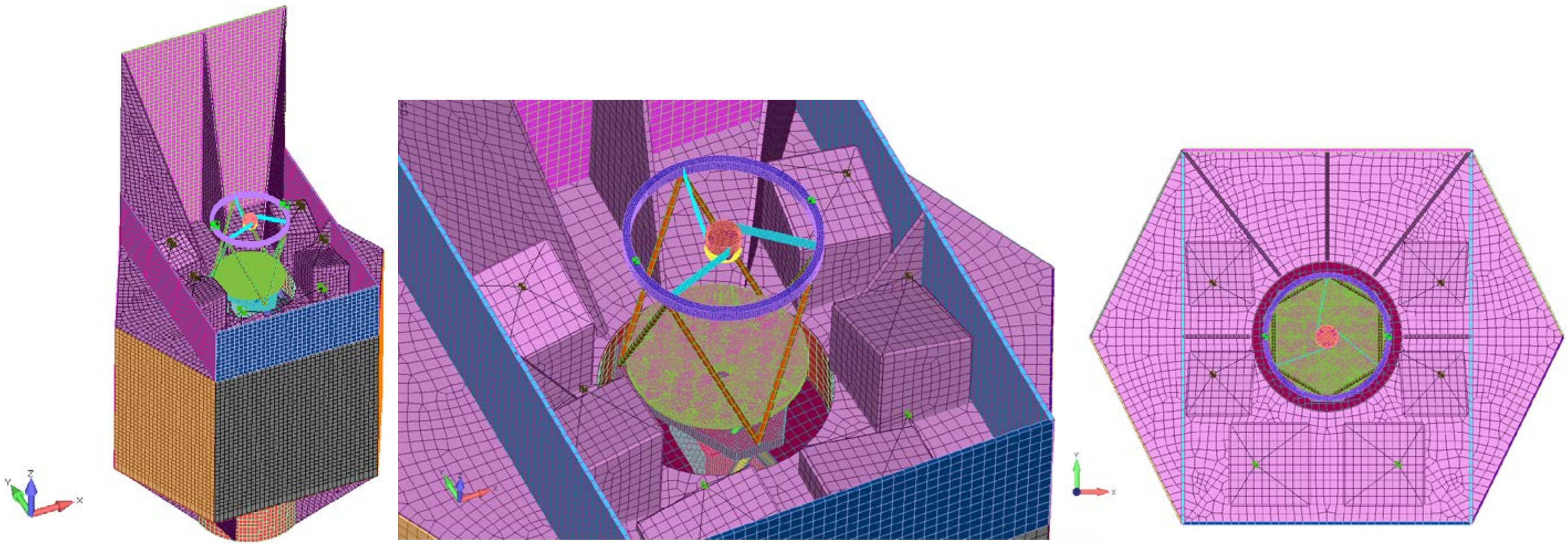
Structure Concept



Total Mass Telescope + Spectrometer + Cryocoolers + Star Trackers = 125 Kg
Total Mass S/C (Structure, Instruments, Telescope, Hardware) = 1195 Kg

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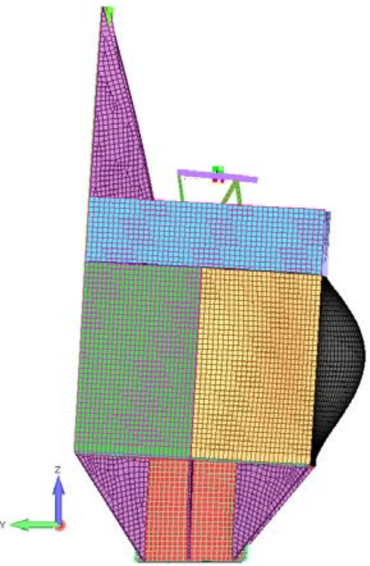
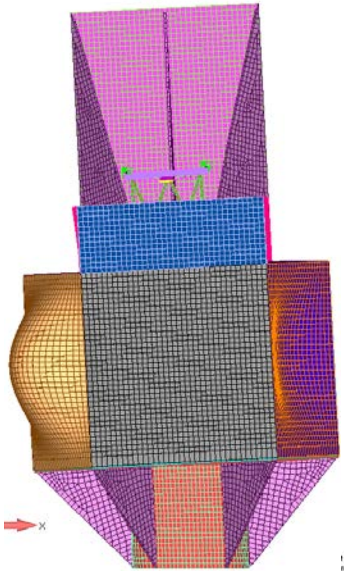
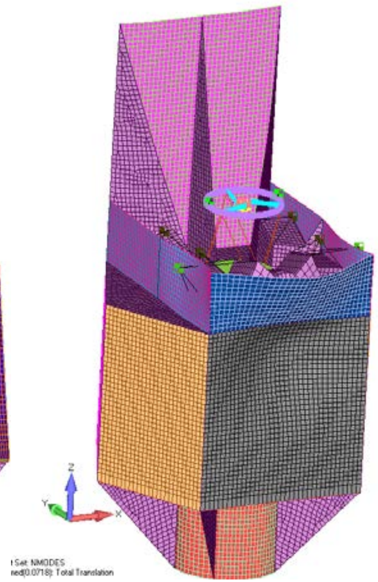
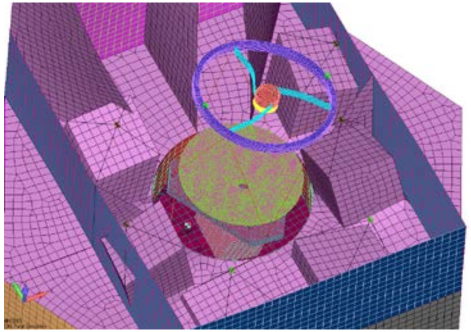
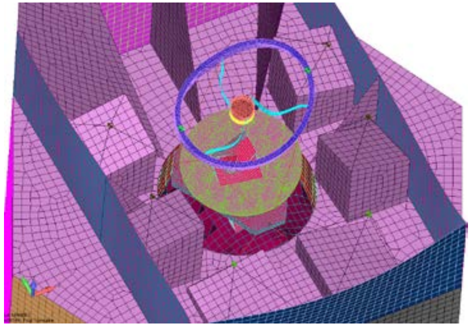
Structure with SiC Telescope











Mode 1 27 Hz

Mode 2 29 Hz

Mode 3 36 Hz

Mode 16 67 Hz

Mode 19 85 Hz

Eigenmodes 1 and 2 dominated by bending modes of structure. Eigenmode 3 dominated by panel modes of SVM radiator panel.Eigenmodes 16 and 19 are dominated by local modes of telescope truss and upper cage. Structure with SiC telescope fully compliant with Eigenfrequency requirements.

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Mass Breakdown

Panel Description	Panel Construction	Panel Area	Panel Mass	Panel Non Structural Mass	Total Mass	Mass Margin	Comment
Central Cone	CFRP layup 44 laminates 0.0001 thk	9.701	70.429	0	70.429	0	
Shear Panel 1	20 mm CFRP Al honeycomb	1.803	5.544	0	5.544	0	
Shear Panel 2	20 mm CFRP Al honeycomb	1.803	5.544	0	5.544	0	
Shear Panel 3	20 mm CFRP Al honeycomb	1.803	5.544	0	5.544	0	
Shear Panel 4	20 mm CFRP Al honeycomb	1.803	5.544	0	5.544	0	
Shear Panel 5	20 mm CFRP Al honeycomb	1.803	5.544	0	5.544	0	
Shear Panel 6	20 mm CFRP Al honeycomb	1.803	5.544	0	5.544	0	
Shear Panel 7	20 mm CFRP Al honeycomb	0.466	1.435	0	1.435	0	
Shear Panel 8	20 mm CFRP Al honeycomb	0.466	1.435	0	1.435	0	
Shear Panel 9	20 mm CFRP Al honeycomb	0.466	1.435	0	1.435	0	
Shear Panel 10	20 mm CFRP Al honeycomb	0.466	1.435	0	1.435	0	
Shear Panel 11	20 mm CFRP Al honeycomb	0.466	1.435	0	1.435	0	
Shear Panel 12	20 mm CFRP Al honeycomb	0.466	1.435	0	1.435	0	
Sunshield Support Panel 1	20 mm CFRP Al honeycomb	0.887	2.728	0	2.728	0	
Sunshield Support Panel 1	20 mm CFRP Al honeycomb	1.274	3.92	0	3.92	0	
Sunshield Support Panel 1	20 mm CFRP Al honeycomb	1.274	3.92	0	3.92	0	
SXI & XGIS Support Panels	20 mm CFRP Al honeycomb	4.306	13.241	0	13.241	0	
PX Panel	20 mm CFRP Al honeycomb	4.887	15.03	0	15.03	0	
MX Panel	40 mm CFRP Al honeycomb	4.565	16.963	57.527	74.49	0	12.6 kg/m^2 non structural mass for 57.5 Kg of hardware
Sunshieldwith solar array	20 mm CFRP Al honeycomb	7.948	24.444	9.538	33.982	0	1.2 kg/m^2 non structural mass for solar arrays
SXI Radiator	20 mm AL Al honeycomb	1.519	4.581	12.305	16.886	0	8.1 Kg/m^2 non structural mass for radiator
SXI Radiator	20 mm AL Al honeycomb	1.519	4.581	12.305	16.886	0	8.1 Kg/m^2 non structural mass for radiator
Telescope Floor Panel	20 mm CFRP Al honeycomb	0.688	2.117	0	2.117	0	
MYPZ Panel	20 mm CFRP Al honeycomb	2.449	7.532	2.939	10.471	0	1.2 kg/m^2 non structural mass for solar arrays
PYPZ Panel	20 mm CFRP Al honeycomb	2.449	7.532	2.939	10.471	0	1.2 kg/m^2 non structural mass for solar arrays
XGIS Upper Radiator Panel	20 mm AL Al honeycomb	1.17	3.528	9.477	13.005	0	8.1 kg/m^2 non structural mass for radiator
MZ Panel	20 mm AL Al honeycomb	3.385	10.209	43.668	53.877	0	8.1 kg/m^2 non structural mass for XGS+SVM radiator + 4.8 Kg/m^2 for 16.235 Kg of hardware
MYMZ Panel	20 mm AL Al honeycomb	2.449	7.387	77.619	85.006	0	8.1 kg/m^2 non structural mass for radiator + 23.59 Kg/m^2 for 57.8 Kg of hardware
PYMZ Panel	20 mm AL Al honeycomb	2.449	7.387	64.172	71.559	0	8.1 kg/m^2 non structural mass for radiator + 23.59 Kg/m^2 for 44.34 Kg of hardware
	Total Mass Structure		**247.4**	**292.489**	**539.9**		

XGIS 1					85.536	0	Lumped Mass
XGIS 2					85.536	0	Lumped Mass
SXI 1					37.296	0	Lumped Mass
SXI 2					37.296	0	Lumped Mass
SXI 3					37.296	0	Lumped Mass
SXI 4					37.296	0	Lumped Mass
Propellant Tank 1					104.9	0	18.8 Kg dry tank mass + 86.1 Kg propellant
Propellant Tank 1					104.9	0	18.8 Kg dry tank mass + 86.1 Kg propellant
Telescope SiC					45.376	0	
Spectrometer					60.262	0	1.38 Kg for Bipods + 58.874 Kg for spectrometer
Star Tracker					2.5	0	Mounted on telescope upper cage
Star Tracker					2.5	0	Mounted on telescope upper cage
Cryocoolers					15	0	2 cryocoolers @ 7.5 Kg each
	Total Mass Instruments + Hardware				**655.7**		
	Total Mass S/C				**1196**		

NOTE : Zero Mass Margin Applied In These Calculations

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Mechanisms

Mechanisms

- **M2 Refocusing Mechanism**
- **Solar Array Release & Deployment Mechanism**
  - Hold Down & Release Mechanism
  - Root Deployment Hinges

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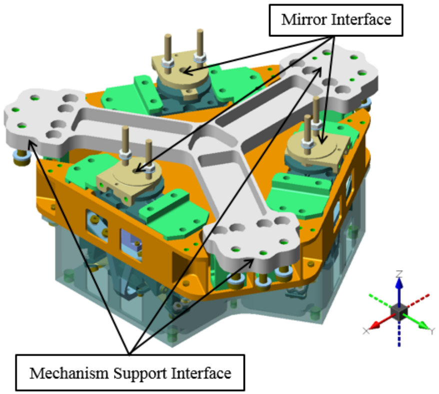
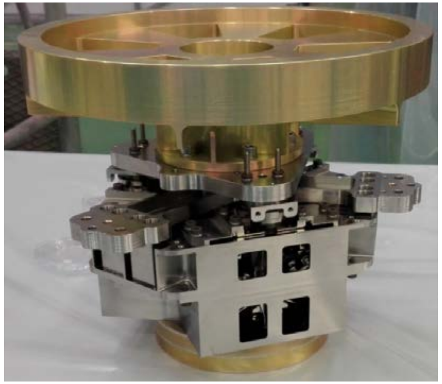
M2 Refocusing Mechanism

EUCLID M2MM	
DoF	3
Company	Sener
Mass	< 3.1 kg
Operational Stroke	±200 µm ±1500 µrad
Max. op. loads	97 N
First resonance freq.	161 Hz
Power	15 W
Operational Temperature	-173 °C / +25 °C
Dimensions	214 mm symmetric 120° h = 150 mm
TRL	7





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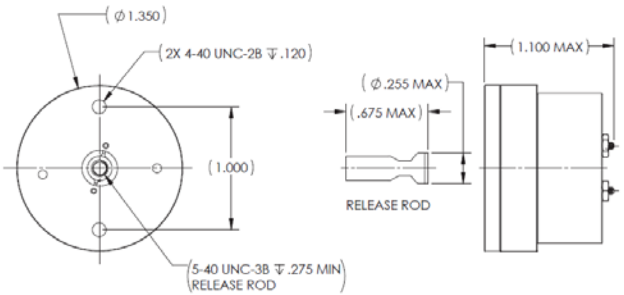
Solar Array Release Mechanism

- Hold Down & Release Mechanism

NEA Model 9100	
Amount	4 (2 HDRM / panel)
Company	NEA Electronics (USA)
Mass	0.070 kg
Release Load	6 kN
Power	25.6 W for 25 ms
Operational Temperature	-135 °C / +135 °C
Dimensions	Ø 34 mm, h = 28 mm
TRL	9

Model 9100 Mechanical Interface Drawing



Note: Model 9100 Release Mechanism shown. Different configurations available with alternate release rods, mounting features, and connectors. Metric configurations are also available.

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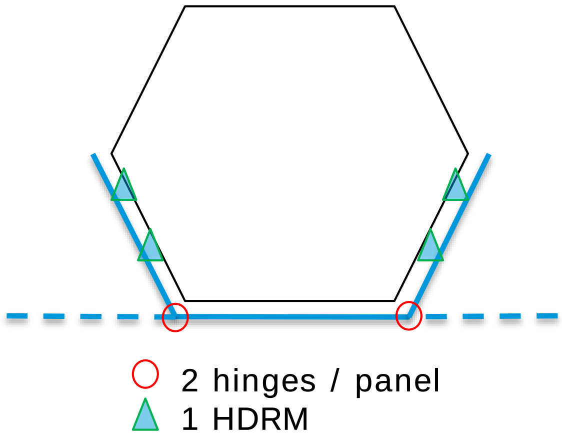
Solar Array Deployment Mechanism

- Hinges

Root deployment Hinges	
Amount	4 (2 hinges / panel)
Company	SENER (Spain), Dutch Space (The Netherlands)
Mass	0.260 kg
Operational Temperature	-95 °C / +105°C
Dimensions	75 mm^3
TRL	7



These hinges need to be customized as the solar panel open with an angle of 60deg.

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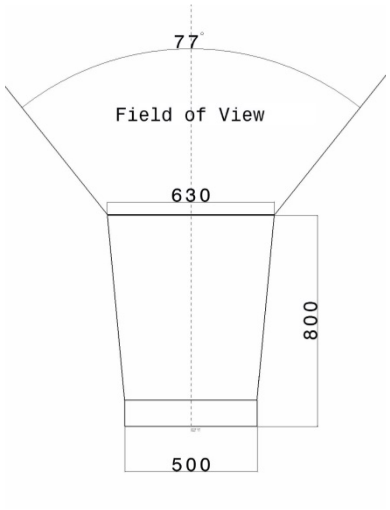
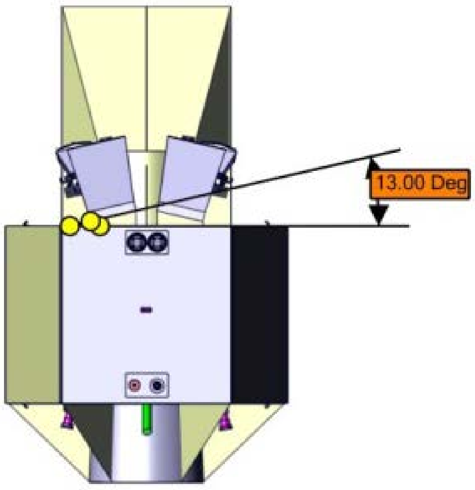
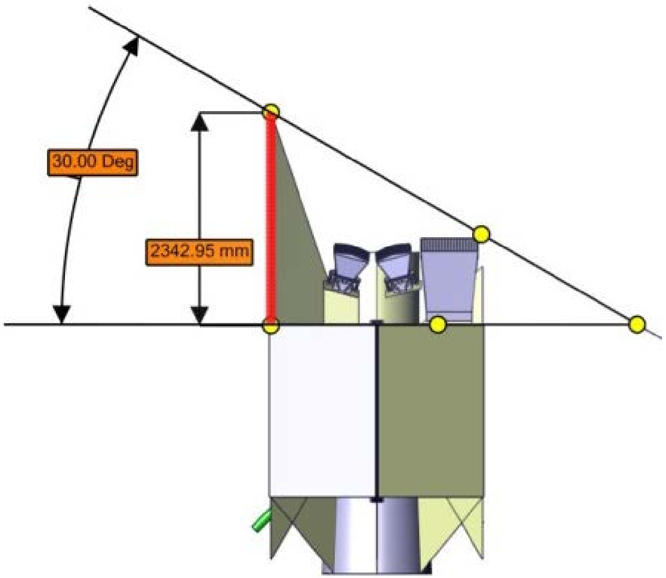
Configuration

Sun angle of 30deg

XGIS basic dimension:







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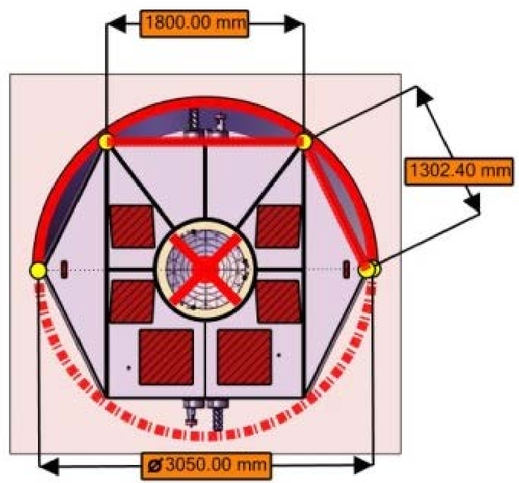
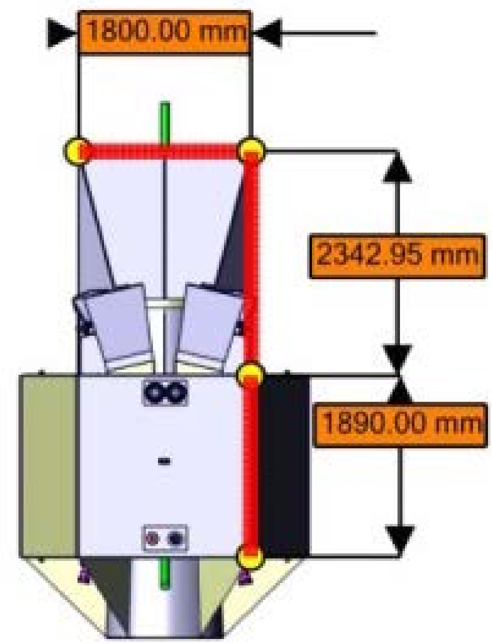
SVM height

Requested solar area (fixed) = 10m2 with reduced factor of 50% for angled side panel

➔ SVM height = 1890 mm

➔ total actual area = 12.3 m2





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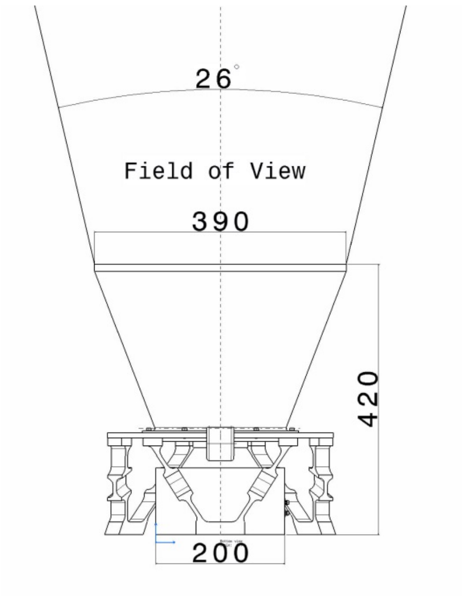
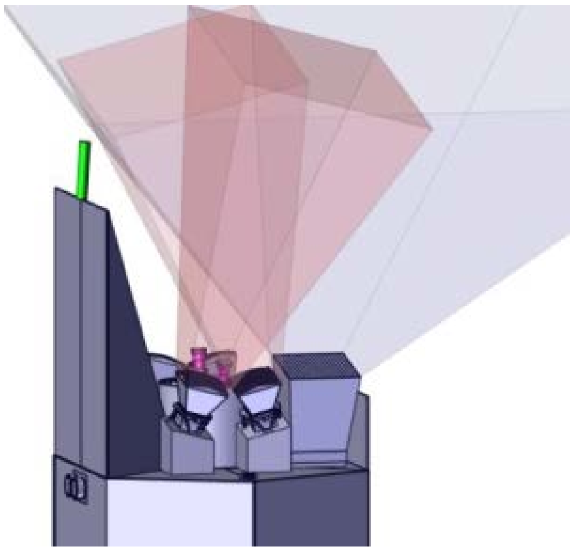
SXI position

SXI FoV = 26° x 31°

XGIS position(incl FoV 77° x 77°)





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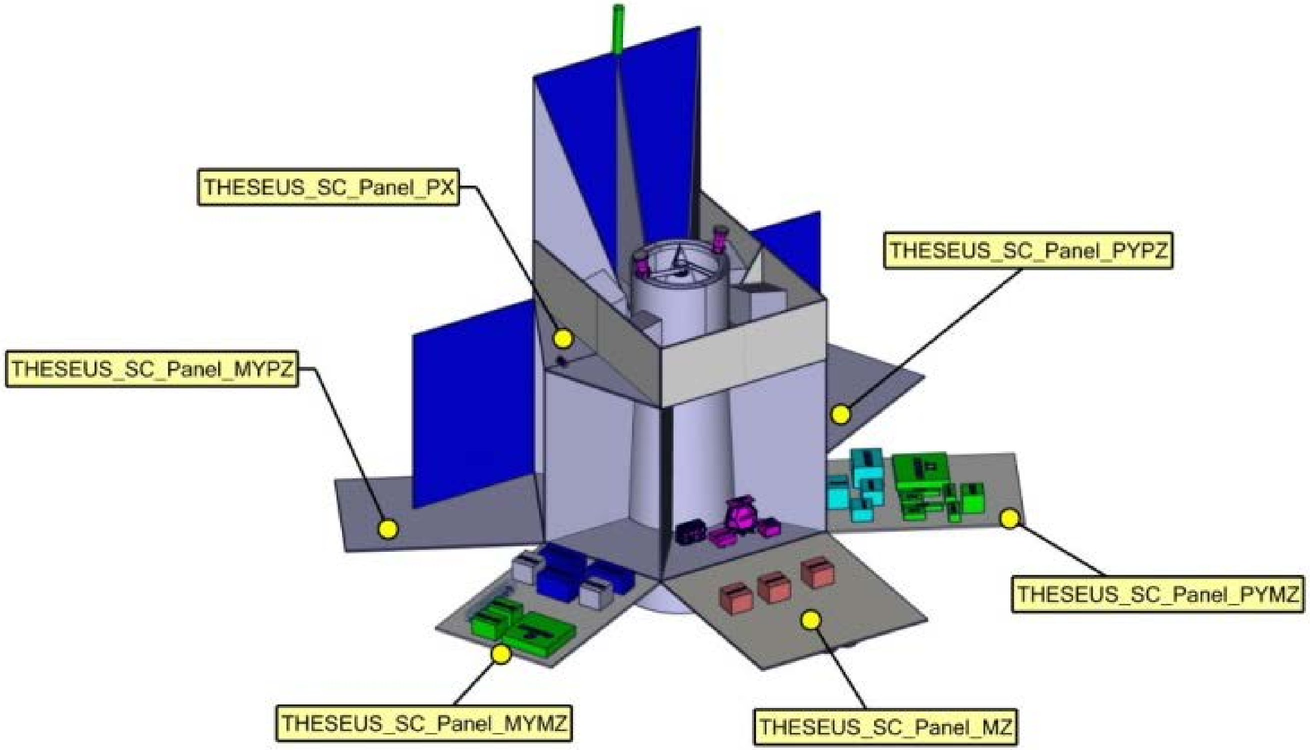
THESEUS accommodation 1 / 6



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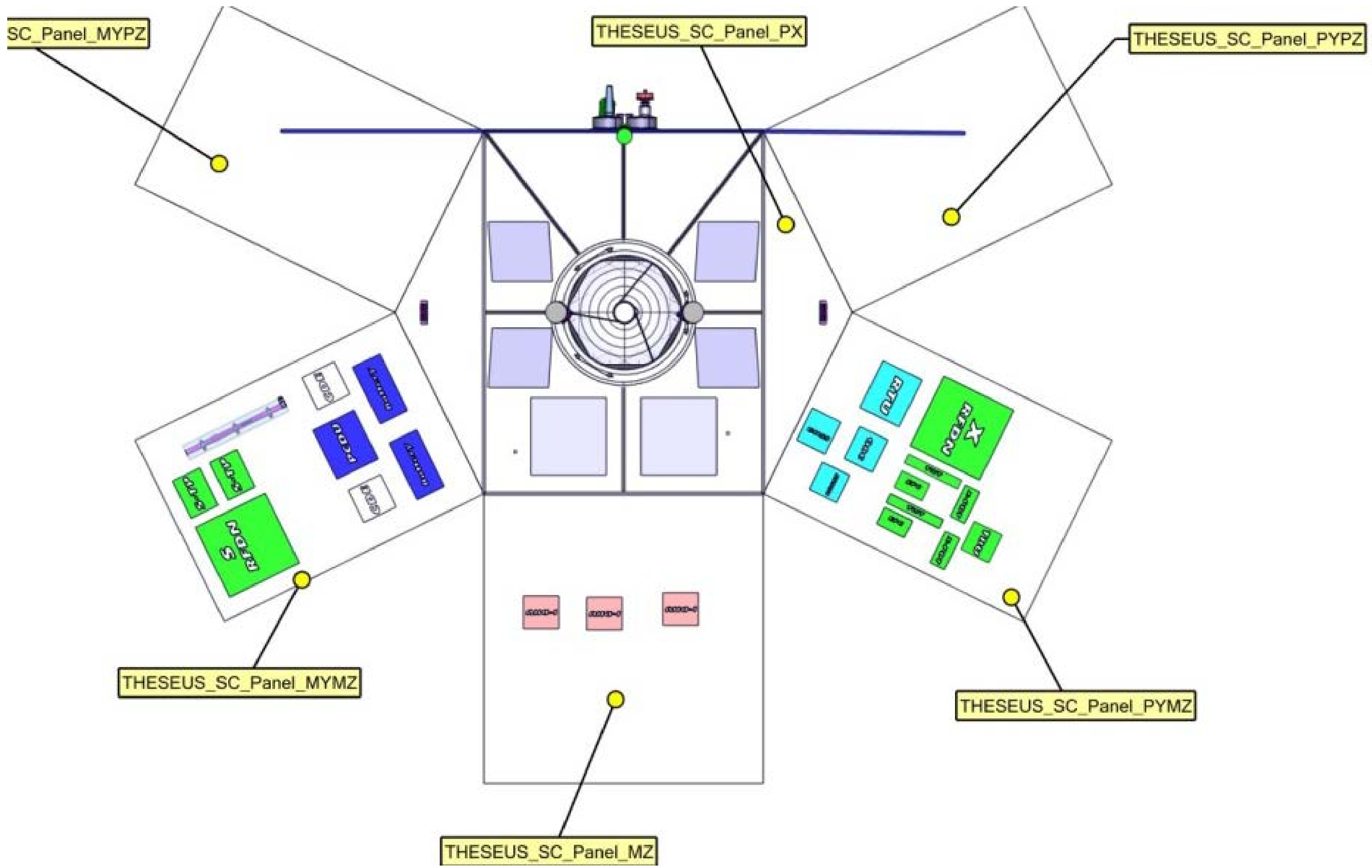
THESEUS accommodation 2 / 6



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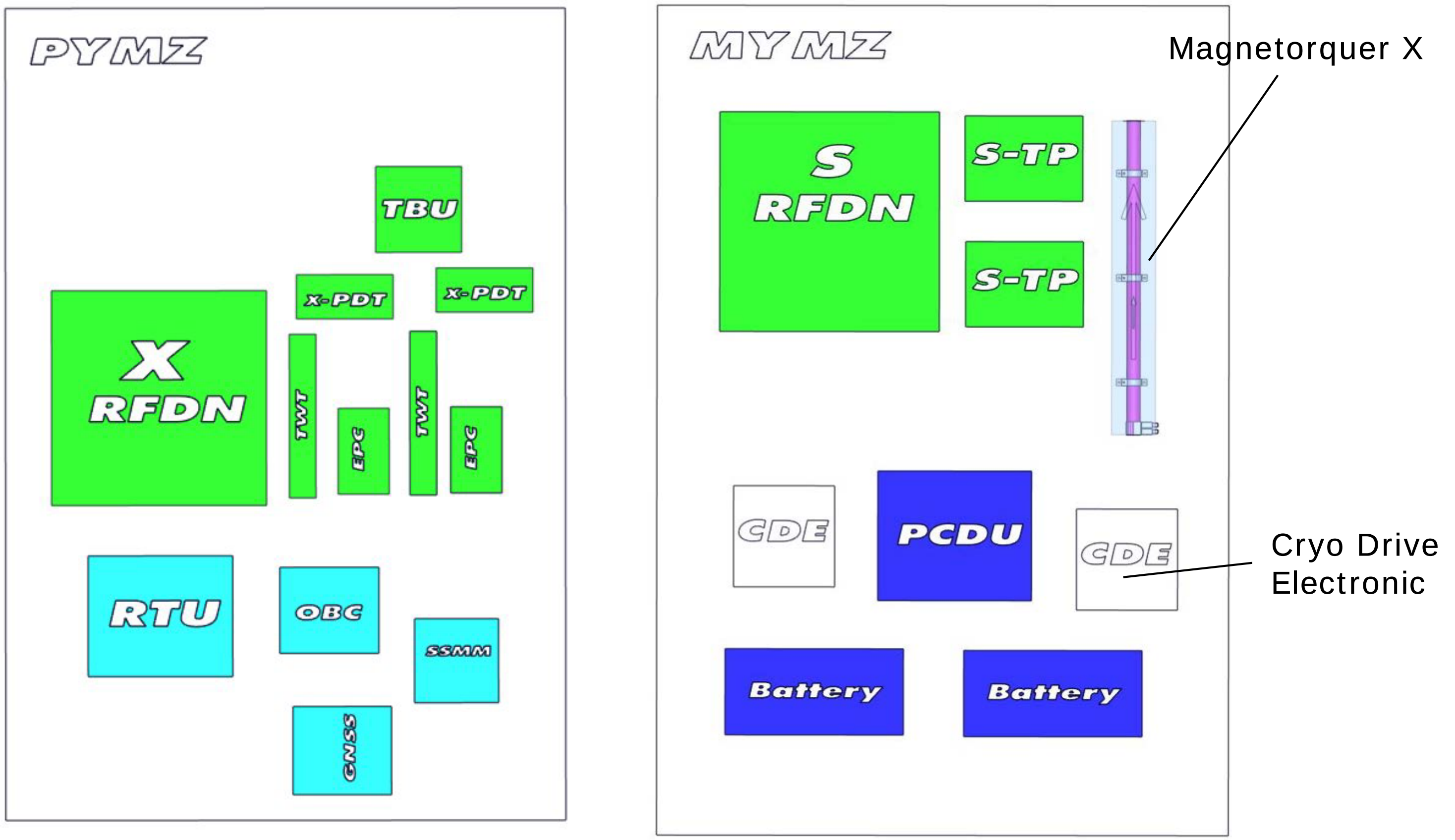
THESEUS accommodation 3 / 6

- COMM
- DHS
- POWER
- GNC



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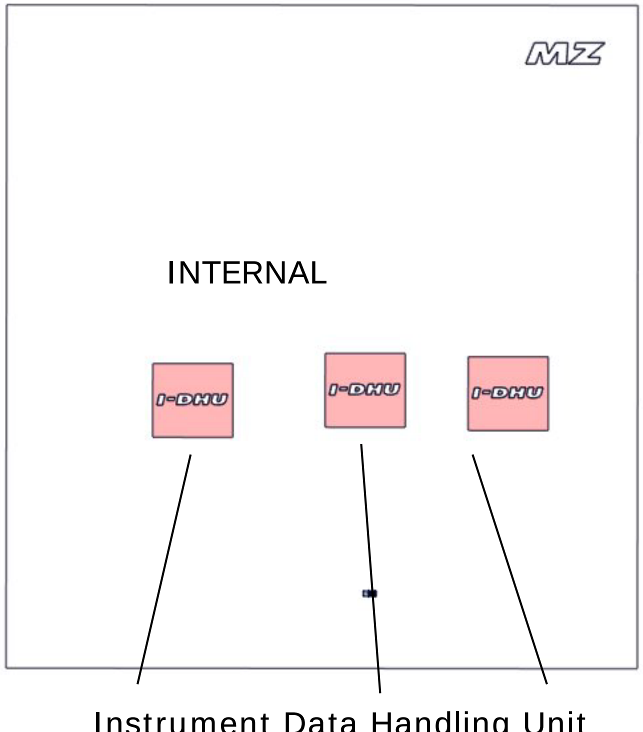
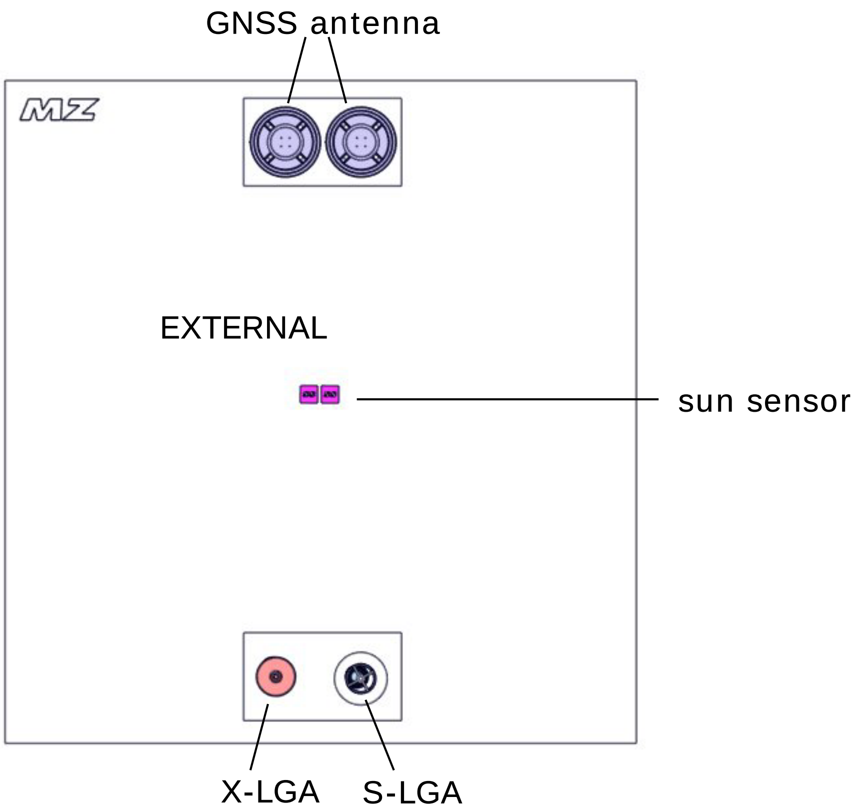
THESEUS accommodation 4 / 6





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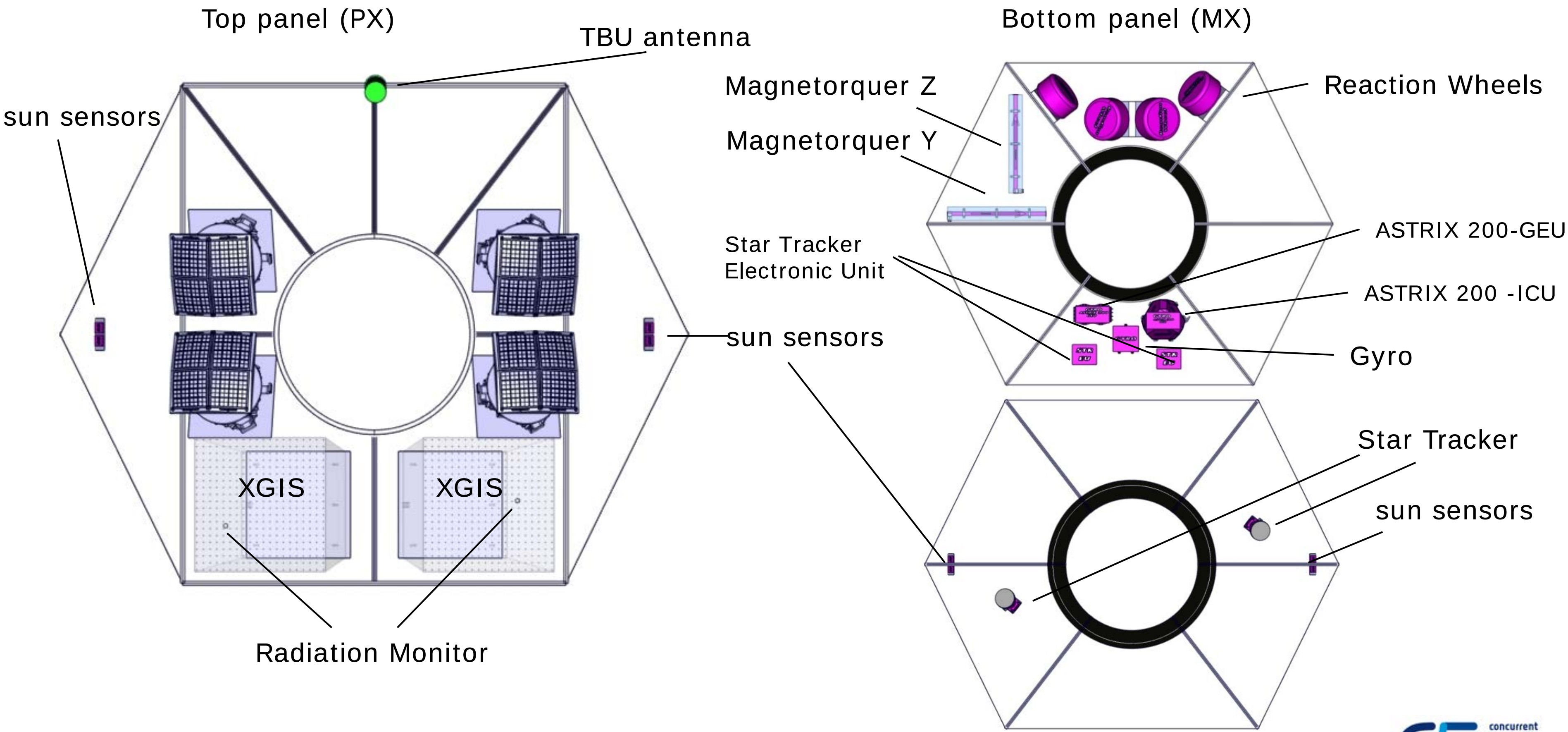
THESEUS accommodation 5 / 6



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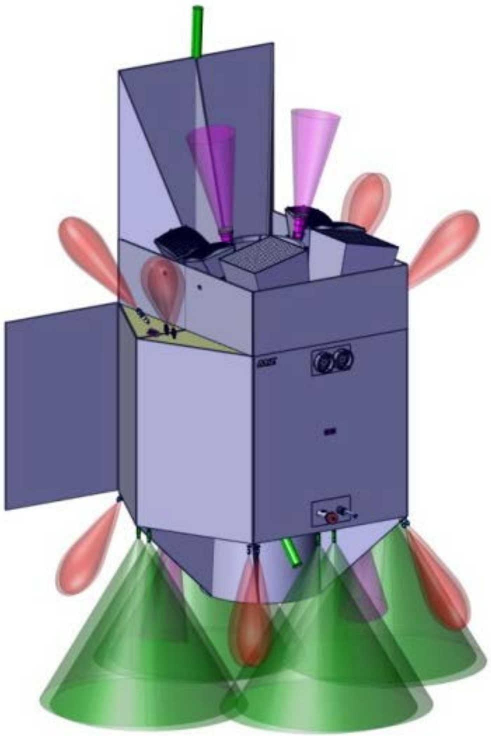
THESEUS accommodation 6 / 6

Thruster location



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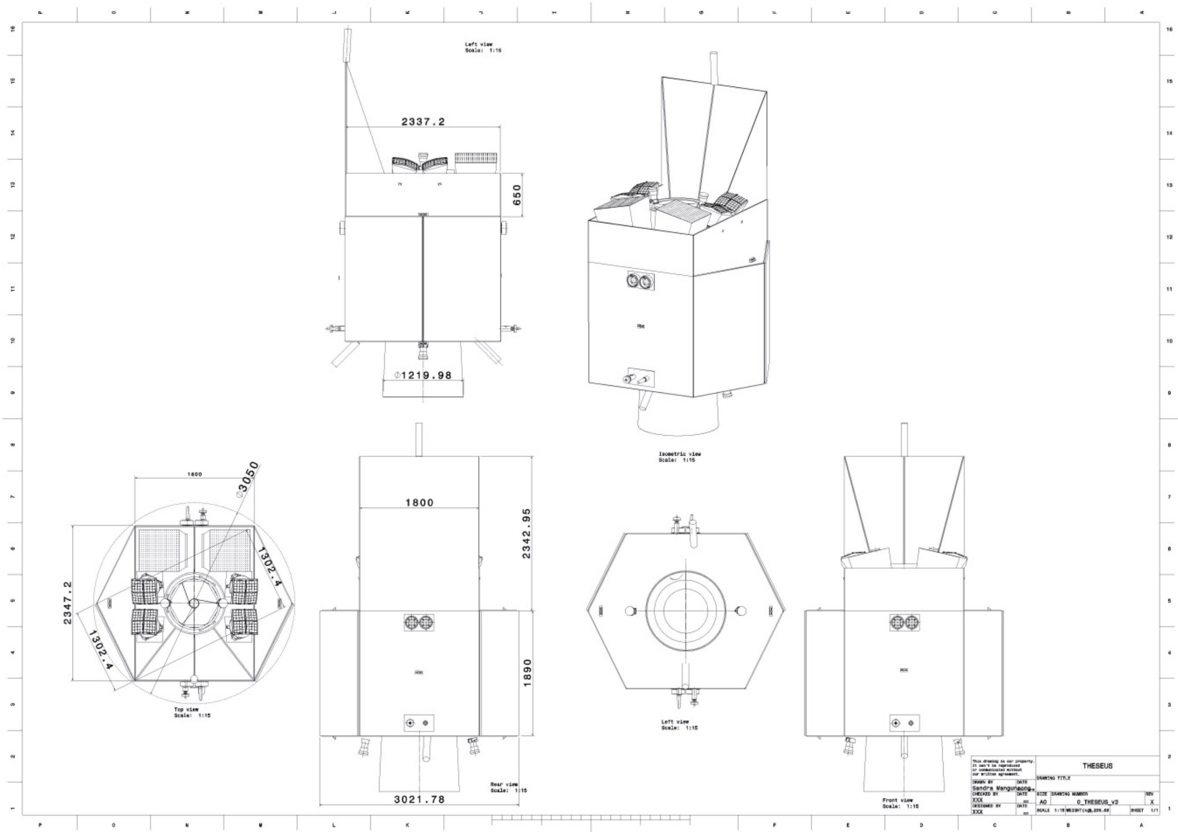
THESEUS overall dimension



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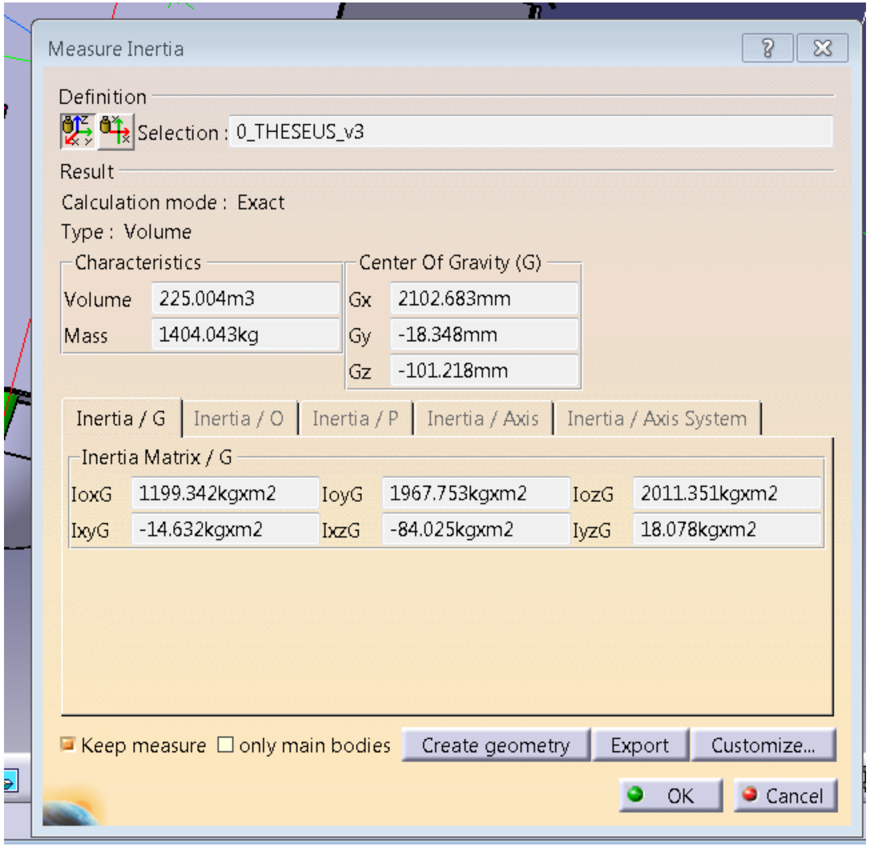
Vega-C CoG requirement



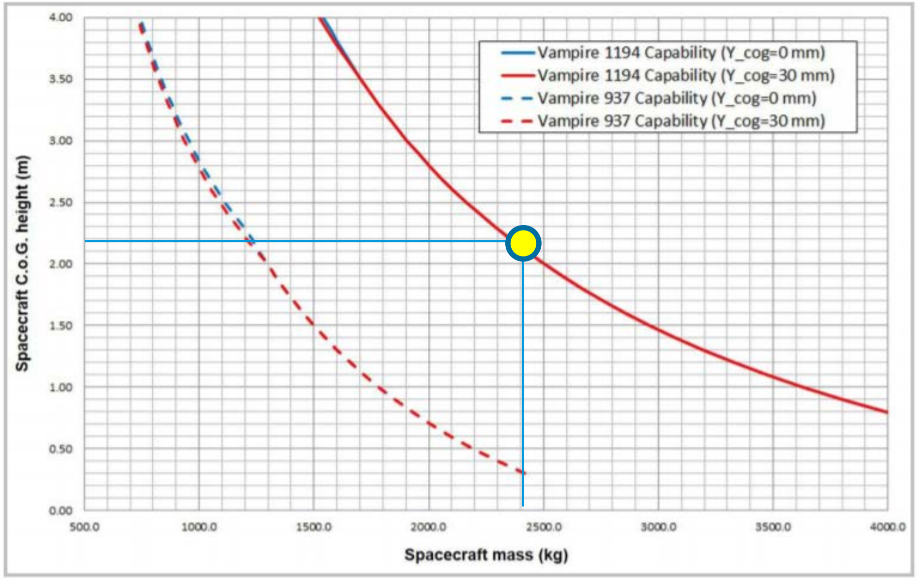


Figure 4.2.3.1.1.a – Limits of spacecraft C.o.G. position vs. spacecraft mass for single launch configuration in case of "VAMPIRE 937" or "VAMPIRE 1194"

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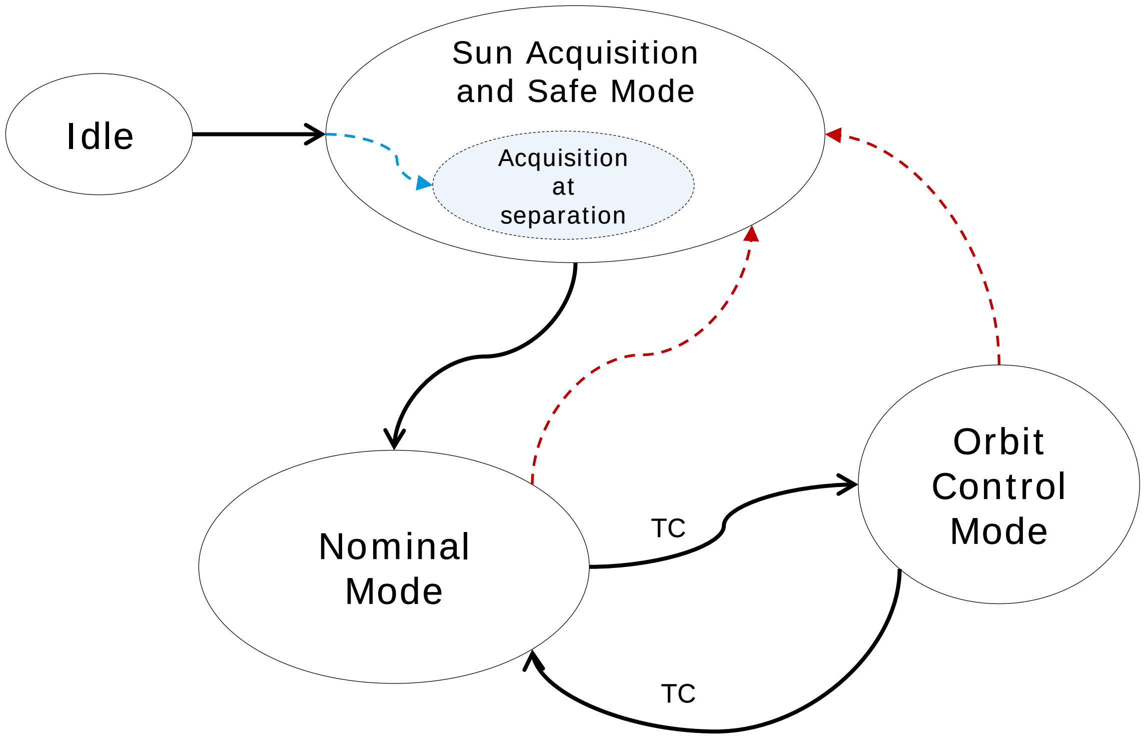
AOCS

Mode architecture



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Acquisition and Safe Mode

Sensors:

- Coarse gyro

  3-axis Coriolis Vibrating Gyroscope (Innalabs - Ireland)

  Low mass, low power (mass~0.6 kg, power~8W)

- Sun sensors (6+6)

  Bison 64_ET_B (Lens R&D – The Netherlands)

Actuators:

- Thrusters 1 N x8 (as XIPE)

Propellant consumption

Total of 16 events over lifetime (3 safe mode events per year for 5 years + 1 for LEOP) and Safe mode duration of 3 days.

- 1.9 kg for rate reduction
- 7.3 kg for attitude hold

➢ Total of 9.2 kg (18.2 kg including 100% margins)

As launcher separation will happened during eclipse, for first attitude acquisition Sun sensors cannot be used for Sun acquisition.
Thus proposed sensors architecture is:

- ***Coarse gyro** for rate reduction*
- ***Star Trackers** for Sun acquisition and instruments protection*

Considering a spin rate of 2 deg/s launcher separation, safe attitude is reached in less than 4 minutes with the 1 N thrusters

STR attitude acquisition from lost in space OK up to 8 deg/s

Propellant budget to be refined considering contingency wheel-offloading due to momentum accumulation due to reduced MTQ efficiency in nearly equatorial orbit and for THR maneuvers during re-entry.

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Nominal Mode

Sensors:

- High Accuracy gyro
  Astrix 200 (Airbus - France)
- Star Trackers STR (3 + 1 OHs)
  Hydra (Sodern - France)
  + 2 Electronic units

Driver for STR selection
Due to thermal constraint of the PLM, STR solution with OH separated by EU is preferred.

Hydra STR allows up to 2 OH to be connected to 1 or 2 EU with up to 8m length cable.

Actuators:

- Reaction wheels RW x4
  RSI 15-215/20 (RCD - Germany)
  Power 90 W, Mass 7.7 Kg
- Magnetorquers MTQ x3
  MT110-2 (Zarm - Germany)
  Magnetic moment 110 Am2
- GNSS receiver

Selected RW provide enough torque/momentum to perform the required agility for slew maneuvers.

Required performance of slew rate of 0.1 deg/s (60 deg slew in 10 minutes) is achieved (a maximum slew rate of about 0.2 deg/s can be achieved).

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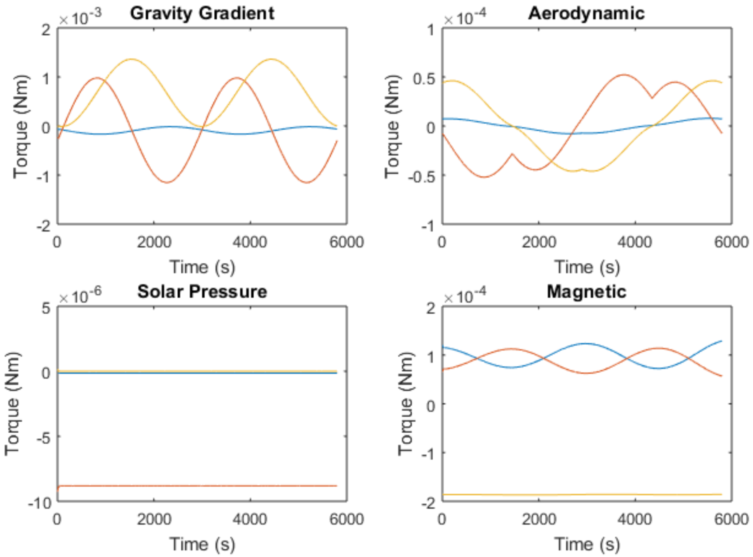
12 Nms vs 15 Nms wheels

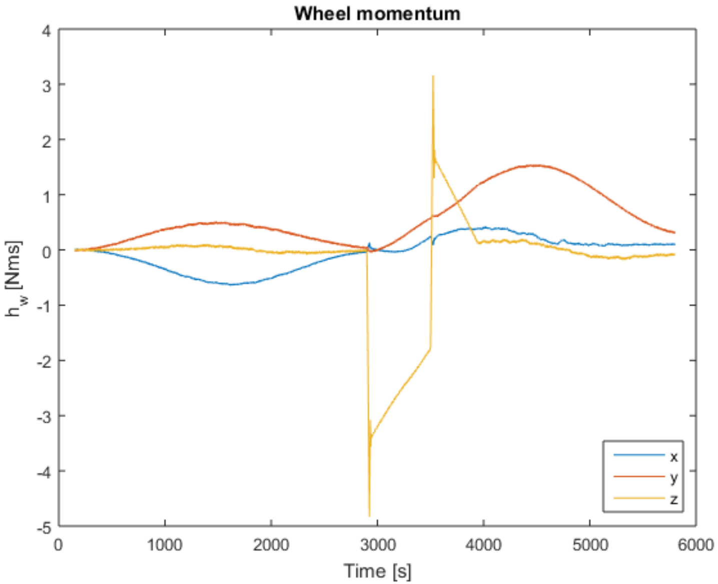
Considering 3 RW (1 RW failure) the required angular momentum is: 4.5 Nms to cover for the cyclic momentum due to the environmental torque + 10.7 Nms for slews

- 15.2 Nms required

Environmental disturbances (1 orbit – fixed attitude)



Wheel Momentum during slew



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RW trade-off

Microvibrations

To mitigate microvibration effects caused by dynamic imbalance, a lower reaction wheel speed is preferred.

Assuming a similar static (1.5 gcm) and dynamic (20 gcm^2) imbalance for both wheel types and considering the max wheel speed of 6000 rpm for the 12 Nms wheel vs 2000 rpm for the 15 Nms, impact on RPE is lower for the 15 Nms wheel.

	RSI12-75/60	**RSI15-215/20**
max speed (rpm)	6000	2000
mass (kg)	4.85	7.70
motor torque at nominal speed (mNm)	75	215
RW Speed to provide 4.5 Nms	2250	600
RPE impact (arcsec)	**2.45**	**0.20**

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Orbit Control Mode

Sensors:

- High Accuracy gyro
  Astrix 200 (Airbus - France)
- Star Trackers STR (3 + 1 OHs)
  Hydra (Sodern - France)

Actuators:

- Reaction wheels RW x4
  RSI 15-215/20 (RCD - Germany)
  Power 90 W, Mass 7.7 Kg
- Magnetorquers MTQ x3
  MT110-2 (Zarm - Germany)
  Magnetic moment 110 Am2
- GNSS receiver
- Thrusters RCS

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STR accommodation

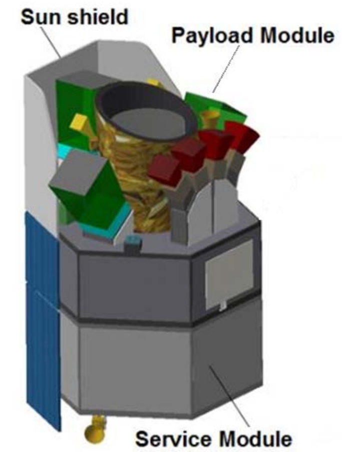
STR accommodation:

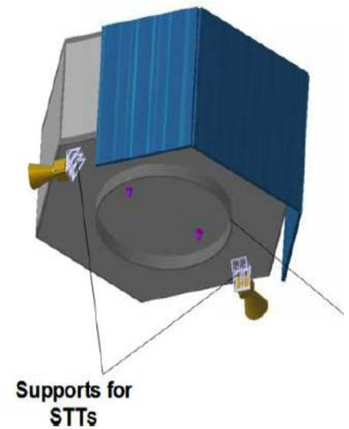
- 2 OHs integrated next to IRT (<0.9 W heat dissipation per OH)
- 2 OH + 2 EU on SVM

Cant angles w.r.t IRT LoS to be optimized in order to:

- avoid any obstruction by satellite appendages (e.g. Sun shied)
- avoid Sun intrusion
- maximise AKE (low cant angle is preferred)
- minimise Earth occultation, thereby ensuring good system availability and performances (in particular after STR failure and in case of 2 obstructed OH)

➢ A cant angle of **10 deg** has been assumed.





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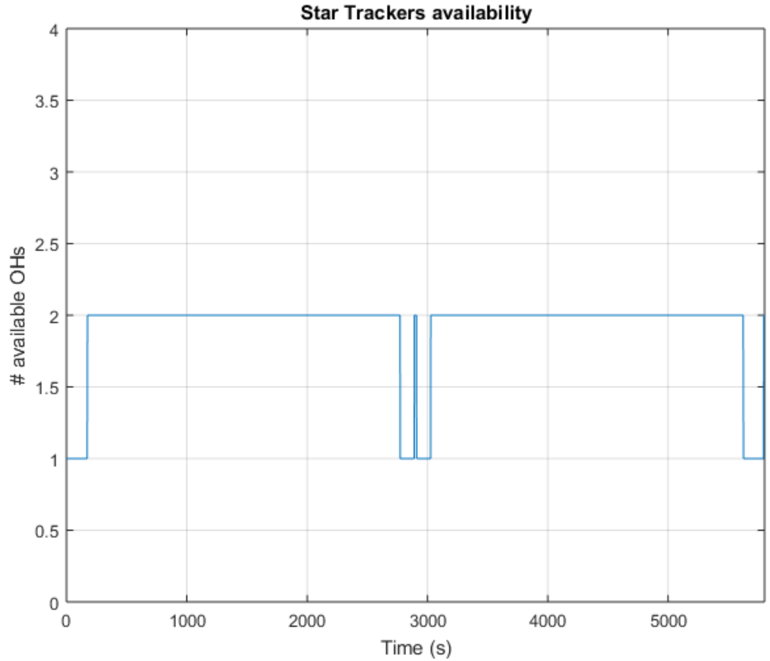
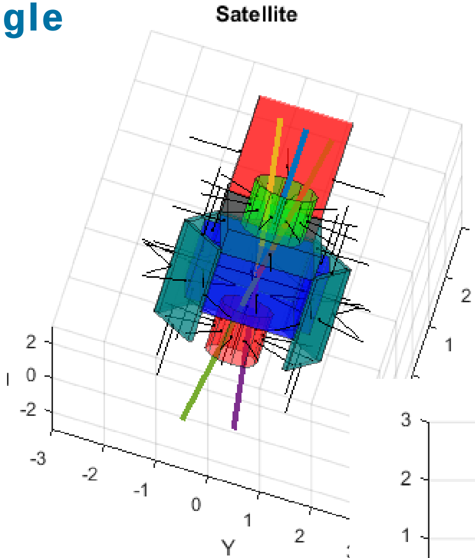
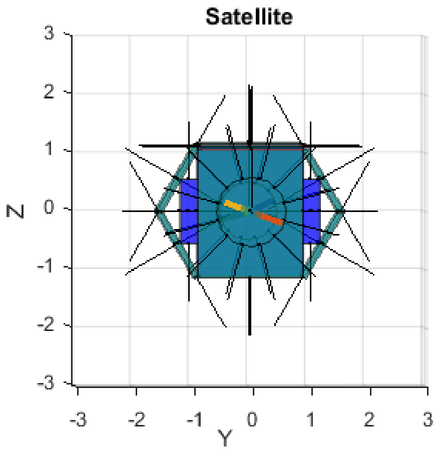
STR Earth occultation

Simulation results assuming 10 deg cant angle w.r.t IRT Los







A reference orbit has been considered, with a fixed pointing towards North Pole at the edge of the FoR (theta = 40 deg)

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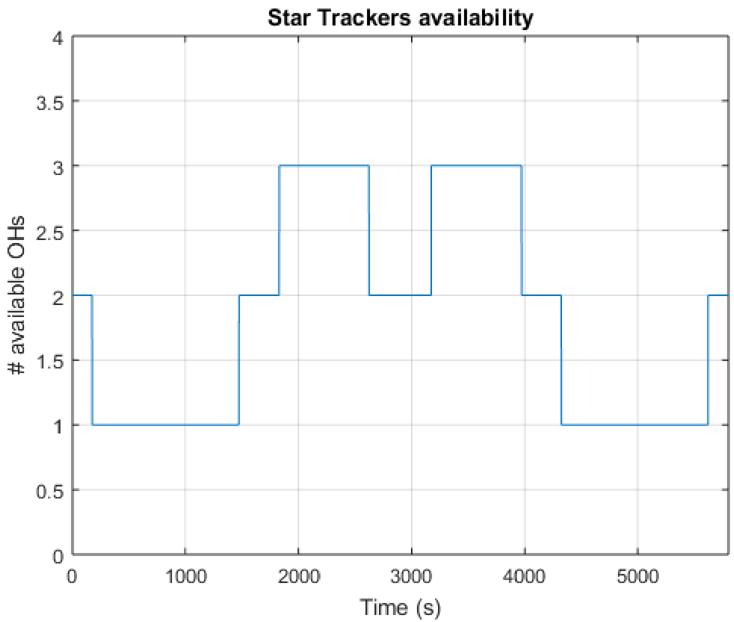
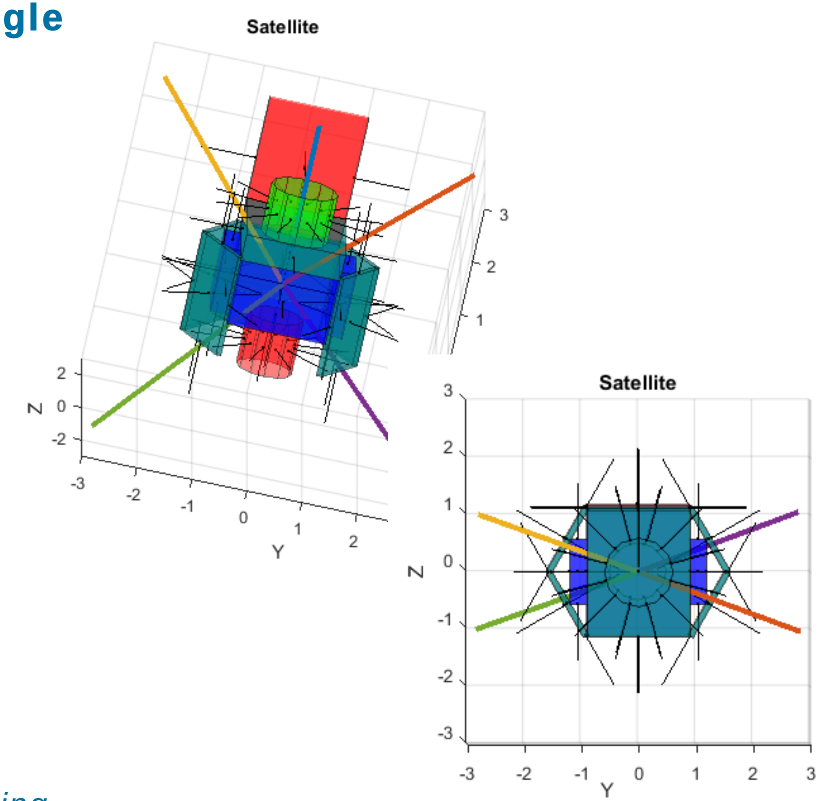
Simulation results assuming 45 deg cant angle w.r.t IRT Los





A reference orbit has been considered, with a fixed pointing towards North Pole at the edge of the FoR (theta = 40 deg)

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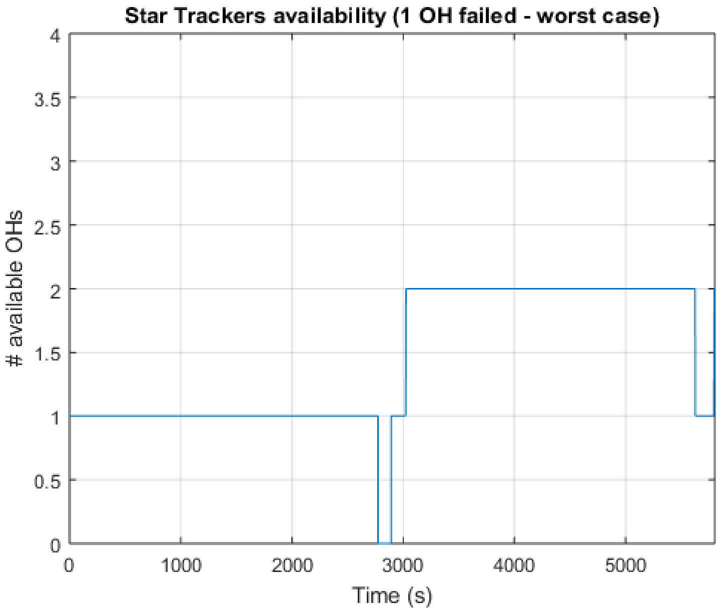
STR Earth occultation

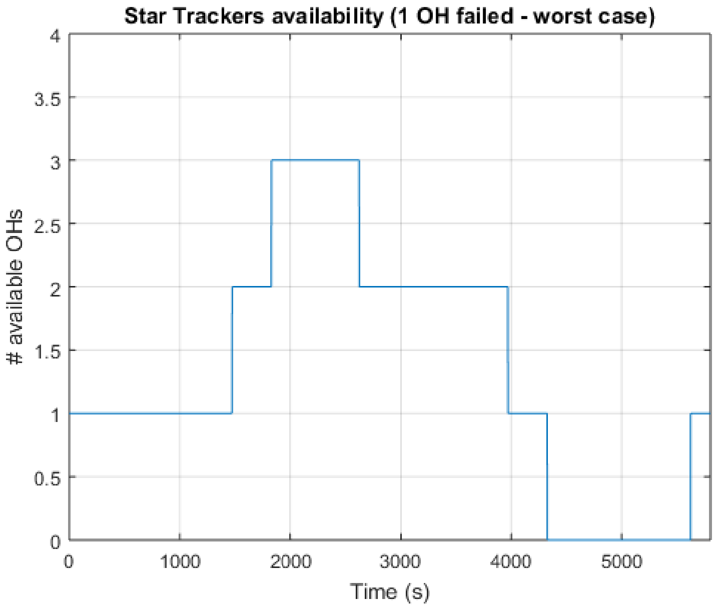
Simulation results (1 failed OH)

10 deg



~ 2 minutes of STR outage

45 deg



~ 15 minutes of STR outage

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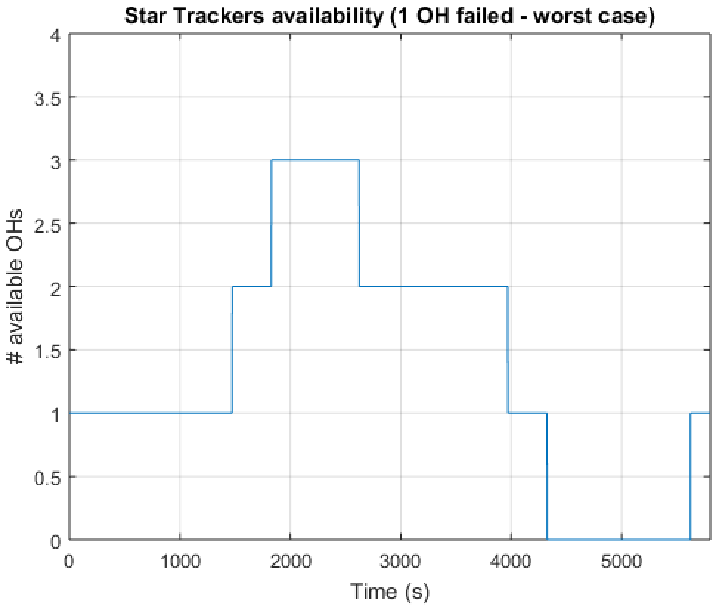
STR Earth occultation

Simulation results (1 failed OH)

Accumulated attitude error in case of STR outage of 15 minutes	Attitude error [arcsec] (1 sigma)	
	Astrix 200	**Astrix 1090**
Error due to RRW	0.23	13.50
Error due to ARW	0.36	9.00
Error due to initial GSE bias error	0.12	2.50
Error due to GSE initial attitude error	0.08	0.40
Total attitude estimation error	**0.45**	**16.42**

45 deg



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Pointing budget – AKE

Absolute Knowledge Error (AKE)

During IRT observation, the spacecraft design shall ensure that the Absolute Knowledge Error (AKE) of IRT's LoS in all axes is 2'' at 95% confidence, using the temporal statistical interpretation.

Error definition	Allocation (2 sigma)	Comment
STR internal TED	0.37	HYDRA - 2 blended OH at 10 Hz
STR FOV Spatial	0.40	
STR Pixel Spatial	1.60	
Gyro-stellar estimator	**0.08**	HYDRA + Astrix 200
AKE	**1.69**	

System specification	**2.00**	
Margin	**15%**	

2 STR OHs + high accuracy gyro is compliant but does not provide comfortable margin, especially at a such an early design phase => recommendation to assess STR-LOS TED and to look at impact of increasing AKE requirement to 3''

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Pointing budget – APE

Absolute Pointing Error (APE)

During IRT observation, the spacecraft design shall ensure that the Absolute Pointing Error (APE) of IRT's LoS is 120'' TBD (3σ) in pitch/yaw and 270'' TBD (3σ) in roll.

- AOCS contribution is driven by the STR attitude knowledge error and the control bandwidth.
- Assuming a control bandwidth of 0.1Hz, an APE of 2.61'' (3σ) is obtained.

Error definition	Allocation (1 sigma)	Allocation (3 sigma)
AOCS AKE	**0.85**	**2.13**
Environmental disturb.	0.1	0.3
Reaction Wheel Quantization	0.01	0.03
Reaction Wheel Torque noise	0.05	0.15
Controller Delay	0.17	0.51
Control Error	**0.20**	**0.61**
AOCS APE	**0.87**	**2.61**

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Pointing budget – RPE

Relative Pointing Error (RPE)

During IRT observation, the spacecraft design shall ensure that the Relative Pointing Error (RPE) of IRT's LoS of 1'' (3σ) over 10 seconds.

- AOCS contribution is given by the gyro-stellar estimator performance (2 STR OH + Astrix-200) plus the control error.
- Including the control error, a preliminary estimate of 0.62'' (3σ) for the overall AOCS contribution is obtained.

Error definition	Allocation (3 sigma)	Comment
Environmental disturb.	0.30	Source: AOGNC workbook
Reaction Wheel Quantization	0.03	
Reaction Wheel Torque noise	0.15	
Controller Delay	0.51	
Control Error	**0.61**	
AOCS RKE (gyro-stellar estimator)	**0.27**	HYDRA + Astrix 200
AOCS RPE	**0.62**	

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Pointing budget – RPE

Relative Pointing Error (RPE)

During IRT observation, the spacecraft design shall ensure that the Relative Pointing Error (RPE) of IRT's LoS of 1'' (3σ) over 10 seconds.

In addition to the AOCS contribution, the Spacecraft RPE shall be computed considering:

- *Micro-vibrations (cryo-cooler and RW)*
- *Sloshing effects*
- *Flexible modes of the payload*

Preliminary system level budget is provided considering:

- 15Nms RCD Wheel, working <600 rpm, with isolator (*same assumptions as on SPICA*) + 50% margin
- Cryo-cooler contribution from SPICA (*note: allocation assumes isolator, which is not in THESEUS baseline*)

Error definition	Allocation (3 sigma)	Comment
Environmental disturb.	0.30	Source: AOGNC workbook
Reaction Wheel Quantization	0.03	
Reaction Wheel Torque noise	0.15	
Controller Delay	0.51	
Control Error	**0.61**	
AOCS RKE (gyro-stellar estimator)	**0.27**	HYDRA + Astrix 200
AOCS RPE	**0.62**	
RW microvibrations	**0.31**	
Cryocooler microvibrations	**0.03**	
Spacecraft RPE	**0.96**	
System specification	**1.00**	
Margin	**4%**	

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RPE – gyro trade-off

Astrix 200

Error definition	Allocation (3 sigma)
Environmental disturb.	0.30
Reaction Wheel Quantization	0.03
Reaction Wheel Torque noise	0.15
Controller Delay	0.51
Control Error	**0.61**
AOCS RKE (gyro-stellar estimator)	**0.27**
AOCS RPE	**0.62**

RW microvibrations	**0.31**
Cryocooler microvibrations	**0.03**

Spacecraft RPE	**0.96**

System specification	**1.00**
Margin	**4%**

Astrix 1090

Error definition	Allocation (3 sigma)
Environmental disturb.	0.30
Reaction Wheel Quantization	0.03
Reaction Wheel Torque noise	0.15
Controller Delay	0.51
Control Error	**0.61**
AOCS RKE (gyro-stellar estimator)	**0.27**
AOCS RPE	**0.85**

RW microvibrations	**0.31**
Cryocooler microvibrations	**0.03**

Spacecraft RPE	**1.19**

System specification	**1.00**
Margin	**-19%**

Accumulated attitude error in case of STR outage of 15 minutes	Attitude error [arcsec] (1 sigma)	
	Astrix 200	**Astrix 1090**
Total attitude estimation error	**0.45**	**16.42**

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Pointing budget – PDE

Performance Drift Error PDE

During IRT observation, the spacecraft design shall ensure that the Performance Drift Error (PDE) of IRT's LoS of 10'' (3 sigma) over 5 minutes.

Considering the APE performance (2.61'' 3 sigma) achieved by the AOCS, PDE performance is expected to be driven by thermo-elastic effects (especially considering the case of eclipse entry/exit during the 5 minutes time-frame).

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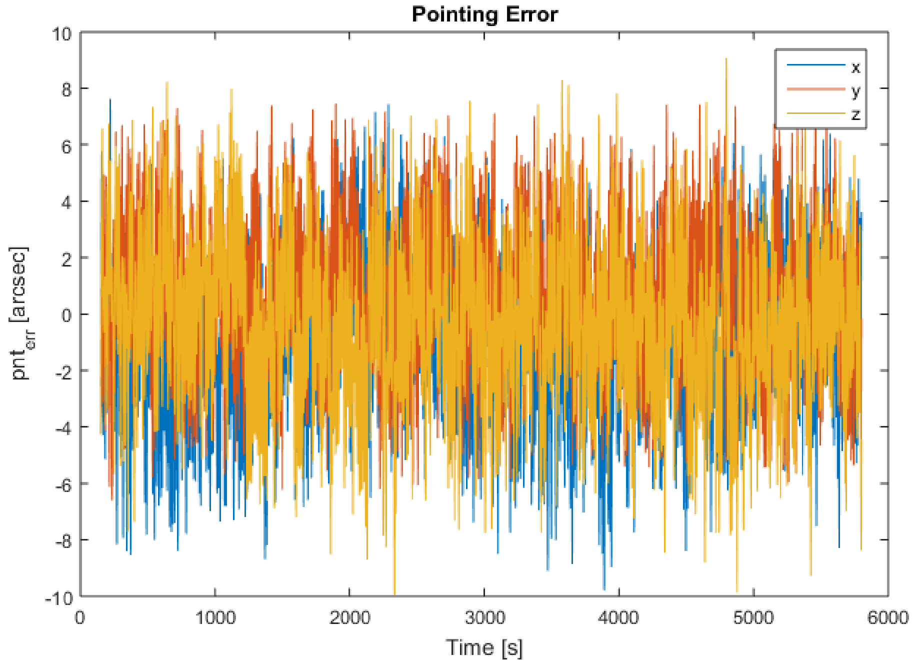
Pointing budget - Simulation results

Results of Simulink simulation (GAST Toolbox) over 1 orbit

Please note that controller and gyro-stellar estimator are not fine-tuned.

	x [arcsec]	y [arcsec]	z [arcsec]
APE (3 sigma)	7.95	7.23	7.91
RPE (3 sigma)	1.26	1.17	1.23
PDE (worst case)	6.77	6.34	7.11



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Pointing Budget: Spacecraft and Telescope contribution

Presented Pointing performances only include AOCS contribution (and rough micro-vibration contribution for the RPE).

However for future phases, final pointing budget of the Instruments LOS has to be refined considering:

- Thermo-elastic effects at Spacecraft level (mitigated by OH location thermally coupled with the IRT) -> APE,AKE,PDE
- Thermo-elastic effects internal to the telescope -> APE,AKE,PDE
- Optical distortion effects -> APE,AKE,PDE
- Knowledge of optical axis (detectors displaced w.r.t. center of the focal plane) -> APE,AKE,PDE
- Micro-vibrations (RW and cryo-cooler) -> RPE
- Propellant sloshing -> RPE
- Structural flexible modes -> RPE

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Communications

S/S/X architecture – Requirements and design drivers

Requirements

- Provide telemetry and telecommand functionalities (at any attitude and mode).
- Provide payload data downlink (at any attitude).
- Provide tracking (ranging) functions (at any attitude, in LEOP & safe modes).

Design drivers

- Payload Data Volume
  - ~70 Gbit/day (average)   Drives data rates, band selection & S/S design
- Omni-directional communications in nominal mode
  - No science interruption during communications.
- Baseline GS (<15 [m])
- DC power consumption

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S/S/X architecture – Assumptions

Assumptions

- As much heritage as possible (from existing commercial LEO platforms).

- Ground station (& orbit)
  - Orbit altitude: 600 [km], quasi-equatorial
  - Elevation angle: 5 [deg]
  - 14.9 orbits per day ; 1 contact per orbit ; 10 minutes per contact (avg)
  - Baseline: Malindi (MAL-1, 10 [m] or MAL-2B, 13 [m])
  - Back-up: Kourou (15 [m])
    - Links computed for all 3 GS → S-band and X-band support is assumed on all
  - S-band and X-band downlinks are supported simultaneously by the GS
    - Confirmed for ESTRACK EO GS, TBC for Malindi (MAL-1 & MAL-2B)

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S/S/X architecture – Assumptions

Assumptions

- Modulation and coding schemes
  - GMSK for X-band tx (most BW efficient) (X-band allocation = 10 [MHz] max.)
  - QPSK for S-band tx nominal (S-band allocation << 6 [MHz] ; highly congested!)
  - SP-L for S-band LEOP & emergency (for ranging)
  - Reed-Solomon coding for X-band
  - Reed-Solomon + Conv. Coding for S-band
- Data rates

X-band – Payload: 8.3 [Mbps] (science bit rate) ⇨ 5 Gbit/orbit (74.5 Gbit/day)

9.1 [Mbps] (information data rate)

10.47 [Msps] (channel symbol rate)

(margins for protocol and re-transmission overheads included)

S-band – HK TM: 128 [kbps] (from TAS XIPE study)

(includes monitored sources, quick look data, payload HK, platform HK)

S-band – HK TC: 4 [kbps] (minimum)

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S/S/X architecture – Trade-offs

[S/S] vs [S/S/X] vs [X/X] architectures

Parameter	Option 1 (S/S)	Option 2 (S/S/X)	Option 3 (X/X DST) (current)	Option 4 (X/X DST) (future)
Complexity	1 band High TRL	2-bands High TRL	1-band High TRL	1-band Delta-dev. needed
Performance	1.9 Gbit/orbit (1 GS pass/orbit)	5 Gbit/orbit (1 GS pass/orbit)	5 Gbit/orbit (1 GS pass/orbit)	8.9 Gbit/orbit (1 GS pass/orbit)
Cost	Recurrent (ADS platform), 1-band	Recurrent (TAS platform), 2-bands	Most expensive	Most expensive + delta-dev.
Mass & power				
Overall				

Best
Good
Poor
Worst

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S/S/X architecture – Trade-offs

SSPA vs TWTA (X-band)

Parameter	Malindi 10m X-band (8475 [MHz]) TWTA	Malindi 10m X-band (8475 [MHz]) SSPA
Tx Power	27 [W]	27 [W]
Unit type	TH 4604 C model Output range: [12 – 45] [W]	Thales SSPA Output range: [10 – 30] [W]
Efficiency	59%	25%
Power consumption	45.8 [W] (TWT) + 3 [W] (EPC) = **48.8 [W]**	**108 [W]**
Mass	1 [kg] (TWT) + 1.4 [kg] (EPC) = **2.4 [kg]**	**1.5 [kg]**
Dimensions	381x62x54 [mm] (TWT) 200x66x119 [mm] (EPC)	Compact

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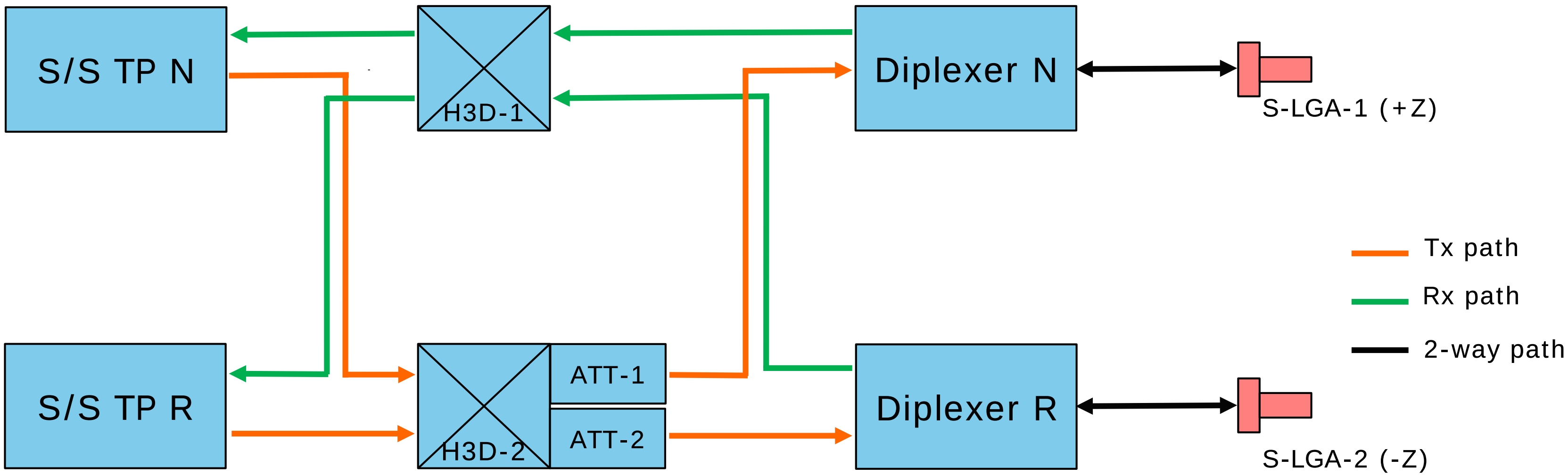
S/S/X architecture – Baseline design – S-band



- Rx in hot redundancy ; Tx in cold redundancy
- Tx output always through both antennas; cross-strapping also guarantees no SPFs (any Rx/Tx with any antenna).
- Attenuators help achieve a positive PFD margin. If removed, the following improvements could be possible, also keeping cross-strapping (but would require less output power from the transponder, maybe too close to its minimum output power capability):
  - Diplexer mounted on the transponder (classical ISBT approach).
  - Removal of one coupler.

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S/S/X architecture – Baseline design – Link budgets – S-band

S-band downlink (suppressed carrier, no ranging)

Parameter	Kourou 15m S-band (2245 [MHz])		Malindi 13m S-band (2245 [MHz])		Malindi 10m S-band (2245 [MHz])	
Scenario	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing
Modulation Coding	QPSK R-S + CC (1/2,7)					
Tx Power	0.5 W					
EIRP	-5.51 dBW	-11.51 dBW	-5.51 dBW	-11.51 dBW	-5.51 dBW	-11.51 dBW
G/T on ground	29.1 dB/K		26 dB/K		21.3 dB/K	
HK TM DR	128 kbps					
Required Eb/No	2.5 dB					
Margin (>3 dB)	27.81 dB	21.81 dB	23.71 dB	17.71 dB	20.31 dB	14.31 dB
PFD Margin (>0 dB)	0.11 dB (worst)					

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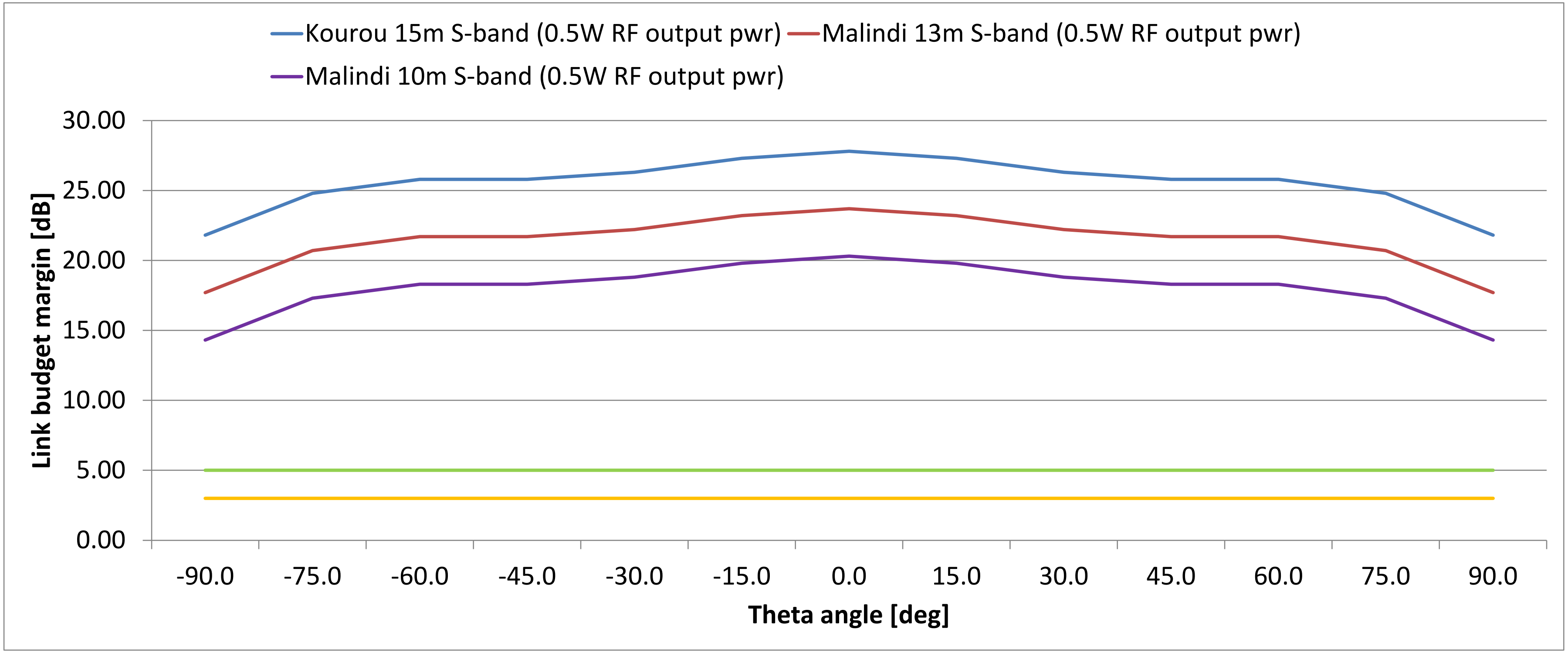
S/S/X architecture – Baseline design – Link budgets – S-band

S-band downlink (suppressed carrier, no ranging) (5 deg. elevation angle)



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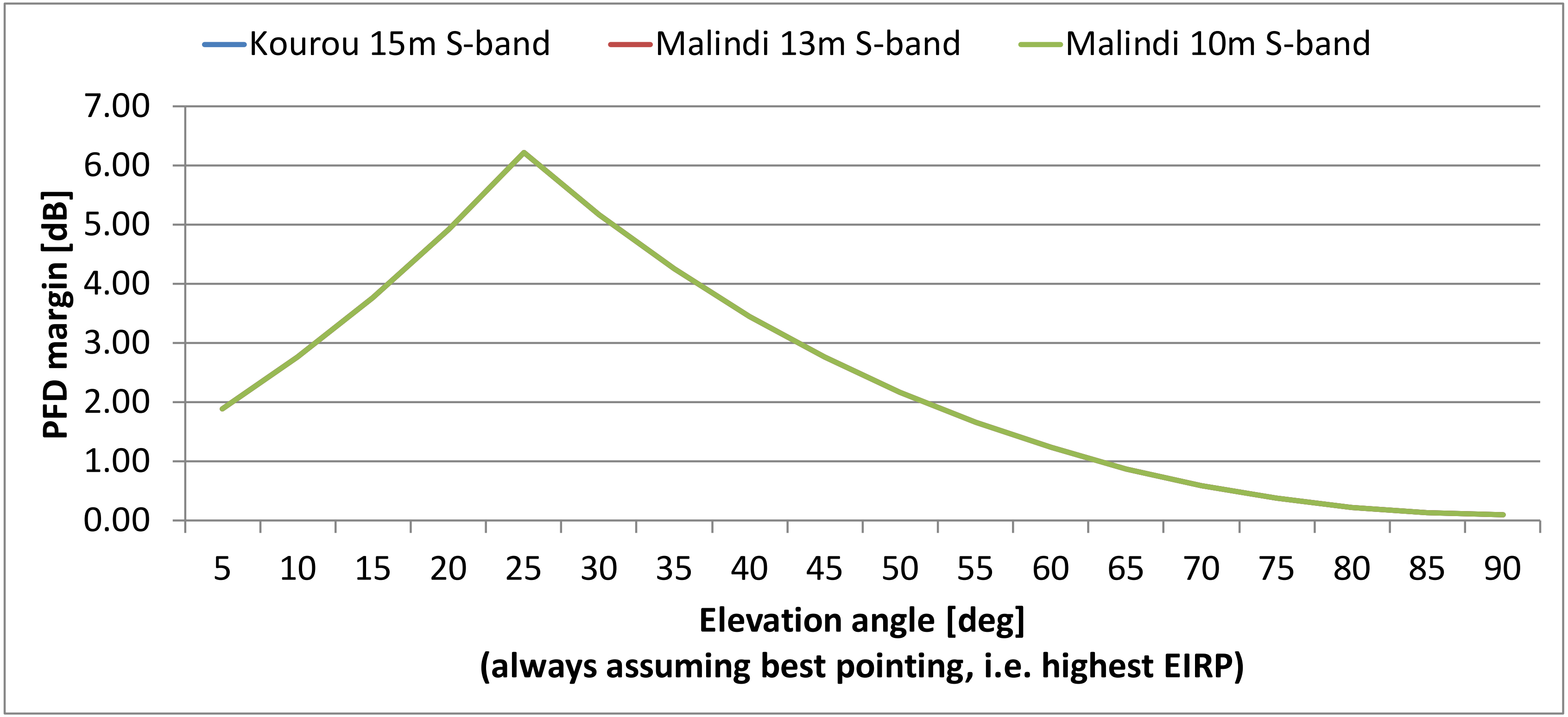
S/S/X architecture – Baseline design – Link budgets – S-band

S-band downlink (suppressed carrier, no ranging) (boresight antenna pointing)



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S/S/X architecture – Baseline design – Link budgets – S-band

S-band downlink (residual carrier)

Parameter	Kourou 15m S-band (2245 [MHz])		Malindi 13m S-band (2245 [MHz])		Malindi 10m S-band (2245 [MHz])	
Scenario	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing
Modulation Coding	SP-L (1.4 TM mod. idx.) R-S + CC (1/2,7)					
Tx Power	0.5 W					
EIRP	-5.51 dBW	-11.51 dBW	-5.51 dBW	-11.51 dBW	-5.51 dBW	-11.51 dBW
G/T on ground	29.1 dB/K		26 dB/K		21.3 dB/K	
HK TM DR	128 kbps					
Required Eb/No	2.5 dB					
Margin TM recovery (>3 dB)	27.68 dB	21.68 dB	23.58 dB	17.58 dB	20.18 dB	14.18 dB
PFD Margin (>0 dB)	1.96 dB (worst)					

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S/S/X architecture – Baseline design – Link budgets – S-band

S-band uplink (residual carrier)

Parameter	Kourou 15m S-band (2245 [MHz])		Malindi 13m S-band (2245 [MHz])		Malindi 10m S-band (2245 [MHz])	
Scenario	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing
Modulation Coding	SP-L (1.4 TM mod. idx.) BCH coding					
EIRP from ground	74.60 dBW		70 dBW		68.70 dBW	
G/T on spacecraft	-28.62 dB/K	-34.62 dB/K	-28.62 dB/K	-34.62 dB/K	-28.62 dB/K	-34.62 dB/K
HK TC DR	From 4 kbps to >128 kbps					
Required Eb/No	9.6 dB					
Margin (>3 dB) (4 kbps)	57.73 dB	51.73 dB	53.13 dB	47.13 dB	51.83 dB	45.83 dB
Margin (>3 dB) (128 kbps)	42.68 dB	36.68 dB	38.08 dB	32.08 dB	36.78 dB	30.78 dB

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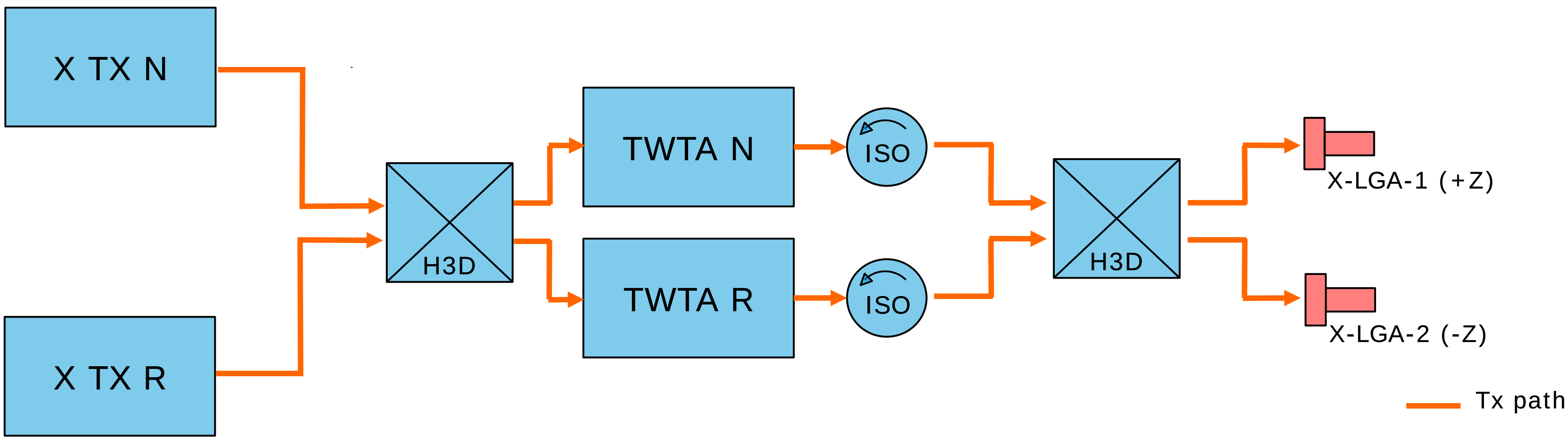
S/S/X architecture – Baseline design – X-band



- Tx in cold redundancy
- Tx output always through both antennas.
- Cross-strapping guarantees no SPFs:
  - Any transmitter with any antenna.
  - Any transmitter with any amplifier.
  - Any amplifier with any antenna.

All antennas must be placed such that there is **no interference among subsystems**:

- S-band Tx to S-band Rx ("self-compatibility")
- S-band Tx to L-band Rx
- VHF-band Tx to L-band Rx
- VHF-band Tx to S-band Rx
- ~~X-band Tx to any Rx~~ (waveguide lower cut-off frequency mitigates this risk)

In addition, antennas (at least X-band & S-band) should have opposite radiation patterns (RHCP, LHCP) to minimize interference patterns (cross-pol).

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S/S/X architecture – Baseline design – Link budgets – X-band

X-band downlink

Parameter	Kourou 15m X-band (8475 [MHz])		Malindi 13m X-band (8475 [MHz])		Malindi 10m X-band (8475 [MHz])	
Scenario	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing	LGA TM Nominal	LGA TM Nominal, worst pointing
Modulation Coding	GMSK R-S					
Tx Power	10 W (SSPA, Pcons = 40 [W])		20 W (TWTA, Pcons = 36.9 [W])		27 W (TWTA, Pcons = 48.8 [W])	
EIRP	6.50 dBW	-1.00 dBW	9.51 dBW	2.01 dBW	11.27 dBW	3.77 dBW
G/T on ground	41 dB/K		34.1 dB/K		31.80 dB/K	
Science DR (gross DR)	8.3 Mbps (9.1Mbps)		8.3 Mbps (9.1Mbps)		8.3 Mbps (9.1Mbps)	
Required Eb/No	6.6 dB					
Margin (>3 dB)	17.49 dB	9.99 dB	13.60 dB	6.10 dB	12.60 dB	5.10 dB
PFD Margin (>0 dB)	13.65 dB (worst)		10.64 dB (worst)		9.34 dB (worst)	

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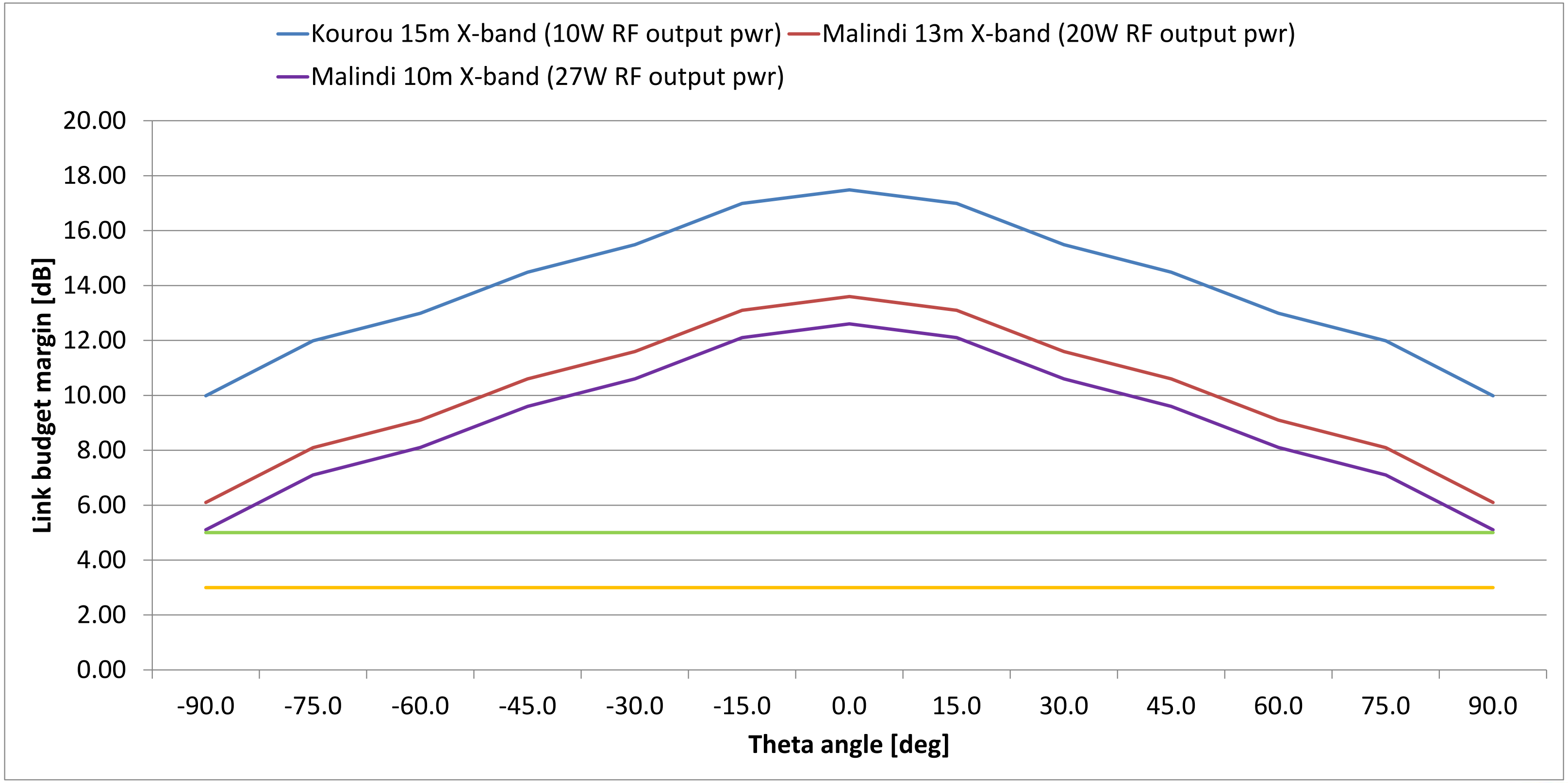
S/S/X architecture – Baseline design – Link budgets – X-band

X-band downlink (5 deg. elevation angle)



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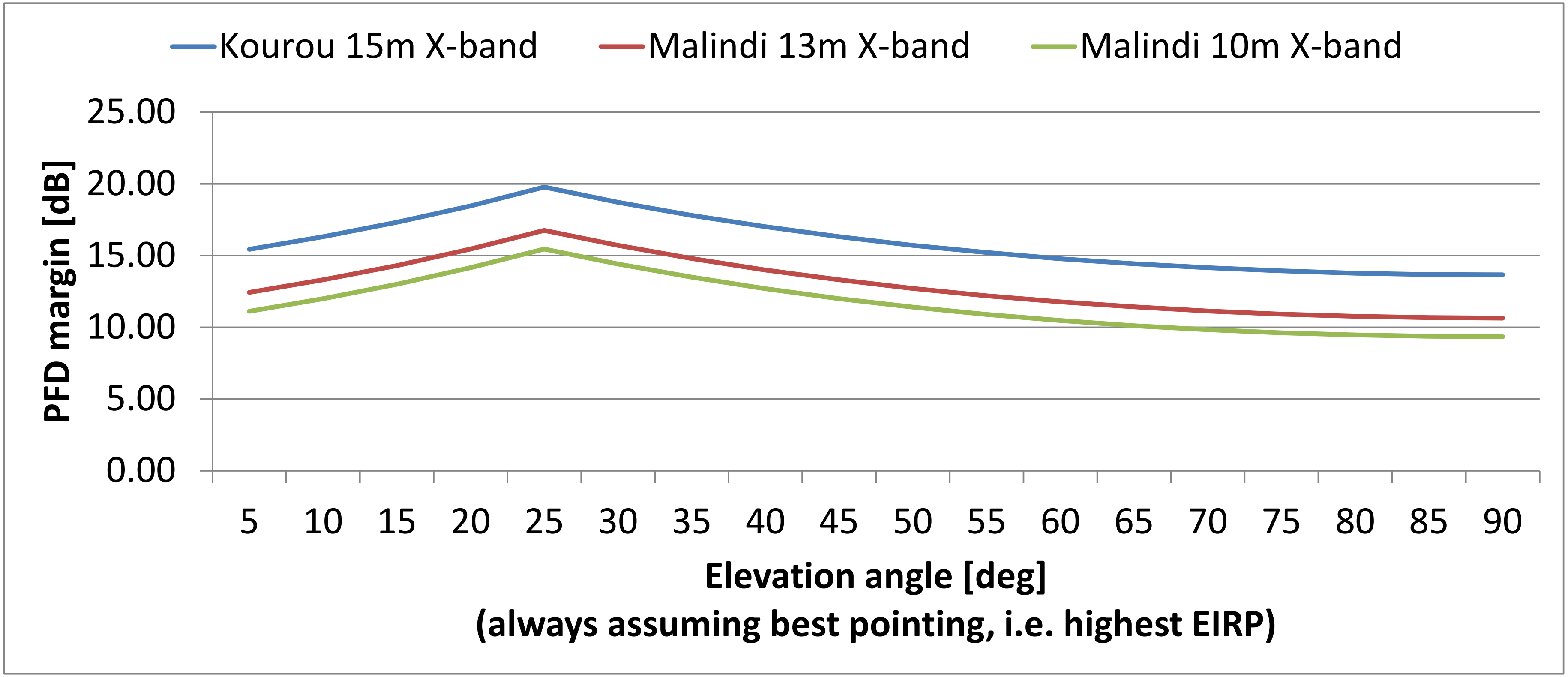
S/S/X architecture – Baseline design – Link budgets – X-band

X-band downlink (boresight antenna pointing)



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S/S/X architecture – Baseline design – Summary

Mass & Power

21 [kg] ; 23 [kg] (incl. margin)
91 [W] peak power consumption (2x S-RX ON ; 1x S-TX ON ; 1x X-TX ON)

Hardware

2 S-LGAs for omni coverage (LEOP, nominal, emergency)
2 X-LGAs for omni coverage (nominal)
High TRL (technologies are flight proven)
1 S-band (TX & RX) RF front-end, redundant, cross-strapping (hot redundancy for Rx) (cold redundancy for Tx)
1 X-band (TX) RF front-end, redundant, cross-strapping (cold redundancy for Tx)
Ranging (RNG) possible via S/S TP (LEOP, emergency)

Data Rates

S-band DR for HK TM & TC: • HK TC: 4 [kbps] ; ~2.5 [Mbit/orbit] (we could consider even rates >128 [kbps] • HK TM: 128 [kbps] ; ~75 [Mbit/orbit]
X-band DR: • 8.3 [Mbps] science data rate ; ~5 [Gbit/orbit] (9.1 [Mbps] gross data rate)

Driving Link Budgets

P/L (science) data downlink (nominal) (X-band)	✓
HK TM downlink (nominal) (S-band)	✓
HK TM downlink (LEOP & emergency (S-band)	✓

✓ ⇨ ➢ **5 [dB] margin**

✓ ⇨ ➢ **3 [dB] margin**

- **Links ✓ :**
  - **For all GS**
  - **For all pointing directions**

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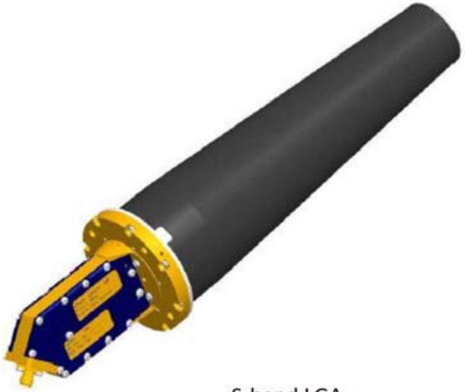
S/S/X architecture – Equipment list – S-band

- **ISBT** (TAS-E): TRL-9
- **LGA** (Rymsa, RUAG): helix, TRL-9
- **RFDN** (several suppliers): TRL-9, coaxial (passive) equipment


ISBT (TAS-E)


S-band LGA

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S/S/X architecture – Equipment list – X-band

- **X-band TX** (TAS-I): TRL-9
- **TWTA (TWT + EPC)** (Thales): TRL-9
- **LGA** (Rymsa, RUAG): choked horn, TRL-9
- **RFDN** (several suppliers): TRL-9, waveguide (passive) equipment

X-band TX (TAS-I)

X-band TWT + EPC assembly (TWTA)

X-Band LGA

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Trigger Broadcasting Unit (TBU) architecture

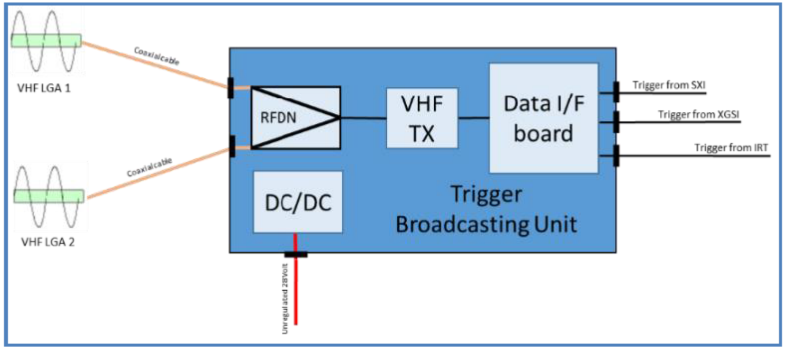

Figure 20: general block diagram of the Trigger Broadcast Unit

- Possible frequency range (VHF):
  137-137.175 [MHz]
- Reference on-board antenna:
  - Quadrifilar helix
    - x3 units, on +X & -X S/C axis
  - Height: 500 [mm]
  - Diameter: 100 [mm]
  - Gain of ~3 [dB] @ 0 [deg] and 0 [dB] @ 60 [deg]
- TBU resources allocation (transmitter beacon box):
  - A cube of approximately 20 [cm] side
  - Mass: ~1-2 [kg] ; Power: 2.0 [W]
  - Operational temperature range: [-20 : +50] [°C]
  - Non-operational temperature range: [-30 : +60] [°C]

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Data Handling

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Requirements & Assumptions

- Top level reqs:
  - Manage modes
  - Manage PF, PLM
  - Dual chain
  - Receive & process commands (slew) from Payload
- Cold dual Redundancy
- DHS provides I/F to thermal subsystem
- DHS interfaces sensors/actuators for AOCS/GNC and propulsion
- OBC is the MILBUS Bus Controller, I-DHUs are RTs
- MILBUS for C&C, SpW for science
- OBC Polls I-DHUs, delivers attitude data
- DHS shall store data acquired over 48 hours

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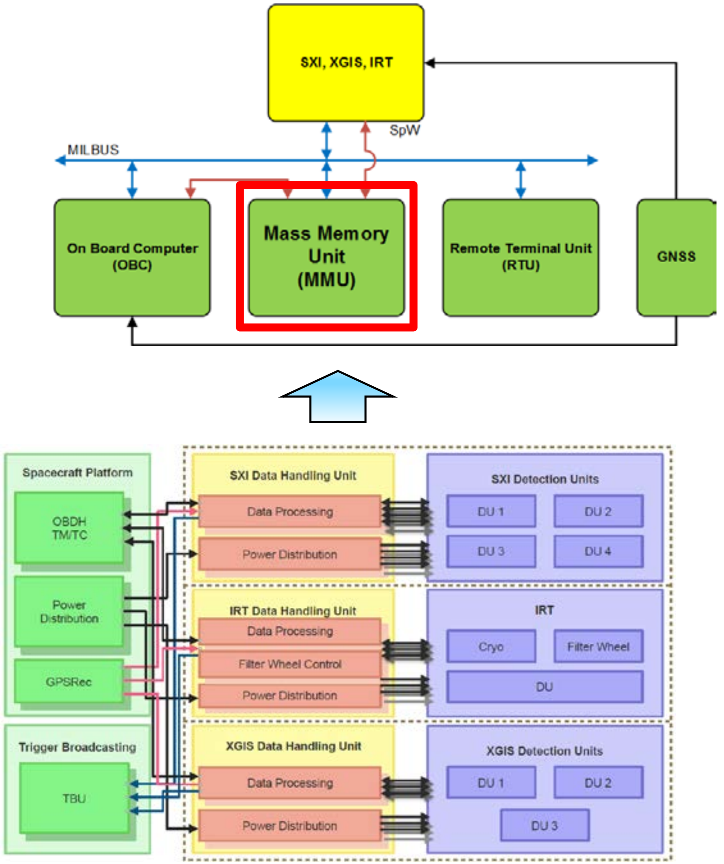
Baseline Design

- Components
  - On Board Computer
  - “*In case of a defect in the memory board, the scientific data stored there will be lost (no backup of the data)*” => <u>Mass Memory Unit on PF.</u> Also eases integration.
  - Remote Terminal Unit
- Interaction between I-DHUs
  - OBC is the BC
  - OBC polls at e.g. 10Hz each I-DHU
  - In case of trigger exchange of information between I-DHUs can be in the order of 300 to 500 ms which is ok
- Slew request:
  - Done by I-DHUs => Provides isolation, simplifies SW verification
  - By DHS using TSP? => Provides isolation but requires performant OBC, not yet mature



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Baseline Design (1/4)

- DHS architecture straight forward
- OBC:
  - OSCAR from ADS (SCOC3) – Baselined here
    - Fully redundant, two boards (PM & IO board and power board), 40 MIPS @ 48MHz, MILBUS, 2xSpW, CCSDS TM/TC, up to 8 reconfiguration scenarios
    - SCoC3 based – TC/TM integrated in ASIC
    - Mass 5 Kgs, Volume 230x160x200 mm, Power 15 W
    - 512 Mbytes Mass Memory -> Separate memory required
- Alternative:
  - RUAG Single Board Computer (SBCC) - CREOLE based "*OBC+MMU integrated*" (8 Kgs, 23W, 208x242x278 mm, >300Gbits capacity). – ***EQM in 2019***

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Baseline Design (2/4) – OSCAR OBC

6) TC/TM connectivity to N, R and EGSE for AIT

4) TC Decoder with output to RM

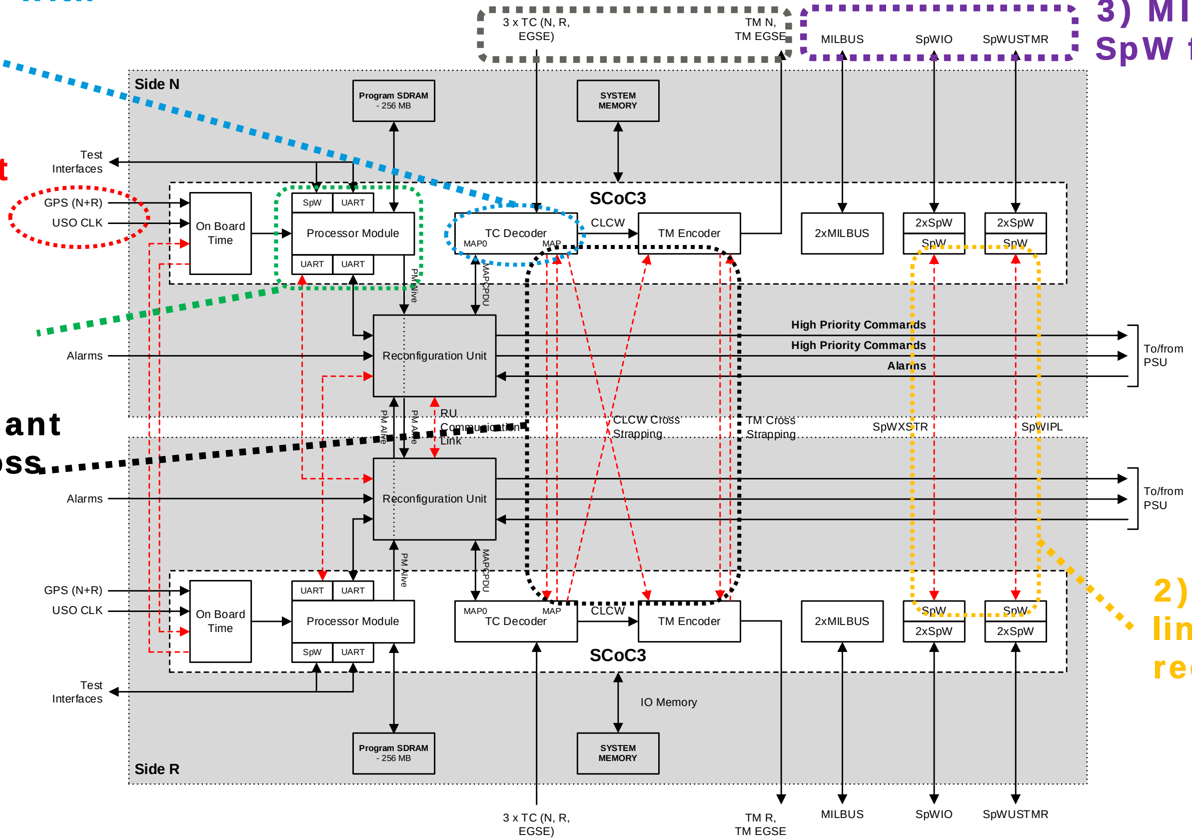
3) MILBUS for C&C, SpW for SSMM

7) GNSS Input

1) LEON3 PM

5) Hot redundant TC, TC/TM cross strapping

2) SpW/RMAP inter-PM links for SGM, MM redundant access



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Baseline Design (3/4) - GNSS

Specs				
	Mosaic	**LION 1300**	**LION 1100**	**LION 1100 Neo**
Mass	4 Kgs	6 Kgs		6.8 Kgs
Volume	272x288x92 mm^3	226x184x205 mm^3		226x229x205 mm^3
Power	8W	20 W		18 W
Radiation	> 30 KRads			
Configuration	No Redundancy/ LNA	Full redundancy, LNA external		Full redundancy includes LNA
Freq.	Mono	Tri	Mono	
	L1 C/A	E1, L1, E5a, E5b, L2, E2		
Position accuracy	10 m LEO	1m LEO	6m LEO	
Velocity Accuracy	0.01 m/s LEO	0.001m/s LEO	0.01m/s LEO	
Time	100 ns LEO	50 ns LEO		

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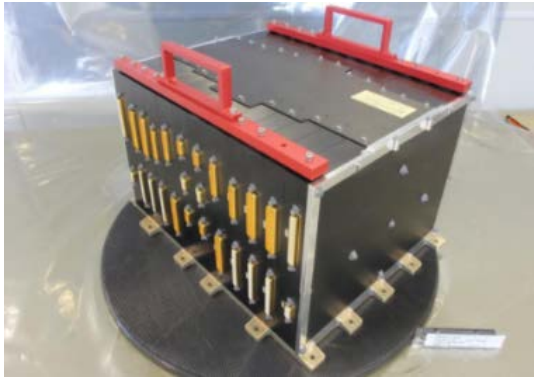
Baseline Design (4/4) – MM, RTU

- Mass Memory:
  - DSI Compact High Performance PDHU (Wavelet compression, 1Tbit, 4Gbps input, 1Gbps output,) – under development but based on JUICE
- RTU:
  - CRISA AS250 RIU
  - Example Configuration



RTU Modules	Number of modules	Mass per module	Total Mass
OPIM (OBC I/F+ Prop)	2	1107 g	2214 g
STDIM (Std I/Fs) A/B	4	1101 g	4404 g
AIM (AOCS)	2	1303 g	2606 g
Motherboard	1	524 g	524 g
Baseplate	1	1101 g	1101 g
Covers	1	853 g	853 g
Assembly tie rods	1	200 g	200 g
TOTAL			11902 g

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Overall

	Mass (kg)	Margin	Total (kg)	Power (W)
OBC	6.0	5%	6.3	20
GNSS Receiver	6.8	5 %	7.14	18
SSMM	6	20%	7.2	7
RTU	12.0	20%	14.4	28
			35.04	**73**

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Propulsion

Requirements

ID	Requirement	Results/ Impacts
CPROP-1	Delta–v for deorbiting, maintenance and collision avoidance given as maximum values	Propellant mass/total Delta-V
CPROP-2	3 safe mode events per year for 5 years + 1 LEOP	Total Delta-V/propellant mass
CPROP-3	Direct launch into operational orbit	No need for correction
CPROP-4	Controlled de-orbiting, 4 options investigated	Different thruster configurations/ Different propellant and system mass
CPROP-5	Investigate solid propulsion option for de-orbiting	Trade off liquid-solid propulsion

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Inputs for operational life and de-orbiting

- Delta-v and AOCS mass
  - SVM + PLM dry mass w/ 20% margin updated to latest dry value
    1350 kg
    (trade-off performed with 1263 kg)
  - RCS propellant for safe mode 16 events
    - 1.9 kg for rate reduction
    - 7.3 kg for attitude hold
      9.2 kg ➔ 18.4 kg (w/ 100% margins)
  - Delta-V for
    - Collision avoidance (550 to 670 km altitude):
      2 m/s ➔ 4m/s (w/ 100% margins)
    - Orbit manoeuvre capability:
      25 m/s ➔ 26.25 m/s (w/ 5% margins)

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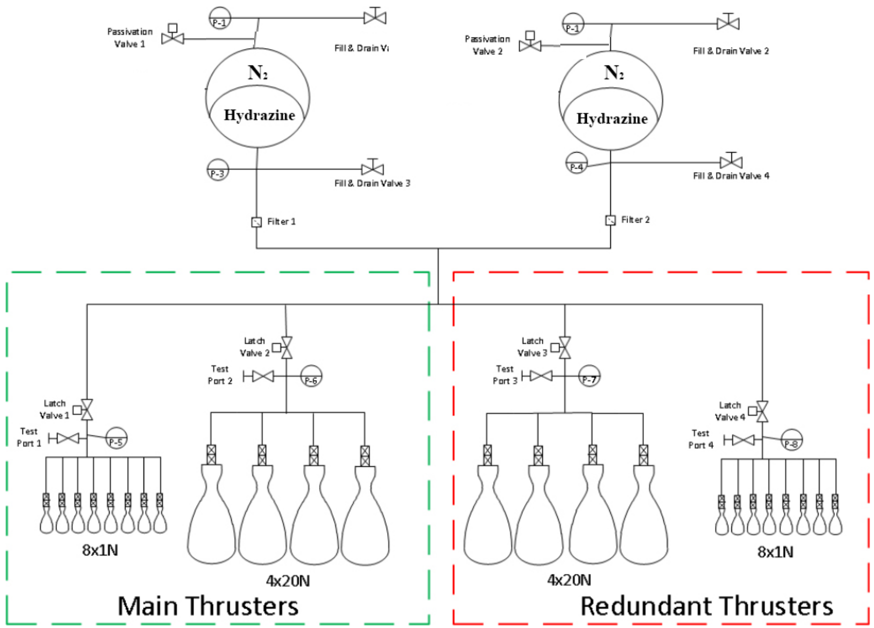
Baseline design – controlled reentry Liquid propulsion

- Controlled De-Orbiting:
  - 8 (+8 Redundant) 1N-Thrusters for sun acquisition and safe mode
  - 4 (+4 redundant) 20N-Thruster

  for deorbiting

  - Additional equipment needed
    - Valves: latch and passivation
    - Tanks: 1 or 2 depending on the number of thrusters
    - pipes, filters and pressure transducers
    - Pressurant N_2

Mono-Propellant (Hydrazine)



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Liquid propulsion de-orbiting trade-off

40 N vs 80 N options for both 2 and 4 burns are investigated, Delta-V requirements from mission analysis

	40 N	80 N
3 burns	239.9 m/s	187.8 m/s
4 burns	203.0 m/s	183.6 m/s

Trade-off assumptions:

- Single burn ➔ constant thrust
- Dry mass 1263 kg
- Updated values have been employed only for the baseline option

Main outcome in terms of masses are:

- Propellant consumption
- Volume and number of tanks
- Number of thrusters

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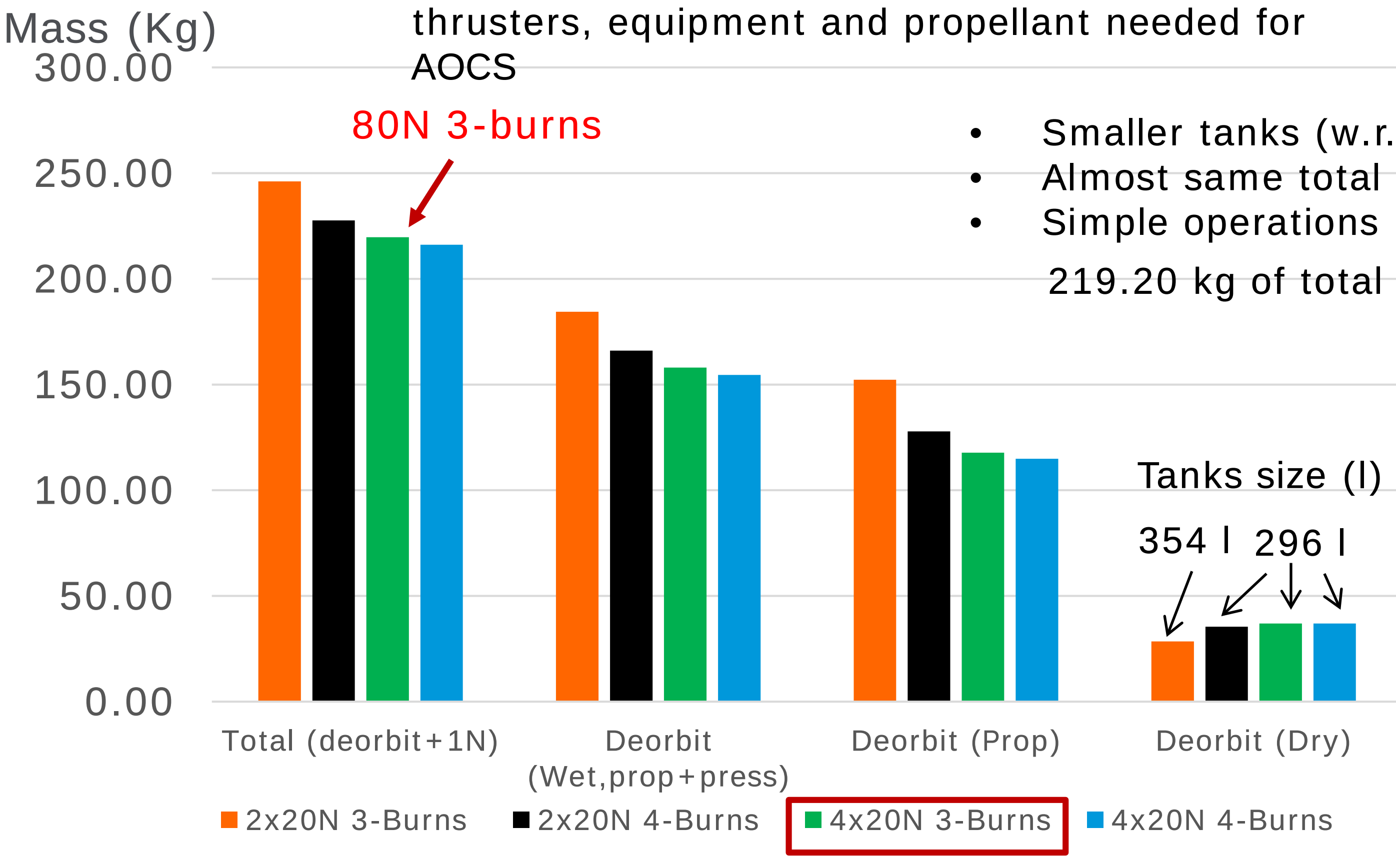
Liquid propulsion de-orbiting trade off

Mass of the deorbiting system, excluding the thrusters, equipment and propellant needed for AOCS



- Smaller tanks (w.r.t. 40N / 4 burns)
- Almost same total mass (w.r.t. 80N/ 4 burn
- Simple operations

219.20 kg of total mass

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Power duty cycle: 80N 3 burns

Power duty-cycle of the RCS/De-orbiting:

Manoeuvre	Thruster	Number	Catalyst bed heater Power [W] (1 unit)	Solenoid valve [W] (1 unit)
Sun pointing and de-tumbling after launch	1N	8(+8)	6.4 (ON after launch phase)	6.5 (ON during firing)
Collision avoidance	1N	8(+8)	6.4 (ON x 2 hrs before firing)	6.5 (ON during firing)
Safe mode	1N	8(+8)	0 (cold start assumed to save power)	6.5 (ON during firing)
Deorbiting	20N	4(+4)	3.05 (ON x 2 hrs before firing)	13 (ON during firing)

- Catalyst bed must be heated after launch operations to avoid oxidation
- CHT-1N thrusters allow up to 10 cold starts. Here considered to save power and just in safe mode operations
- Cold starts should be avoided to prevent degradation of the catalytic bed

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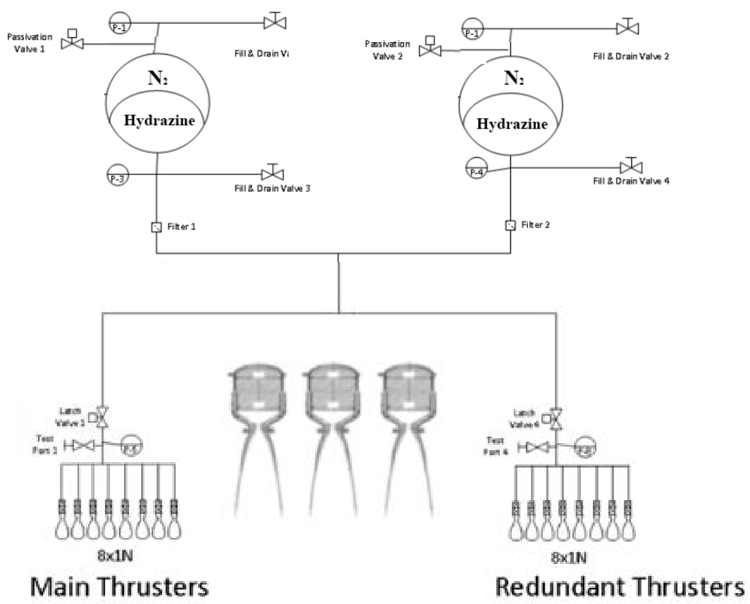
Optional design – controlled reentry
Solid propulsion

- Options for controlled De-orbiting:
    - Solid propulsion (AP-HTPB-Al. TBC)

- Controlled De-Orbiting:
    - Two smaller tanks
    - 8 (+8 Redundant) 1N-Thrusters for sun acquisition and safe mode
    - Thrusters in blowdown mode
    - 250N SRM for deorbiting

Mono-Propellant (Hydrazine) + SRM (SPADES)



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Optional design – controlled reentry
Solid propulsion

- Additional equipment needed
  - TVC for thrust misalignments (RCS is not sufficient to correct 250 N)
  - Dependending on the option additional equipment might vary drastically
    - Basic (SRM+TVC+Electric Drive)
      completely depending on the host S/C
    - Partially independent (SRM+TVC+Electric Drive+COMMS+AOCS+OBC)
      fails to de-orbit only when power bus fails
    - Fully-independent (SRM+TVC+Electric Drive+COMMS+AOCS+OBC+Battery)
      always capable to perform de-orbiting

- Trade-off assumptions:
  - Single burn ➔ constant thrust (true for solid)
  - Dry mass 1263 kg

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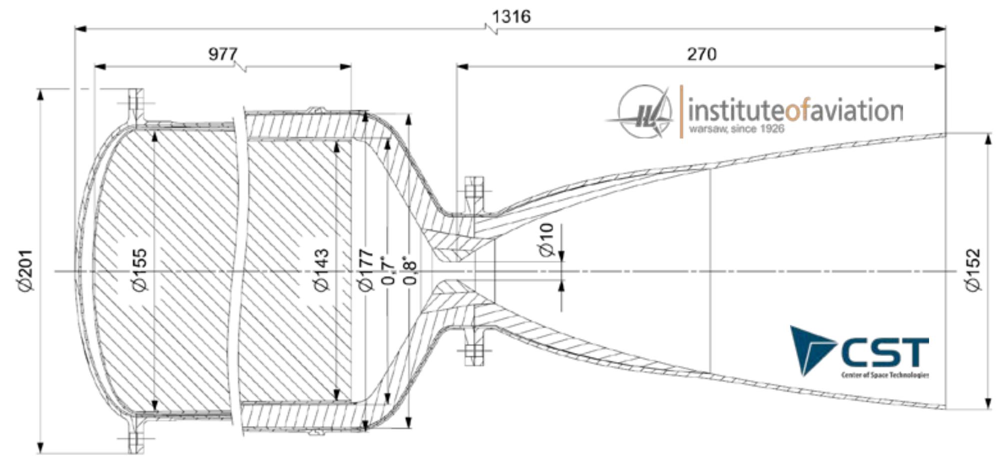
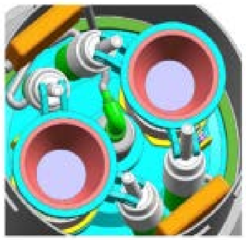
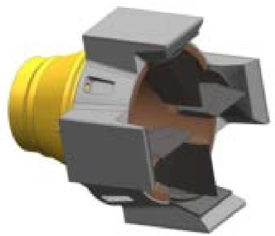
Solid Rocket Motor (SRM): SPADES

Basic characteristics	
Isp	278.2 s
Mean chamber pressure	1.26 MPa
Burn time	324.3 s
Mean thrust	245.4 N
Dry mass	11.55 kg
Propellant mass	28.96 kg
Expansion ratio	231
Total length	1.316 m
Total diameter	0.2







- System depends on hosting S/C
- Host gives COMMS, AOCS, batteries and OBC
- TVC based on vanes in the plume for thrust misalignments (< 5 deg thanks to AOCS at EoL)
- Redundancy on ignition and TVC control

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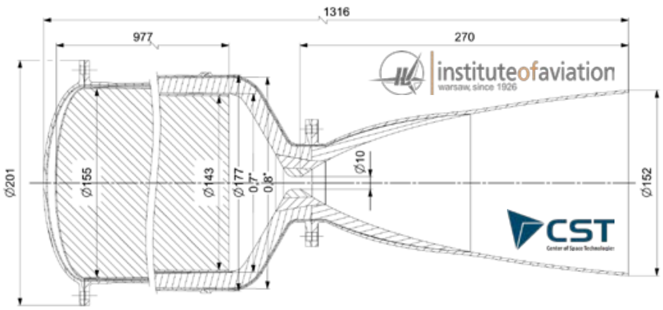
Solid de-orbiting: assumptions



Component	Dry mass (kg)	number	Margin	Total (kg)
SRM	11.55	3	20 % (to be developed)	41.58
TVC+AOCS drive electronics	8.11	3	20 % (to be developed)	29.2
Safe and arm (ignition)	1.5	3	10 %	4.95

- Current design for SRM deorbit is 29 kg of propellant (adjustable propellant loading is foreseen ➔ engine can be chopped)
- Delta-V for solid deorbiting assumed equal to 80N/4 burns (smaller available)
- With this Delta-V 3 SRMs give the propellant needed for deorbiting
- Final configuration: **3 SRMs 3 Burns**

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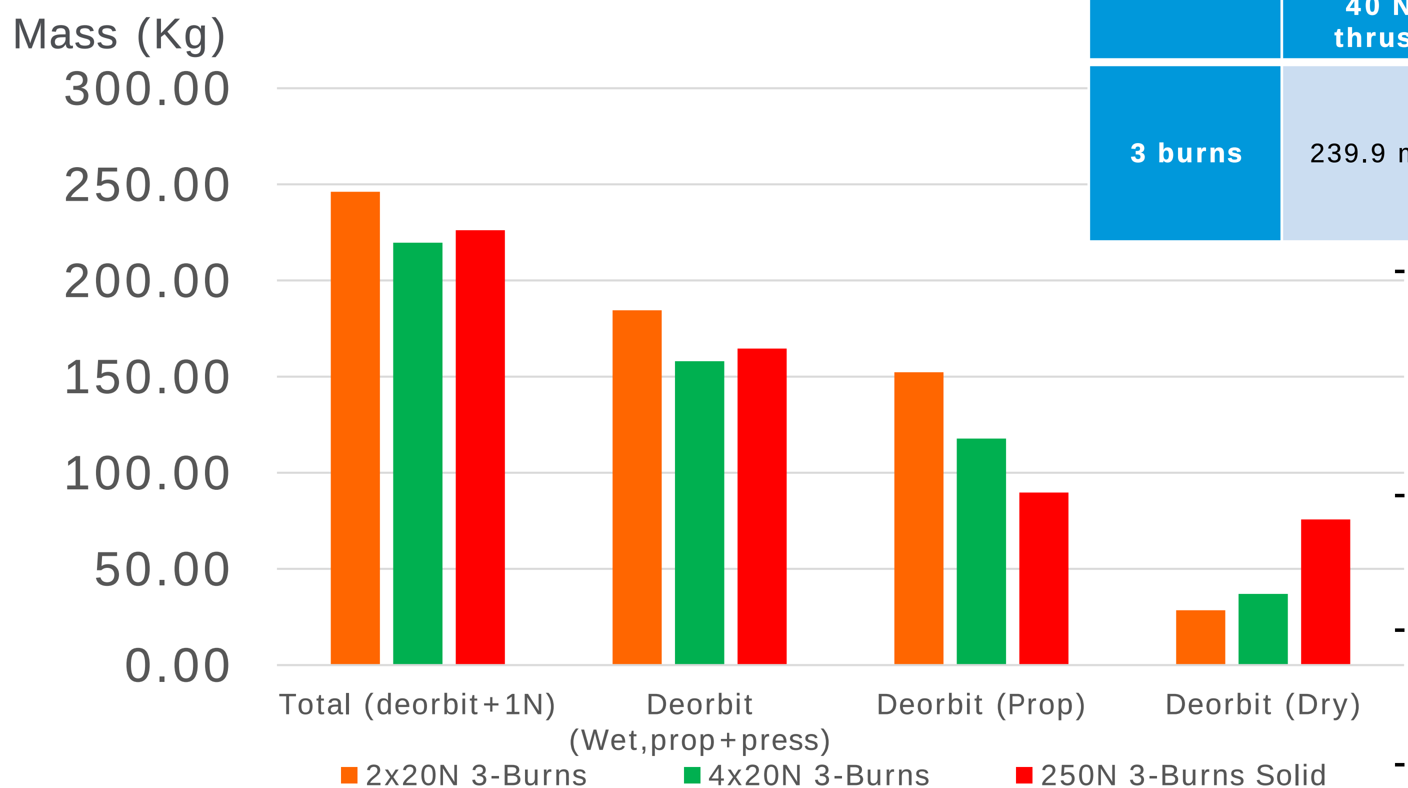
Liquid vs solid de-orbiting



	40 N thrust	80 N thrust	250 N thrust
3 burns	239.9 m/s	187.8 m/s	183.6 m/s (smaller available, closer to impulsive)

- Higher I_{sp} (278s vs 220s) is not enough to compensate margins on masses
- Final mass greater than 80N option
- Reduced costs for SRM (close to 1/4)
- Reduced complexity but no off the shelf components

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Varying thrust analysis for 80 N 3 burns

- Iterating with mission analysis gave the following Delta-V and thrust profiles

	Delta-V [m/s]	Thrust [N]	Propellant Mass [kg]
1st burn	61.74	75.70	41.73
2nd burn	66.36	62.60	44.13
3rd burn	72.14	53.46	46.89
Total (de-orbit)	200.24		132.75
AOCS + coll. avoidance + manoeuvre capabilities	56.70		39.44
Total	256.93		172.19

- The thrusters deliver initially 75.7 N, with 5 % margins on the given Delta-V.

  We should consider that:

  - 25 m/s for attitude hold control can be improved
    - higher tanks pressure and higher thrust level for de-orbiting
  - To increase thrust we could increase the tanks size, present size 2x148 l = 296 l

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Varying thrust analysis for 80 N 4 burns – AFTER IFP

- After IFP the dry mass has been updated to 1503.08 kg (including 20% system margins)
- With this value a 3 burns strategy is not feasible (high gravity losses). The low thrust available for the de-orbiting causes the solution to diverge

	Delta-V [m/s]	Thrust [N]	Propellant Mass [kg]
1st burn	39.64	72.68	30.07
2nd burn	41.22	62.23	31.04
3rd burn	43.10	54.58	32.08
4th burn	77.63	48.73	56.63
Total (de-orbit)	201.59		149.84
AOCS + coll. avoidance + manoeuvre capabilities	52.31		40.63
Total	253.90		190.47

New baseline➔ 4 burns:

- Delta-V for manoeuvre capabilities 26.25 m/s (w/ 5% margins)
- Collision avoidance 2.625 m/s (w/ 5% margins). A dedicated assessment has been performed on collision avoidance to account for higher margins
- Initial thrust level of 72.7 at de-orbiting N

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Varying thrust analysis for 80 N 4 burns Collision avoidance margins –AFTER IFP

- Objective is here to calculate the maximum delta-V that can be allocated for collision avoidance without changing the current configuration of the propulsion sub-system
- The final delta-V budget has been iterated with mission analysis
- Maneuver capabilities 26.25 m/s (with 5% margins)

	Delta-V [m/s]	Thrust [N]	Propellant Mass [kg]
1st burn	39.75	71.28	30.28
2nd burn	41.40	60.80	31.29
3rd burn	43.34	53.18	32.38
4th burn	81.34	47.40	59.50
Total (de-orbit)	205.84		153.45
AOCS + coll. avoidance + maneuver capabilities	53.88		42.04
Total	259.72		195.49

- Maximum achievable collision avoidance is estimated to be **4 m/s** (**60% margin** w.r.t to the baseline of 2.5 m/s).
- A higher Delta-V causes the solution to diverge and the de-orbiting cannot be performed with the current configuration. Bigger tanks should be considered to account for higher margins.

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Conclusions

- The trade-off highlighted that the 80 N 3 burns option is a good compromise between system/mission complexity and overall mass/volume

- Solid rocket motors for de-orbiting are promising thanks to the lower complexity, higher performance and lower costs. Liquid propulsion is however preferred in order to avoid any development

- Blow down mode changes performance ➔ predictions improved with several iterations with mission analysis

- All liquid propulsion system components in the final configuration are at TRL 9

- Due to the dry mass update after IFP the 3 burns option could not be used. A 4 burns option with 80 N guarantees de-orbiting capabilities and sufficient collision avoidance margins without any additional impact on the system

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Power

Power System Inputs (I)

Requirements	
Orbit	Equatorial orbit 600km with e=0 inclination 5.4 deg
Launch	2032
Lifetime	3 years (+ 2 years consumables)
Power consumption with 30% margin	LAU: 724 W (during 60min) SUN: 852 W (during 20min) SAFE: 1.350 W SCI: 1.283 W SCI_COM: 1.366 W Psun & Peclipse → PLM & SVM ON
Solar array surface	12.31 m^2
Off-pointing angles	SAA ≤ 30deg

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Power System Inputs (II)

Hypothesis	
SA redundancy	1 string lost
Solar Array radiation degradation	Low Radiation fluence (less than 1e14MeV)
DoD for the battery	Approx. 30% for LEO missions
Bus voltage	28V regulated
PCDU	Based on MPPT

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Current Baseline Design

- Baseline Design:
  - Solar Array cells: 3G30 from AzurSpace
    - Triple junction solar cell
    - Efficiency ~30% (BOL), 30.18 cm^2
    - Max temperature ~ 110 °C
    - 1 string lost
  - Battery cells: VES16 Li-Ion cells from SAFT:
    - 33 mm diameter by 60 mm high
    - Nominal mass: 40.5g
    - 4.5Ah total capacity per cell
    - 4.1V EoC and 2.7V EoD per cell
  - PCDU unit
    - Architecture MPPT and regulated bus of 28V

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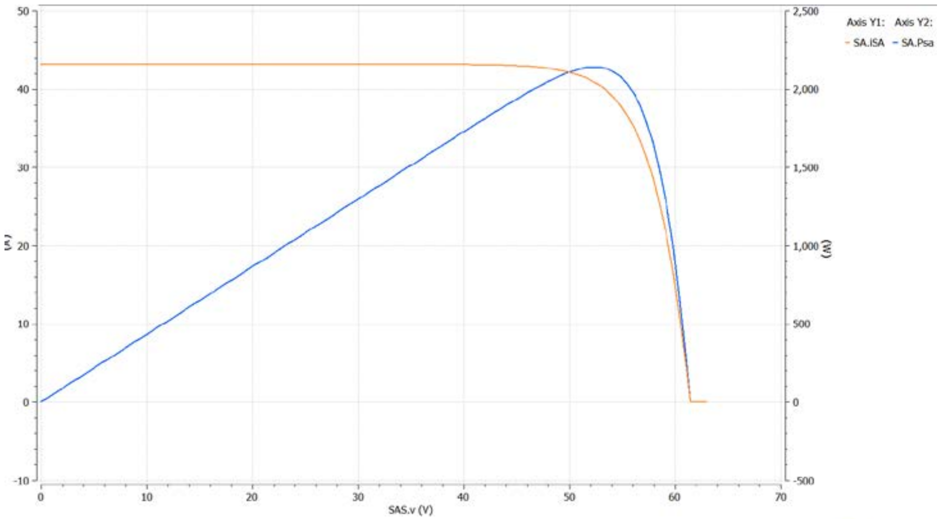
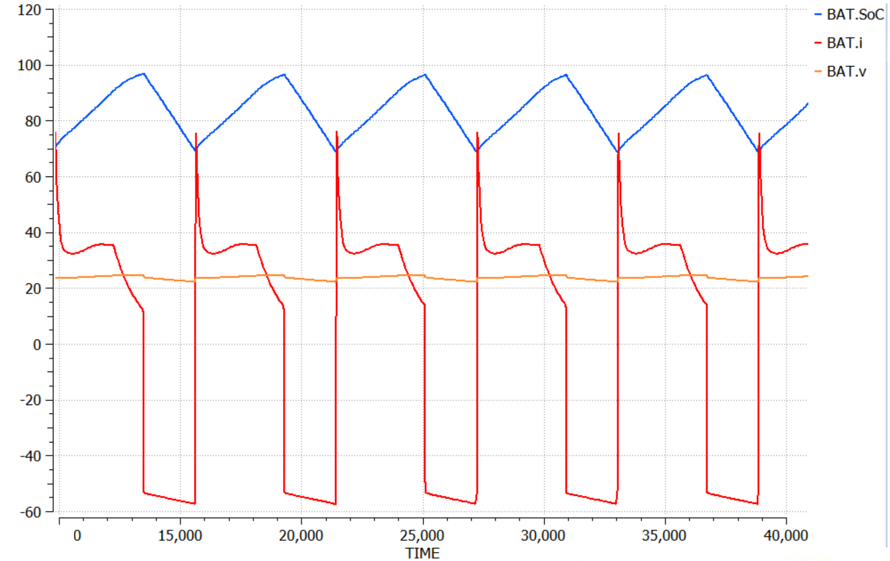
Current Baseline Design

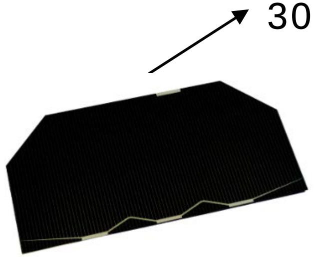
EOL Solar Array characteristics at 110⁰C

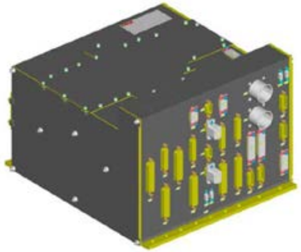


Battery design results



30s98p





PCDU: MPPT regulated bus

2 x 6s16p

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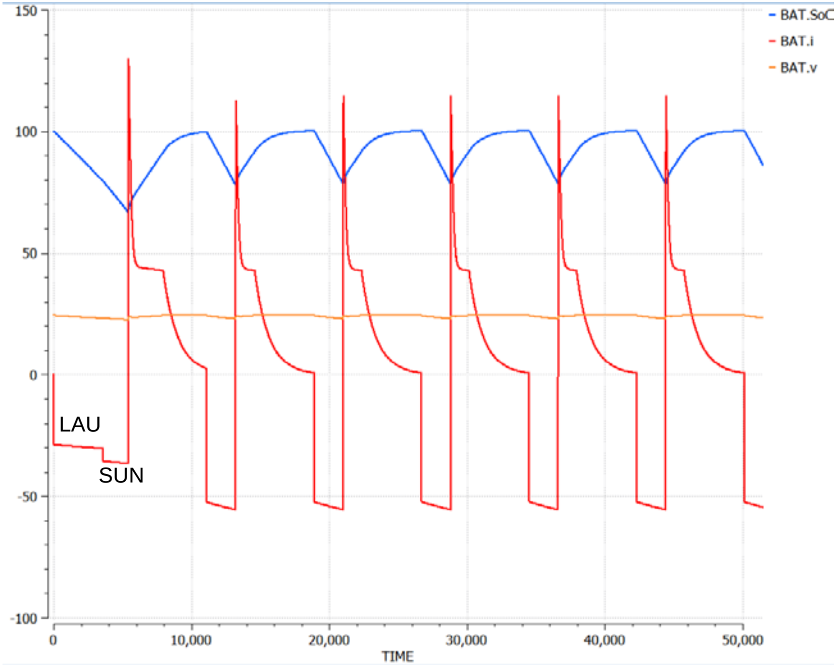
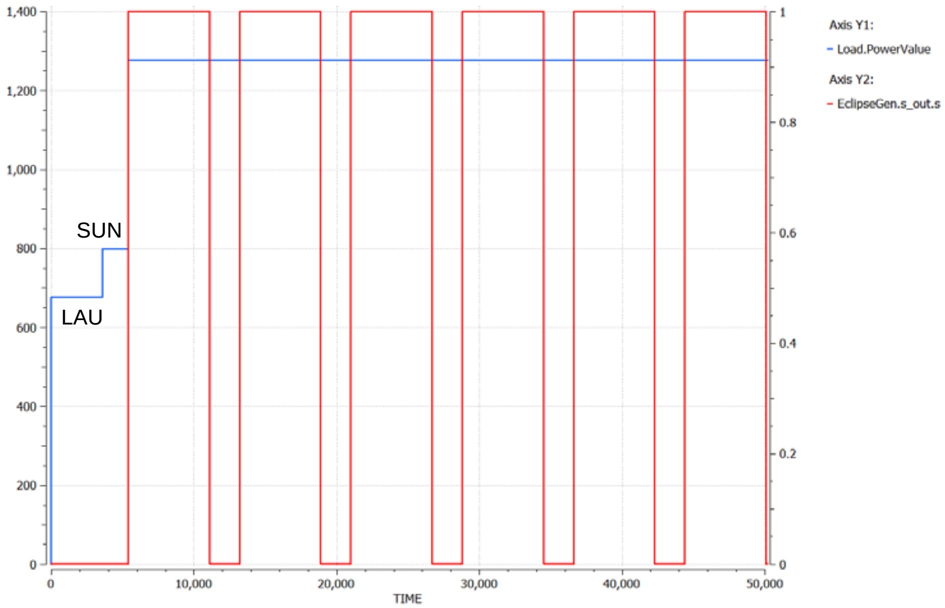
Simulation results: LEOP mode





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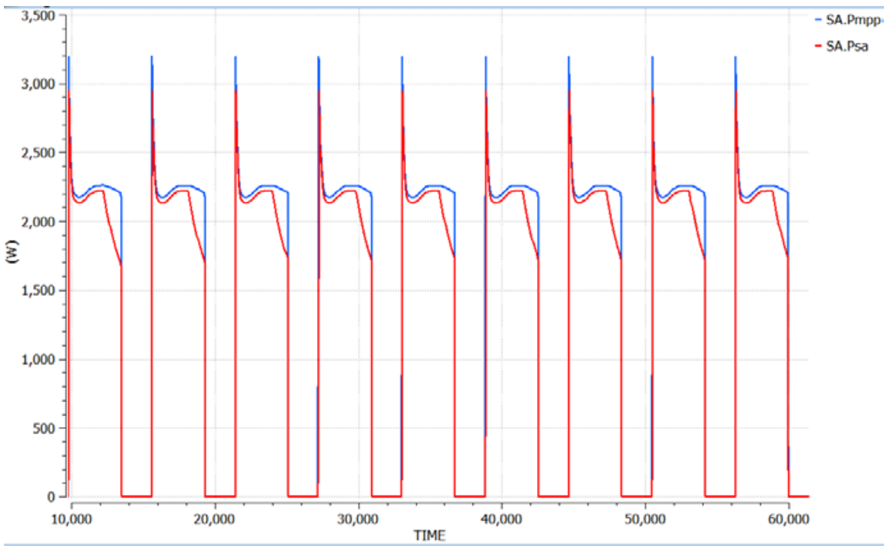
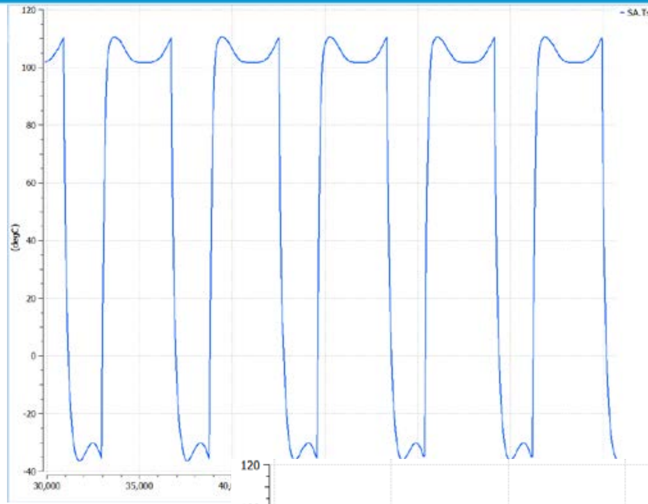
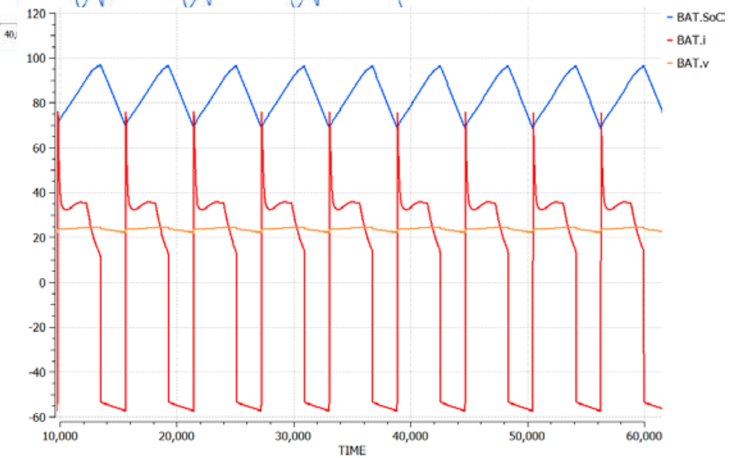
Simulation results: SCI_COMS mode







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Elements of the Power System

	Characteristics	TRL	Heritage
Battery	Configuration 2 modules 6s16p Mass per module 16.512 kg ± 5% Surface per module 406 x 235 x 165 mm^3 Energy 1536 Wh per module at C/2 , 20ºC	7	MTG Cheops Euclid
Solar Array(1)	Configuration 30s98p Mass 45.7 kg ± 20% Surface 11.07 m^2 < 12.31 m^2 (power margin ~11%) Height ~20mm 115.36 W/m^2 for SAA 30deg 131.47 W/m^2 for SAA 0deg	7	Proba 3 Euclid Cheops EDRS-C MTG
PCDU	Mass 22kg ± 20% Volume 565 x 297 x 245 mm^3 Fix power dissipated ~ 45W	7	Bepicolombo Gaia Solar Obiter

(1) The use of solar cells type 4G32, which are under qualification (TRL 3-4), could reduce the size surface of the solar array to 9.63 m^2 and the mass to 42.7 kg.
-> The qualification is expected for next year.

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Ground Segment and Operations

Band considerations

S-BAND

- Sensitivity to **spread-F** is an ionospheric disturbance in tropical areas during evening and night hours. Causing strong variation in the received signal power leading to the loss of the link and interruption of TT&C communications. This may be mitigated by high link margins and/or site diversity.

  Reference *ESA-GRST-RF-TN 0002_Effects_ F_Spread_link_disturbance*

- ***A#6-3*** *Look into the legislation issues with the availability of S-band in the 2032-2037 timeframe:* S-band is **congested** but can still be used for moderate occupied bandwidth. **Difficult** to **foresee** what will happen in **2032**, it shall not be completely discarded. It is not in the agenda for 2019 ITU's meeting (every 4 years).

VHF

- F-Spread Effect very bad at very high frequencies.

X-BAND

- **Limited** to 15m (or smaller) and **8450-8500 MHz.**

  DSA 35m Az-El Speed 1 deg/s not suitable for Low Earth Orbit.

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Ground Stations - Science&HKTM – S/S X-Band SR

Assumptions:

- **S-band** up and down (TT&C) & **X-band** downlink **8450-8500** MHz (Science)
- Longitude (deg): +/- 18 deg

Location	Diameter	Band	Service
Kourou	15m	SX/SX	EES&SR
Malindi	MAL-1: 10m MAL-2A: 10m MAL-2B: 13m MAL-X: 2m	MAL-1: S/SX MAL-2A: S/S MAL-2B: SX/SX MAL-X: X/X	MAL-1:EES&SR MAL-2B:EES&SR MAL-X:EES&SR
Alcantara	11m	S/S	
KSAT Bangalore	11m (+9,7,3.7 m)	S/SX	EES
ISTRACK	Ground Stations Specs (band, size, location, etc.) will be available mid Oct. 2018		

Earth Exploration (EES) 8025-8400MHz and Space Research (SR) 8450-8500MHz

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ASI MALINDI Ground Antennas Status

A#5-2: *Check availability of X-band at Malindi. Consider making it the baseline since it is an Italian contribution to the mission.*

ANTENNA	SIZE	BAND	COMMENTS
MAL-1	10 m	L-band S-band up&down X-band chain to be refurbished	S-band In use **Status Q42018 X-Band upgrade** X-Band has been dismounted and taken down to the lab for inspection/fixes. ASI plans to render X-Band reception operational in 2019. X-Band SR frequency TBC.
MAL-2A	10 m	S-band only	In use
MAL-2B	13 m	S-band up&down 2019 X-Band upgrade foreseen	**Status Q32018** Antenna installation foreseen to start in **Oct/Nov**. S-band is foreseen to be operational Mar-Apr 2019. Contractually, the upgrade to X band has to wait until all testing activities (for the upcoming installation) have been completed -> The **X band down upgrade** would not start before the **2nd half of 2019**. Expect 1.5-2 years until completion (e.g. by 2021) No G/T spec for X-band yet -> What is required for Theseus? -> COMS G/T required 34.1 [dB/K] -> **10 m** also achievable (MAL-1 upgrade) ASI X up or X up and down? -> Theseus: X down only.

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ASI Malindi Assumptions

- **Malindi (**prime**)**:
  - **Letter of commitment** from ASI shall be requested to mitigate potential risk at ESA Mission Selection Review: same approach as it was done for XIPE via "ASI_2.REGISTRO UFFICIALE.U.0001764.21-02-2017" . Antennas should be **compliant** with THESEUS Requirements (e.g. support s-band reception and commanding as well as x-band telemetry reception in 8450-8500 MHz Frequency Band with a single antenna , etc.).
  - ***A#7-7:*** *Investigate the possibility of simultaneous use of S and X band for the different antennas in Malindi.*

    All Ground Stations used by ESA missions have independent downlink chains for different Communications Bands: it shall be ensure that, when MAL x-band chains are available, they will also support it.

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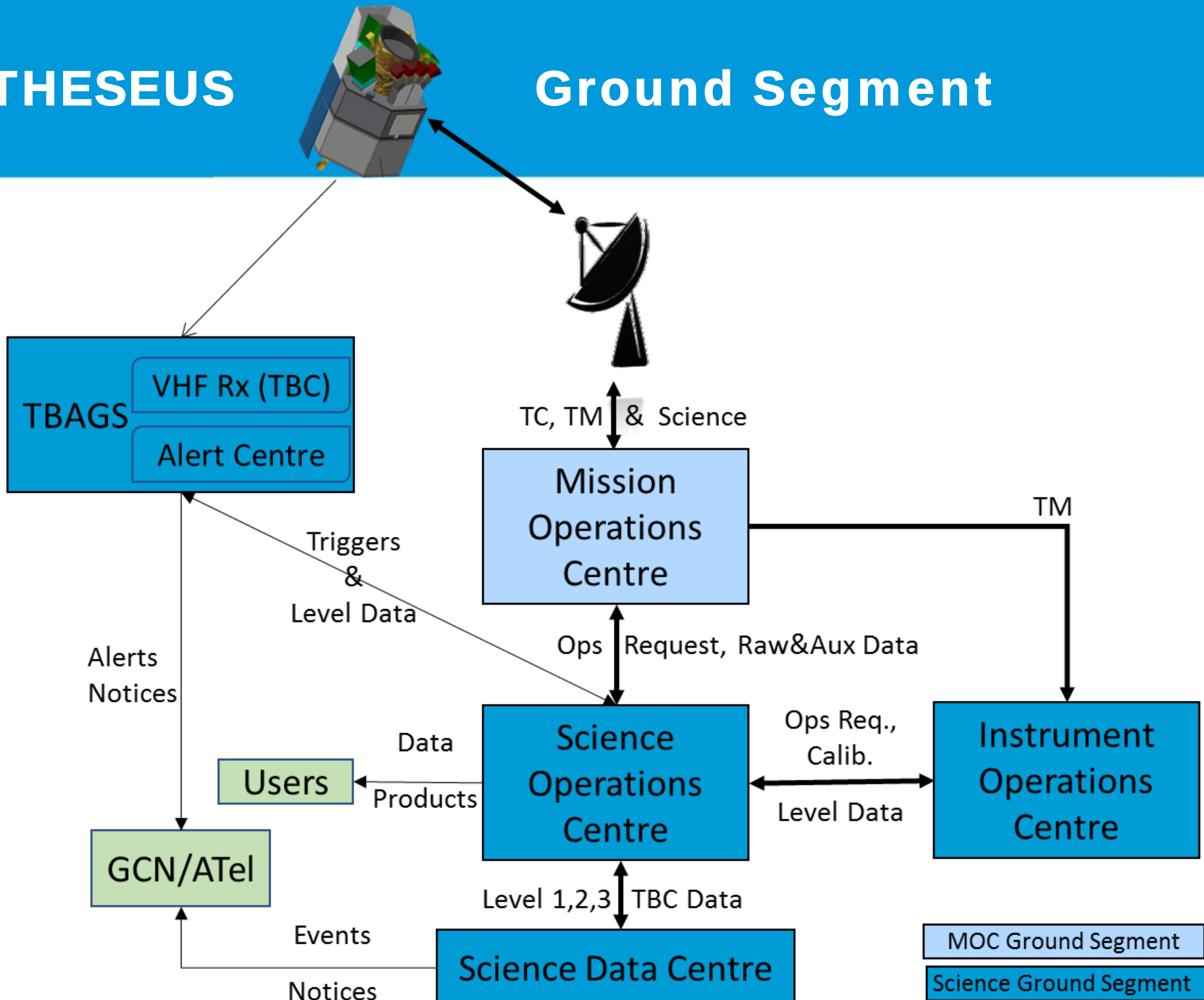
Ground Segment



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THESEUS Operations assumptions

THESEUS MOC Operations tasks, among others:

PHASE	Operations
LEOP (< 7 days)	• Night-side Launch to avoid straight light into Payload • S/A deployment and regular LEOP activities
Commissioning (~ 3months)	• Platform and Payload Commissioning • Payload Calibration and Performance Verification activities
Science	• Maintenance manoeuvres: RoW • Collision Avoidance Manoeuvres • SOC External triggers: reaction time similar to XIPE (no driving req.) • SOC Science Planning: 1 month (TBC) in advance
Disposal (< 1 month)	Controlled re-entry: • 1 burn per week • Mini-sim campaign

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Programmatics

Requirements and Assumptions

- Requirements
  - Launch in 2032
  - Compatibility with M-size mission
  - TRL 6 by Mission Adoption

- Assumptions
  - Conventional SVM with heritage
  - Complex thermal control with both passive and active solutions under trade off
  - IRT qualified and accepted before integration on PLM
  - Instruments can be fully qualified and accepted before their integration on PLM

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Model Philosophy

- The following model philosophy is proposed:
  - The PLM thermal design is complex, and needs dedicated qualification

	Instruments	SVM	PLM	S/C
STM	X	X	X	X
AVM	BB/EM	BB	BB	X
QM	X	I/F Sim	EQM	-
PFM	X	X	X	X

  - A S/C STM will be subjected to full thermal and mechanical environment qualification. The thermal design will be verified at S/C level.
  - A S/C AVM will support functional test of the avionics including Instruments

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Instruments testing

- The following specific assumptions have been made for the Instruments procurement:
  - The Instrument teams qualify their equipment
  - A qualification test campaign of each full Instrument is planned by the Instrument teams (as far as technically feasible)
  - The Instrument team accept the FM Units and deliver to the Prime for AIT, with limited integrated instrument acceptance. In any case integrated acceptance at Instrument level needs to be quantified in the next phase.
  - Telescope is fully acceptance tested before handing over to the Prime

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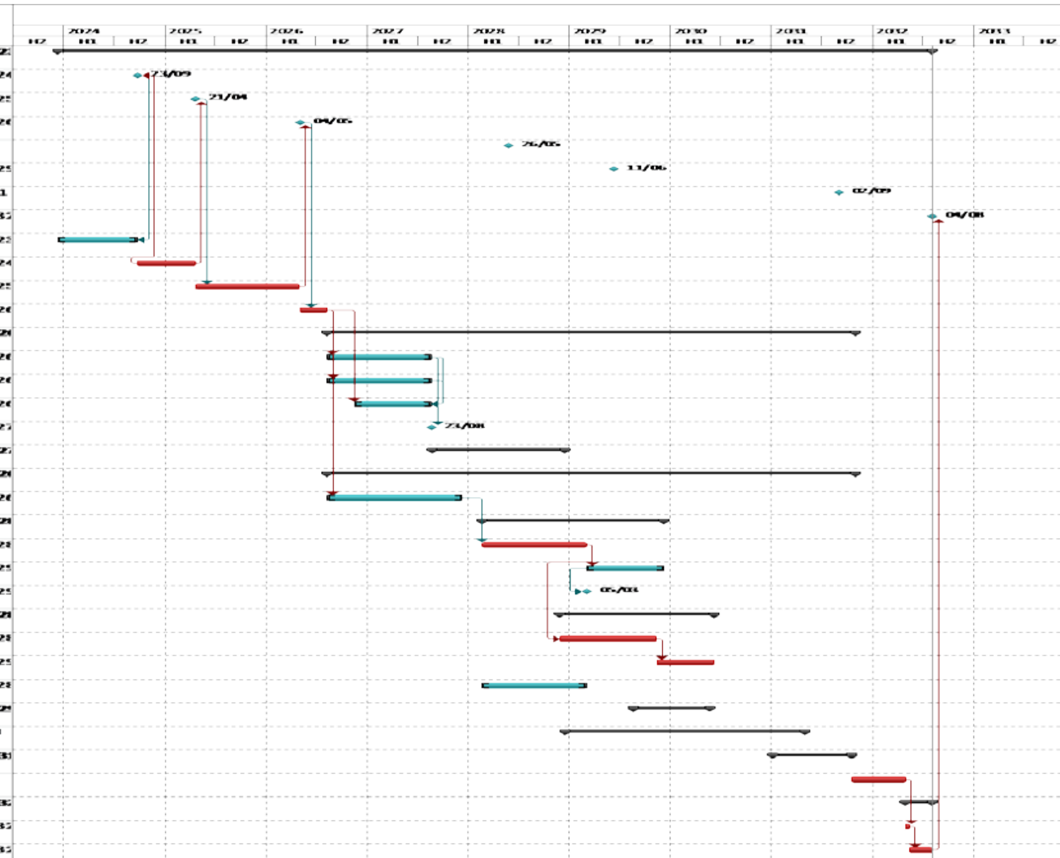
Master schedule

ID		Task Mode	Task Name	Duration	Start
2			THESEUS	2257 days	Mon 11/12/2
3			Mission Adoption Review	0 days	Mon 23/09/24
4			SRR	0 days	Mon 21/04/2
5			System PDR	0 days	Mon 04/05/2
6			System CDR	0 days	Fri 26/05/28
7			System QR	0 days	Mon 11/06/2
8			System FAR	0 days	Tue 02/09/31
9			Launch	0 days	Wed 04/08/3
10			Phase B1/1	205 days	Mon 11/12/2
11			Phase B1/2	150 days	Mon 23/09/24
12			Phase B2	270 days	Mon 21/04/2
13			post PDR activities	70 days	Mon 04/05/2
14			Phase C/D	1365 days	Mon 10/08/2
15			SVM Structure Procurement	270 days	Mon 10/08/2
16			PLM Structure procurement	270 days	Mon 10/08/2
17			Structural dummies MTD procurement	200 days	Mon 16/11/2
18			MGSE need date	0 days	Mon 23/08/2
19			STM AIT	344 days	Mon 23/08/2
74			AVM	1365 days	Mon 10/08/2
83			Hi-Rel Parts Procurement	350 days	Mon 10/08/2
84			QM Instruments	470 days	Mon 21/02/2
85			Instr. QM Units Mfg and test	270 days	Mon 21/02/2
86			Instr. QM integrated test campaign	200 days	Mon 05/03/2
87			S/C Interface Simulator Need Date	0 days	Mon 05/03/2
88			FM Instruments	400 days	Mon 27/11/2
89			FM Instrument Units Mfg and acceptance te	250 days	Mon 27/11/2
90			FM Instruments integrated test campaign	150 days	Mon 12/11/2
91			FM SVM and PLM Bus Units mfg and test	270 days	Mon 21/02/2
92			FM SVM AIT	199 days	Mon 20/08/2
105			FM PLM AIT	619 days	Fri 15/12/28
118			FM S/C AIT	204 days	Mon 06/01/3
133			ESA Contingency	138 days	Fri 17/10/31
134			Launch campaign	70 days	Wed 28/04/3
135			Shipment to launch site	10 days	Wed 28/04/3
136			Launch campaign	60 days	Wed 12/05/3



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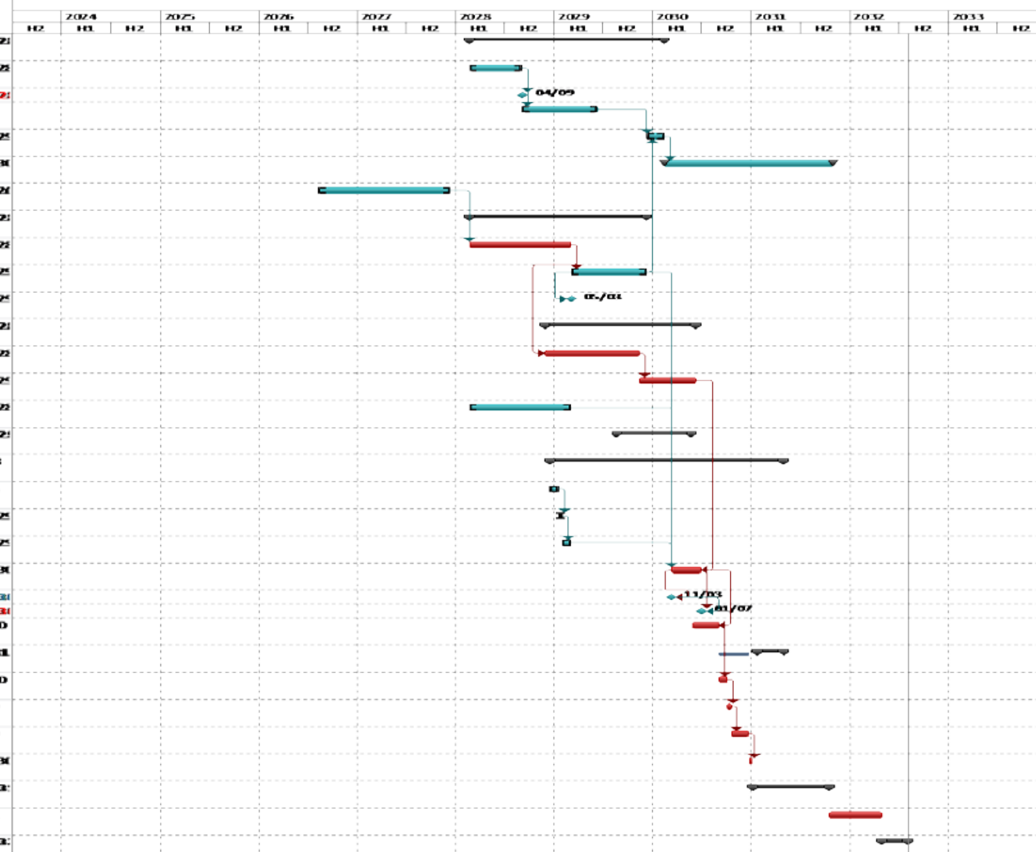
Schedule Details

ID		Task Mode	Task Name	Duration	Start
77			**AVM AIT**	516 days	Mon 21/02/2
78			AVM SVM and PLM Bus Units Integration	140 days	Mon 21/02/28
79			AVM Instrument BB units need date (ear	0 days	Mon 04/09/2
80			AVM functional test campaign including instruments	200 days	Mon 04/09/28
81			AVM PLM Instr. BB Units Swap with QM (	46 days	Mon 10/12/2
82			AVM Support	450 days	Mon 11/02/3
83			Hi-Rel Parts Procurement	350 days	Mon 10/08/2
84			**QM Instruments**	470 days	Mon 21/02/2
85			Instr. QM Units Mfg and test	270 days	Mon 21/02/28
86			Instr. QM Integrated test campaign	200 days	Mon 05/03/2
87			S/C Interface Simulator Need Date	0 days	Mon 05/03/2
88			**FM Instruments**	400 days	Mon 27/11/2
89			FM Instrument Units Mfg and acceptance te	250 days	Mon 27/11/28
90			FM Instruments integrated test campaign	150 days	Mon 12/11/2
91			FM SVM and PLM Bus Units mfg and test	270 days	Mon 21/02/28
92			**FM SVM AIT**	199 days	Mon 20/08/2
105			**FM PLM AIT**	619 days	Fri 15/12/28
106			FM PLM panels preparation, ty bases, brackets etc.	23 days	Fri 15/12/28
107			FM PLM harness installation	10 days	Wed 17/01/2
108			FM PLM thermal control installation	23 days	Wed 31/01/2
109			FM PLM Mechanical Integration	80 days	Mon 11/03/3
110			FM Instruments need date (earliest)	0 days	Mon 11/03/3
111			FM Instruments need date (latest)	0 days	Mon 01/07/3
112			FM PLM Electrical Integration	70 days	Tue 28/05/30
113			**FM PLM Functional test**	70 days	Thu 23/01/31
114			FM PLM Bus functional test	23 days	Tue 03/09/30
115			FM PLM Instruments to bus I/F test	10 days	Fri 04/10/30
116			FM PLM Instruments special performance	46 days	Fri 18/10/30
117			FM PLM EMC Test CE-CS, RE-RS	10 days	Mon 23/12/3
118			**FM S/C AIT**	204 days	Mon 06/01/3
133			ESA Contingency	138 days	Fri 17/10/31
134			**Launch campaign**	70 days	Wed 28/04/3



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Conclusions

- The complex thermal design of the PLM brings the need for
  - A full S/C STM on which the thermal design will be verified with the support of a S/C level thermal balance test.
  - The S/C STM needs to be mechanically and thermally representative. No need for EQM unit, just mass and thermal dummies, but the thermal control needs to be completely flight representative including LHP/HP
  - The STM structure shall be refurbished to be used as FM (this is so far compatible with both SVM and PLM schedules)
- From the schedule:
  - The procurement of the QM and FM units of the instruments is on the critical path, FM units mfg needs to start just after (E)QM units
  - As a consequence, the FM PLM is on the critical path
  - Margin on structures refurbishment: 6 months SVM, 1 year PLM
  - CDR after STM test campaign, QR after AVM test campaign

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Notable dates

Launch	August 2032
Instrument STM mass and thermal dummies	October 2027
Instrument BB Units for AVM	September 2028
Instrument FM units need date (earliest)	March 2030
Instrument FM Units need date (latest)	July 2030

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Instrument Performance

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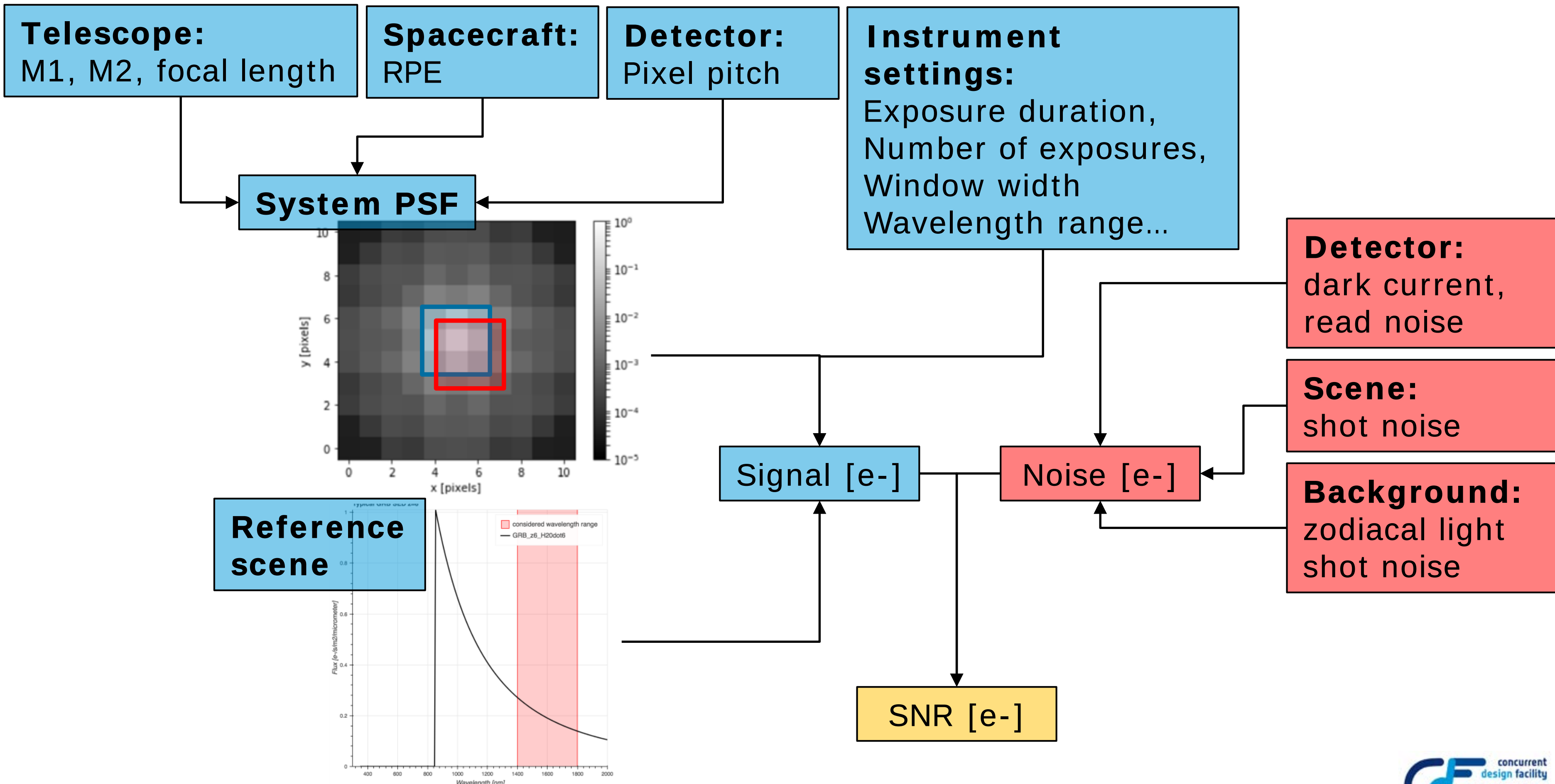
IRT performance model: imaging only



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IRT performance model validation

Model input parameters:

- Diffraction limit wavelength = 1800 nm
- Telescope throughput = 0.4
- M1 diameter = 0.7 m
- M2 diameter = 0.2 m
- **Pixel scale = 0.3 arcsec/pixel**
- Detector pixel pitch = 15 um
- Detector dark current = 0.1 e-/pixel/s
- **Detector readout noise = 18 e- rms per pixel readout**
- **Individual exposure integration duration = 10 s**
- **Number of individual exposures = 30**
- **Window width = 4 pixels**
- Background magnitude (V) = 21.2
- Wavelength range considered = [1400,1800] nm

SNR results breakdown:

- Signal = 102 e-
- PSF crop factor (max, min) = 0.83, 0.78
- Cropped signal = 90 e-
- Background = 0.67 e-/pix/s
- Total background = 108 e-
- **Total readout noise = 72 e-**
- Total background noise = 10.4 e-
- Shot noise = 9.5 e-
- Total dark noise = 4.0 e-
- Total noise = 73.3 e-
- SNR per exposure (max, min) = 1.2, 1.1
- **Total SNR (max, min) = 6.3, 6.0**
- **Consortium value = 6.0**

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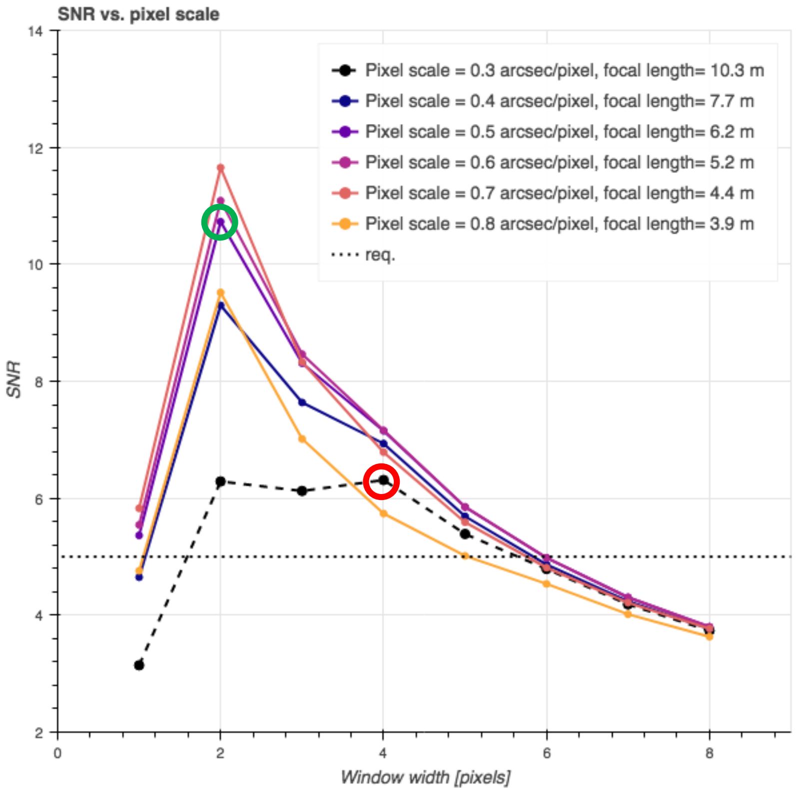
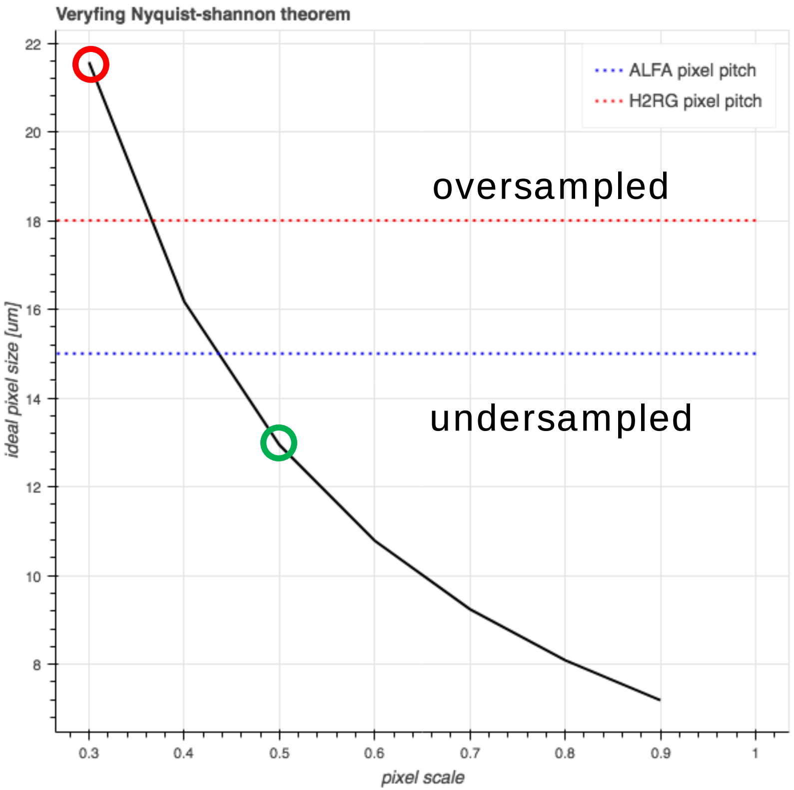
Performance optimization: pixel scale





Note: for larger pixel scale, efficiency also increases because FoV increases

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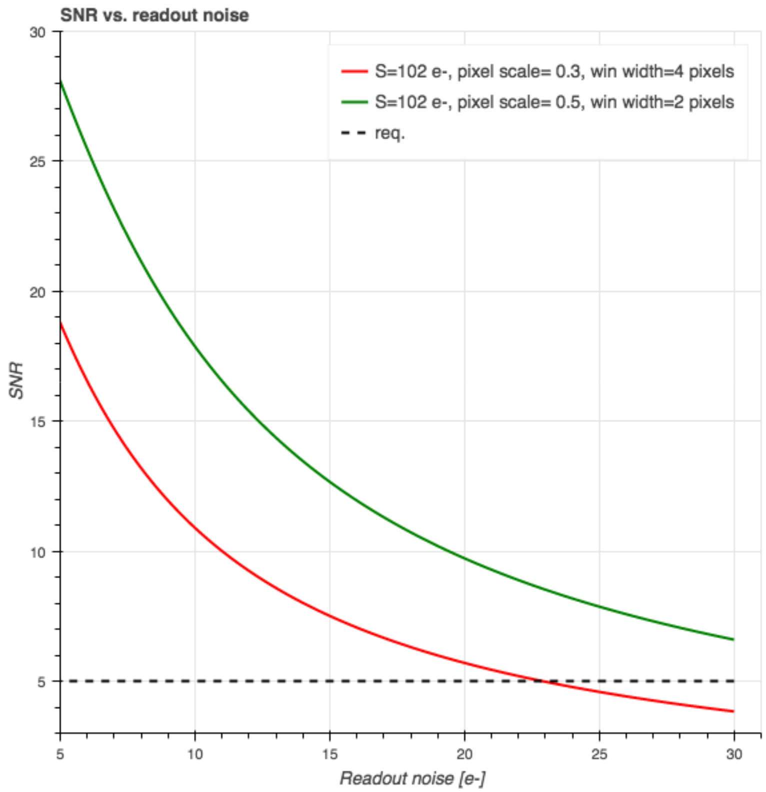
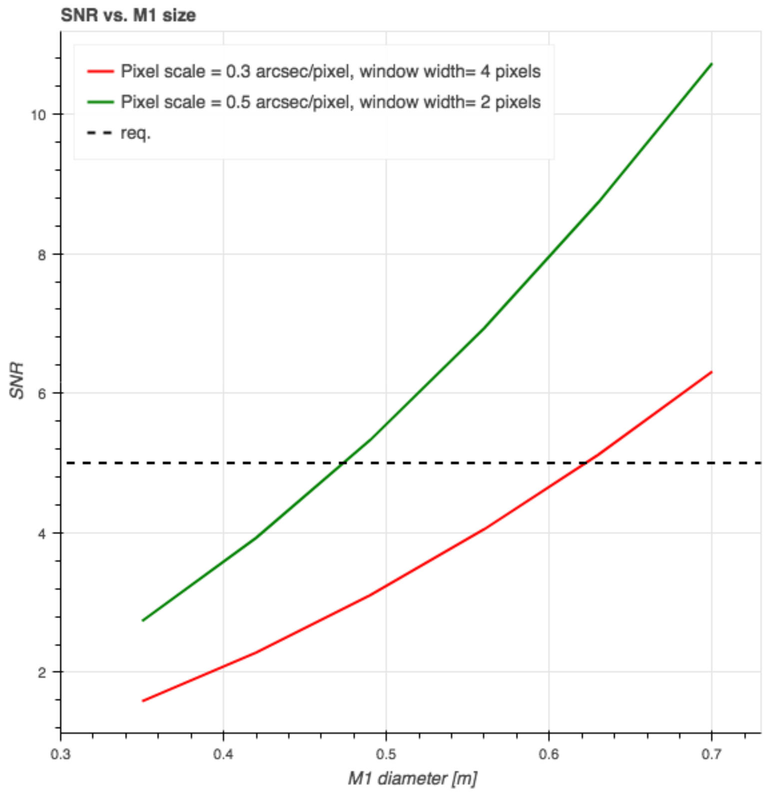
Further optimization: readout noise, M1





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IRT detector discussion

- CDF baseline: ALFA (Sofradir, Fr)
- Proposal baseline: Euclid SCS, H2RG (Teledyne, US) – not off-the-shelf, but possible reuse of Euclid spares?
- Main differences ALFA vs. H2RG:
  - Current TRL: 4 vs 9
  - Pixel pitch: 15 vs 18 um
  - Cut-on wavelength: 800 nm vs. 400 nm
  - Cut-off wavelength: possible implications in terms of Top
  - Front-end electronics: ad-hoc development vs. off-the-shelf TRL9
- TDAs:
  - in roadmap: TRL 6. by 2024 achievable
  - additional: development needed to reach 400 nm cut-on
  - (consortium): front-end electronics development

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IRT conclusions

- From a purely imaging point of view there seems to be room for improvement, in particular by increasing the pixel scale, diminishing the integrating window and using more advanced readout modes to decrease the read noise
- To make further progress, we need to establish a worst case and realistic set of SNR contributors/model input parameters, agree on margins
- A small decrease of M1 seems affordable pending the criticality of accommodation/integration issue
- However a similar exercise need to be performed first for the other IRT modes of operation: high and low resolution spectroscopy
- The detector choice at present does not seem critical only if cut-on wavelength in visible range is a must-have.

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SXI: CCD vs. CMOS trade-off

- Baseline: 16x SMILE Te2v CCD (but specific development likely to have thicker)
- Risks: Complex thermal design, Te2v CCD availability in late 2020s
- Several alternatives identified:
  - Inverted Mode Operation CCD: better b.o.l. performance @ higher T
  - thin CMOS e.g. Te2v CIS120: smaller energy range, Top=0 degC
  - thick CIS120 development on-going (GSTP): imprv on upper energy limit
- CMOS pros & cons:
  - Pros: higher Top, more radiation-hard, faster and more flexible readout
  - Cons: smaller pixels, no noise-less binning, thinner, lower TRL, smaller FoV (for CIS120 option)
- TDAs:
  - on-going: Thick CIS120 with Te2v
  - additional: Thick CMOS with large pixels? Open ITT
  - (consortium): Experimental testing of CMOS for X-ray science @ Leicester

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SXI conclusion

- The CMOS option is very interesting both programmatically and from system point of view
- However at present it is not clear if the science requirements can still be achieved with CMOS
- Detailed analysis is on-going at consortium level both through modelling and experimental tests in order to understand the performance impact

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Conclusions

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Success!

- **Feasible mission**
- **Good collaboration** amongst all CDF experts, SCI Study team and Instrument Consortium members
- **Verifiable science / mission requirements met** (caveats e.g. RPE and volume accommodation)
- **Robust design** almost in all fronts
- Rather **sparse** (but not empty) **Risk Register**!
- **High TRL units**. Small additional of dedicated development activities required
- **Cost expected to be within M5 CaC cap** even with risk allocations wrt. some elements which were proposed as instrument CFI in the proposal (e.g. SXI MPO, SVM ground stations, ...)

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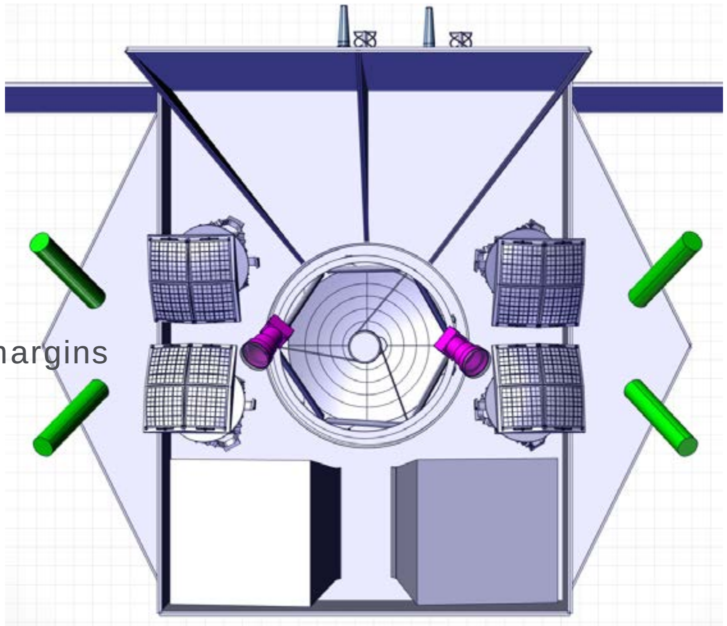
But… What can be improved in the design?

- **Instrument accommodation in PLM is very tight and not compatible with required comfortable margins**, particularly:
  - In the inter-instrument unit clearances
  - IRT-cone diameter clearance
  - SXI and XGIS footprint AIV clearances
- Situation can be improved by **optimising radiator areas** (particularly SXI) and trying space units further apart
- However, there are lot of constraints and **the risk remains** (margins for phase A are rather large).
- The **best mitigation** would be to **ensure that the science requirements can be achieved with slightly smaller instruments**. Studying the science impact of:
  - x% reduction in XGIS units FoV. (still square), maybe explore 9x9 modules instead of 10x10
  - x% reduction in the SXI units
  - x% reduction in the M1 diameter (not so much gain in changing FL)



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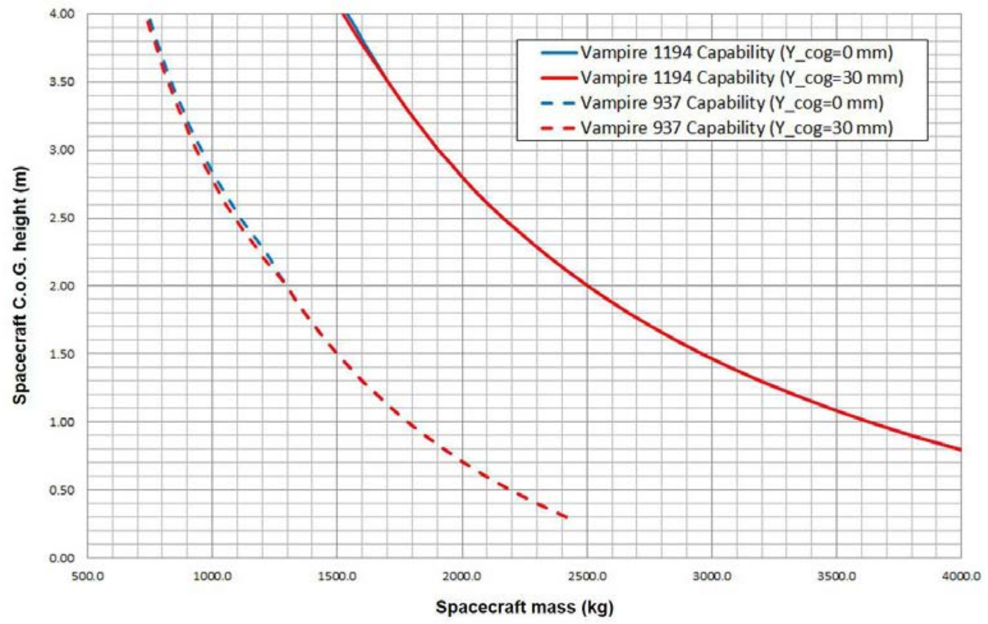
But… What can be improved in the design?

- Even though there is (almost) no constraints of **lateral deltas of the SC CoG wrt. to the launcher axis** (especially for the 1194 PLA) it is still advisable to keep **a centred configuration** for SC agility and optimal AOCS. Currently, although not monitored, it is likely there is an offset due to the XGIS position. Possible solutions:
  - Move the propellant tanks from central cone,
  - Ballast mass.



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What needs further work

- **Consolidation of the requirements**. Currently there is no breakdown from the science requirements of 30 GRB with z>x to a requirement on observation efficiency that can be verified at SC level.
- More work needs to be done on the **consolidation of the instruments**. The configuration and **thermal design** is very important and driving the configuration.

  Particularly for SXI, the use **CMOS detectors to relax thermal design shall be studied for SXI** (dedicated equipment – LHPs)
- **Achieve a better definition of the I/Fs for the IRT (not very discussed during the sessions). Programmatically best solution shall be pursued.**
- The **performance budgets for the different instruments need to be consolidated**
  - **Try to achieve necessary XGIS sensitivity with smaller units (e.g. changing overlaps)**
  - **Try to accomplish SXI science even with CMOS "degradation"**
  - **Try to relax the RPE requirement once SNR budget of the IRT is assessed**
- **Straylight issues** are likely to become relevant with the tight configuration and multiple reflections foreseen.

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What would be nice to have

- **Study the impact of different observation strategies on the observation performance**. Maybe pursue an option with a SADM allowing to extend the FoR in the away form the sun direction without increasing the size of the Sunshield.
- Currently we **assumed that there is no "useful" science done during eclipse**. Even with this assumption the science requirements are achieved. However, with a more consolidated design it is important to check the **thermal transient cases during eclipse to check the TRP stability** => maybe there is "useful" science to be done in this period.

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Knowledge gaps/lower readiness level

- **Instruments design has a low TRL**. Even the instrument configuration is not yet consolidated => **dedicated instrument related Phase A activities** would be highly advisable
- **Instrument I/Fs and resources need consolidation** to allow proper SC designs during the Phase A (by the primes) => **dedicated instrument related Phase A activities** would be highly advisable
- **The VHF SC equipment and network** => **ensure design visibility of SVOM activities**. Assess criticality and check in dedicated activities are needed (maybe only after MSR).
- **The CMOS detector for the SXI** => **highly advisable** to have dedicated activities to allow the relaxation of SC design and, more importantly, **risk mitigation of future CCD unavailability**.

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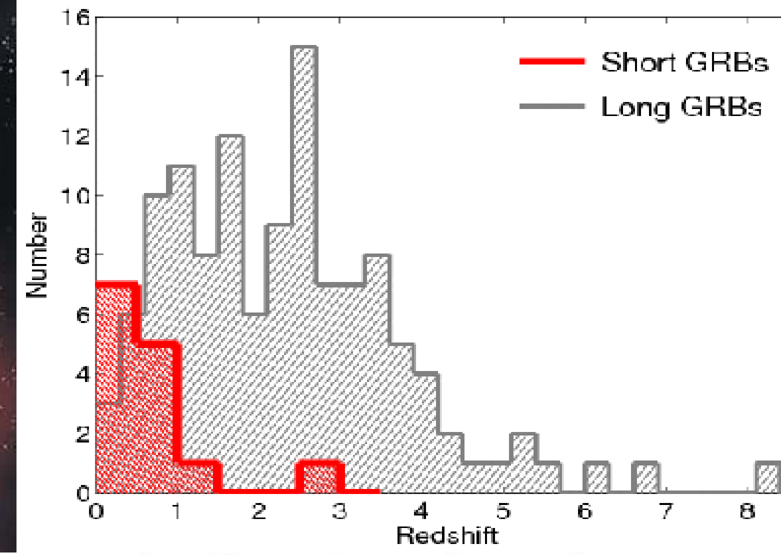
THANK YOU EVERYONE!



LIGO, Virgo, and partners make first detection of gravitational waves and light from colliding neutron stars