THOR

Agenda

IFP
ESTEC, 9th July 2015

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

THOR IFP AGENDA - AM

Title	Time
Introduction	09:30
Instruments	09:40
Mission Analysis	10:00
Radiation	10:15
Systems	10:30
COMMS	11:00

Title	Time
DHS	11:15
AOGNC	11:30
Power	11:45
Programmatics	12:00
Cost	12:15
Risk	12:30

THOR IFP AGENDA - PM

Title	Time
Operations	13:45
Propulsion	14:00
Mechanisms	14:15
Configuration	14:30
EMC	14:45
Thermal	15:00
Structures	15:15

Presentations Numbering

1. Introduction
2. Instruments
3. Mission Analysis
4. Radiation
5. Systems
6. COMMS
7. DHS
8. AOGNC
9. Power
10. Programmatics
11. Cost
12. Risk
13. Operations
14. Propulsion
15. Mechanisms
16. Configuration
17. EMC
18. Thermal
19. Structures
20. Conclusions

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INSTRUMENTS

IFP
ESTEC, 09/07/2015

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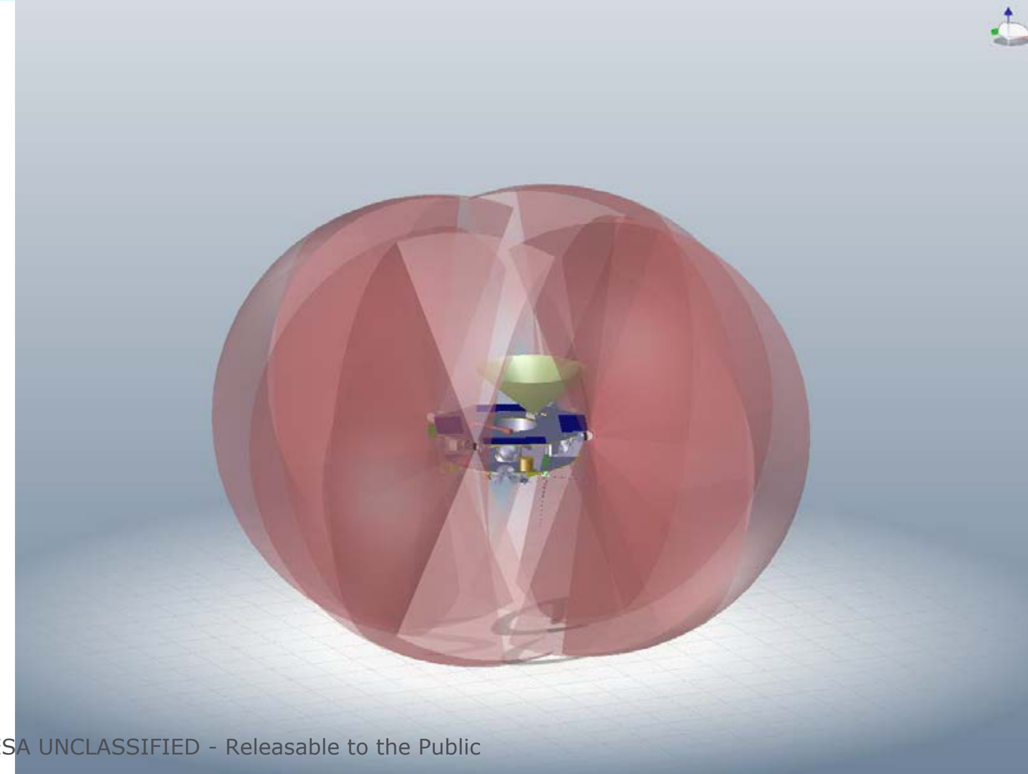
Payload resource budgets (top level)

Instrument	Measurement	Mass [kg]	Power[W]	TRL	Heritage
MAG	2x Fluxgate magnetometer	1.0	3	8	BepiColombo, VEX
SCM	Search coil magnetometer	2.4	1	5	Cluster, MMS
EFI	4x EFI-SDP (50 m wire booms), 1x EFI-HFA (3 orthogonal pairs of 2.5 m on boom)	13.2	3	5	Cluster, RBSP, JUICE
FWP	EM field and wave receiver "e-box"	7.05 (7.2)	20	5	Solar Orbiter, JUICE
ESA/TEA	4x electron spectrometer	34.4 (32.4)	34	5	Stereo, Solar Orbiter
IMS	4x Ion spectrometer with TOF	36.6 (28.8)	41.2	6	Cluster, IBEX, MMS, Stereo
CSW	Electrostatic analyzer	8.0	10	6	Solar Orbiter
PPU	Digital electronics "e-box"	8.0	25	5	Solar Orbiter
FAR	Faraday cup	4.8	4.0	7	Spectr-R
EPE	2x Solid state detector	4.8	10	6	Solar Orbiter
Harnesses		24.0			
Total (nominal mass)		144.25	151.2		

Instrument accommodation

- All instruments have been accommodated
- ==> Marine's presentation!
- Driving parameters
- Separation of multiple instrument ie 90 degree
- FoV
- Electronic units inside (shielding and harness)
- Solid booms outside instrument FoV
- Sufficient distance between wire booms and solid booms
- ? Still some fine tuning required
- ? EPI accommodation angle requires another support structure
- ? EFI wire boom release angel to be modified (design feature)



Operations & Data Volume

- P/L on
  - Science
  - Comms
  - Science Comms
  - Short eclipses (<100 minutes)
  - Short eclipses comms
- P/L on or standby
  - station keeping
  - Transfer manoeuver
- P/L off long eclipse (>100<370 minutes)

❑ Modified (Survey) data volume compared to proposal
- longer orbital period
- HF spectra included

	4x16 R_E	4x26 R_E	14x60 R_E
$Survey_{prod.}$	5.9 (3.9)	10.7 (7.4)	6.0
$Burst_{download}$	36.9	27.8	18.6
$HRWF_{download}$	4.1	3.1	2.1
total	46.9 Gbit	41.6 Gbit	27.2 Gbit
$THOR_{CDF*}$	49.8	41.6	34.8

* 1 ground station, ~8 hours, 55 W output

❑ Required mass memory of 5 Tbit is included in the design

Radiation environment - TID

mm Al	Dose[kRad(Si)]
3	104
4	49.43
5	26.5
All mission phases	
Margin factor of 2 is applicable	

- Current estimate and valid for the CDF study
- Most instruments are by design radiation tolerant already
  - MAG, SCM, EFI, IMS, FWP, PPU - tolerant to 70-100krad
  - ESA/TEA, CSW, FAR, EPE no analysis
- Instruments designs must consider TID and max. flux conditions (noise in particle instruments)
- Currently an additional mass margin of 5% has to be considered

P/L summary

- No significant changes on the P/L throughout the study
  - Slight increases on mass, power and data volume
- All above can be accommodated in the S/C design
- Physical accommodation following instrument requirements is flawless
  - Yet more detailed work is required
  - Solid booms are included into S/C design
- Radiation/environment analysis will be continued, P/Ls still need to be fully adapted
- Thermal design, no specific issues identified
  - With the exception of FAR, => requires more in depth analysis (instrument team - industrial teams)
- No operational constraints identified, data can be stored and downloaded as required
- All P/Ls on an appropriate development level
  - the EFI-HFA is under development for JUICE
- Working groups on instrument accommodation wrt EMC constraints are recommended
- **No severe challenges or show stoppers identified**

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Mission Analysis

Internal Final Presentation
ESTEC, 9th July 2015

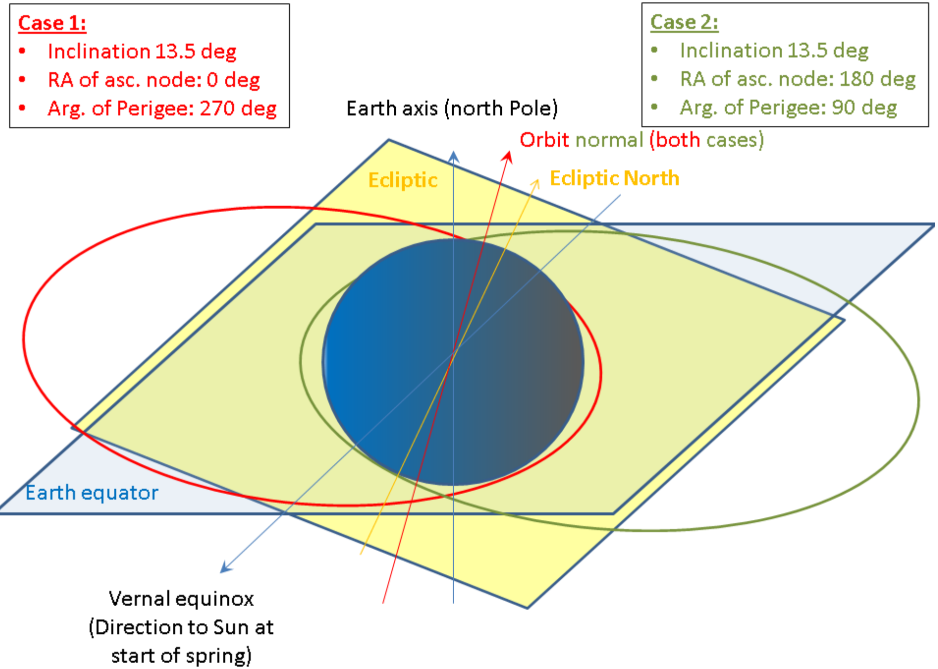
Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Assumptions and Requirements

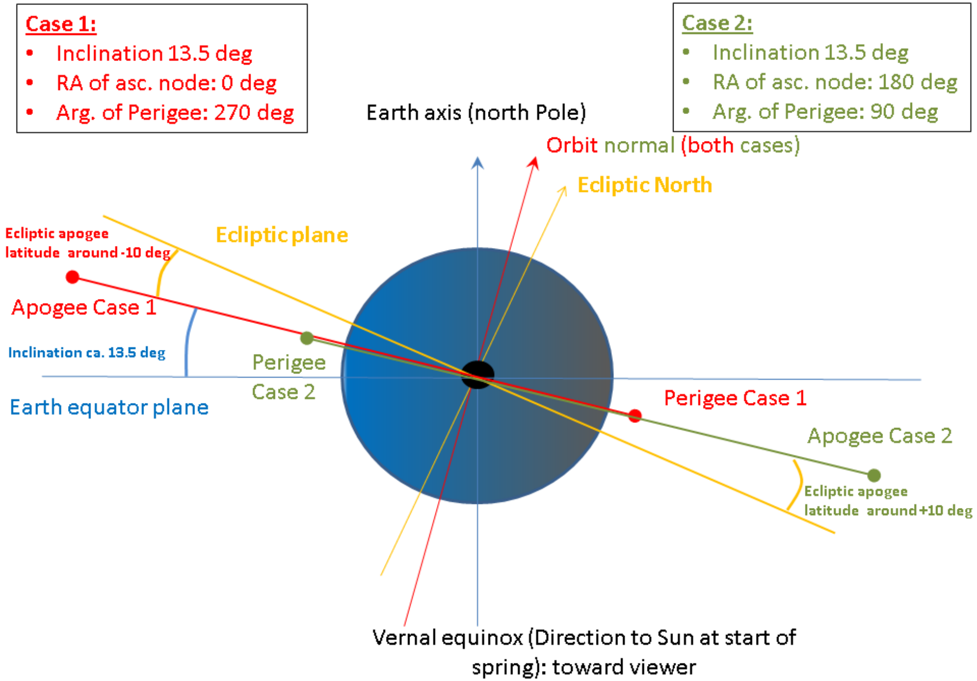
- Three mission phases have been defined beforehand, with around 1 year spent in phases 1 and 2 and up to 2 years in phase 3. One more phase was added during the study:
  1. Perigee / apogee radius: 4 / 16 Re (1 Re=6378 km. NB: Radius, not altitude)
  2. Perigee / apogee radius: 4 / 26 Re
  3. Perigee / apogee radius: 14 / 61 Re TBD
  4. Transfer to L1 orbit (Lagrange point in Sun direction)
- Additionally, the target location for the apogee shall be at an elevation of 10 deg with respect to the ecliptic plane.
  - This heavily constrains the search space, leaving only two solutions
- Launch:
  - Baseline: Ariane 62 directly into phase 1 orbit
  - Backup: Soyuz-Fregat directly into Phase 1 orbit
  - Also studied: Launch into transfer to Phase 1 orbit

Possible Orbit Planes (3D View)



- Two cases have been identified that satisfy the science requirements
  - Target orbit conditions independent of launch date
  - Significant simplification of planning, coverage analysis etc.
  - One launch opportunity per day for each case
  - Lunar encounter (and swingby) possible
- However!
  - Orbital state subject to perturbations
  - These are especially large in phase 3
  - Eclipse duration!

Possible Orbit Types (Side View)



Manoeuvre Budget

- Manoeuvre budget (all data are impulsive, no margins, no gravity losses)
  - Transfer 1 → 2: at perigee, 204 m/s
  - Transfer 2 → 3a: at perigee, 211 m/s
  - Transfer 3a → 3: Either at apogee, 263 m/s, or lunar swingby, ~0 m/s
  - Transfer 3 → 4: Either at perigee, 300 m/s, or lunar swingby, ~0 m/s
  - Navigation, stationkeeping, targeting, contingencies: TBD
    - 15 m/s per lunar swingby
    - 2.5 m/s/year in L1 orbit, assuming spherical thrust capability, low s/c noise
  - Final disposal:
    - From Phase 3: at apogee, 437 m/s, if lunar swing-by or Moon impact, ~0 m/s
    - From Lissajous orbit around L1: 20 m/s

Launch options (Ariane 62 and Soyuz)

- Dedicated launch
  - Either into Phase 1 orbit (radii 4 x 16 Re)
    - Soyuz 2.1b / Fregat MT from Kourou, payload mass at separation from Fregat: 1956 kg minus ca. 200 kg penalty for Fregat deorbit
    - Ariane 62: TBD. Performance should be considerably higher than that of Fregat, but it is not known whether a ~1 day delay of final manoeuvre is feasible with a cryogenic stage
  - Or into transfer to Phase 1 orbit (low perigee x 16 Re apogee)
    - Soyuz 2.1b / Fregat MT from Kourou, payload mass at separation from Fregat: 2679 kg
    - Ariane 62, TBD, tentatively assumed to be 66% higher than for Soyuz
  - Note: payload masses are inclusive of adapter!

Identified Issues

- Orbits are subject to strong perturbations, especially in phase 3
- Long eclipse phases, especially in phase 3
- TBD feasibility of direct insertion into Phase 1 Ariane 62 (propellant boiloff)
- Manoeuvre durations with low thrust levels
- Sun Aspect Angle constraints during manoeuvres
  - Currently 42 deg off-pointing allowed
  - In best case, this leaves few days for manoeuvre execution
  - However, this cosntrains the dates for manoeuvre execution

Identified issues (cont'd)

- Baseline phase 3:
  - raise apogee from 26 to 61 Re
  - Raise perigee from 4 to 14 Re (months later)

- 14 x 61 Re orbit: 1:2 resonance with the Moon
  - Easy stationkeeping to avoid getting close to the Moon (risks: strong perturbations, significant changes of inclination, eccentricity, period, argument of pericenter. Very difficult to control this

- Intermediate 4 x 61 Re orbit: 1:2.5 resonance with the Moon orbit. It is not possible to avoid close Moon encounters with this resonance

Potential Solutions to be further analysed

- **Either** insert into 4 x 61 intermediate orbit such that 5 orbits later a planned encounter of the Moon is performed with pericenter raise at no delta-v cost (maintaining inclination and other orbital parameters)bearing in mind the rather limited capability of THOR SC on the possible directions allowed to impart manoeuvres.
- This swingby would be mission critical. If targeting manoeuvres are not performed correctly, THOR will fly by the Moon anyway, but in an untargeted fashion, so the science orbit will be completely destroyed.

- **Or** redefine phase 3 orbit to 4 x 71 Re, with 1:2 resonance with the Moon (rather straightforward to control, TBC by analysis). But this is not the orbit the scientists asked for

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Radiation

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ESTEC, 9th July, 2015

Prepared by the CDF* Team

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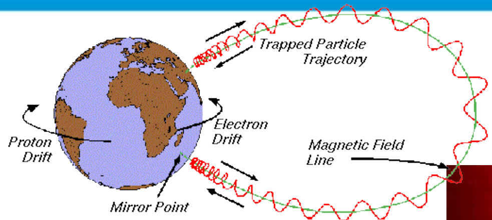
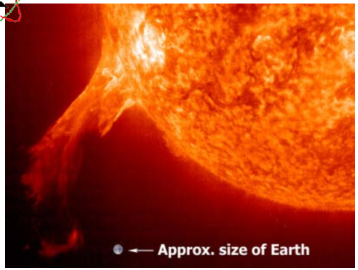
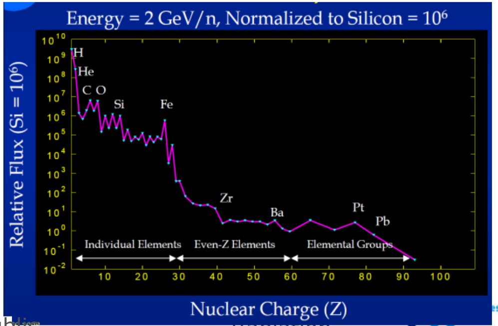
Environment Sources

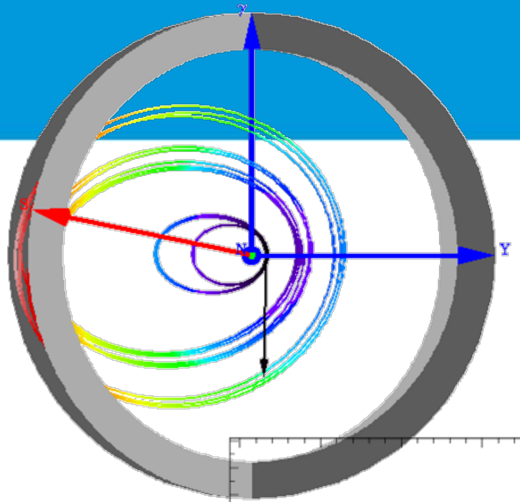
- Terrestrial Magneto-spheric Orbit
  - Trapped Protons & Electrons
    - AP8MAX/AE8MAX
    - AP8MIN/AE8MIN
  - Solar Protons
    - ESP/PSYCHIC model
    - Geomagnetic shielding
  - Cosmic Rays
    - ISO-15390 model (ECSS-E-ST-10-04C standard)
    - Geomagnetic shielding
- Shielding:
  - Generally assume 1 g/cm² of spherical shielding.
  - SEE calculations are generally stable with shielding (penetrating particles) over s/c shielding range.





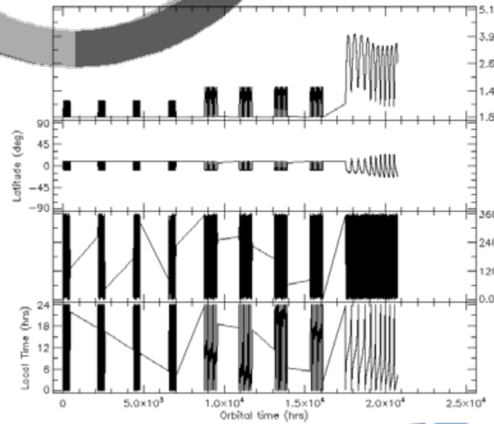


Mission Profile – Baseline



9 mission segments of 10 orbits each were analysed:

- 4 in 2026 at 3 month intervals:
  e=0.6, a=63773 km, Inclination=10°
- 4 in 2027 at 3 month intervals:
  e=0.73, a=95667 km, Inclination=10°
- 1 from 01/2028to 01/2031
  e=0.63, a=239168 km, Inclination=10°

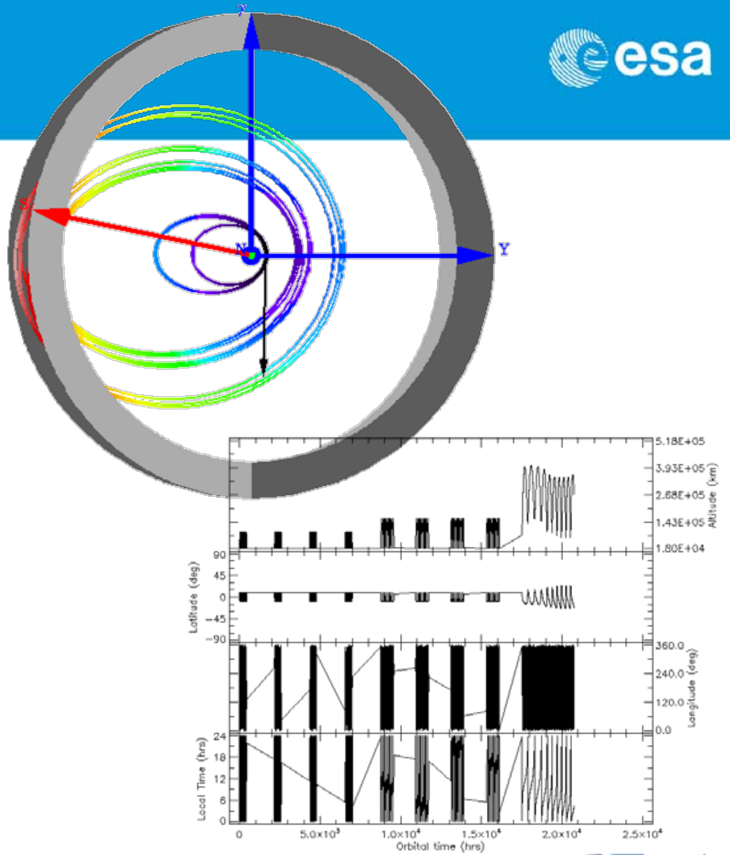


Mission Profile – Alternative

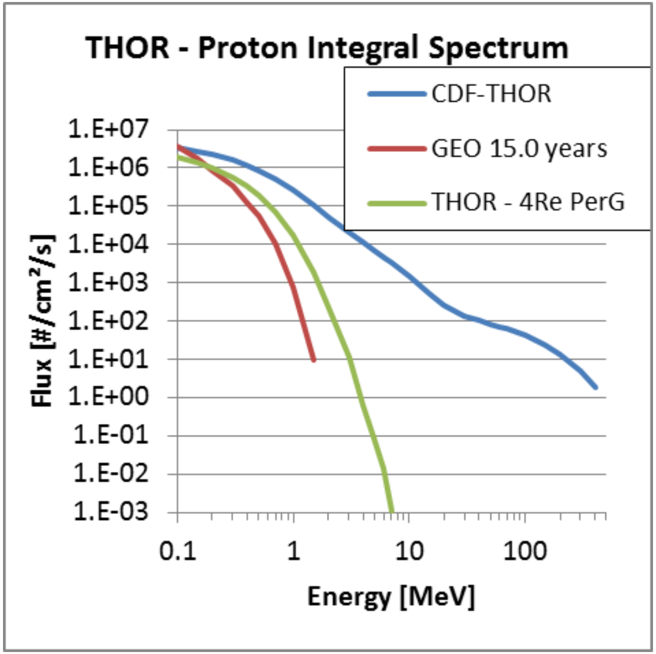
Delta is to have a perigee altitude of 2000 km in phases 1 and 2.

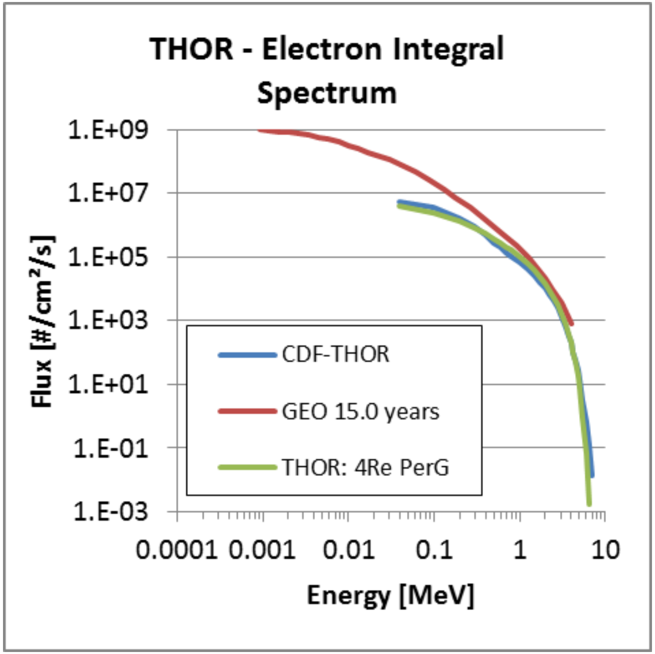
9 mission segments of 10 orbits each were analysed:

- 4 in 2026 at 3 month intervals:
  e=0.85, a=55206 km, Inclination=10°
- 4 in 2027 at 3 month intervals:
  e=0.90, a=87096 km, Inclination=10°
- 1 from 01/2028to 01/2031
  e=0.63, a=239168 km, Inclination=10°



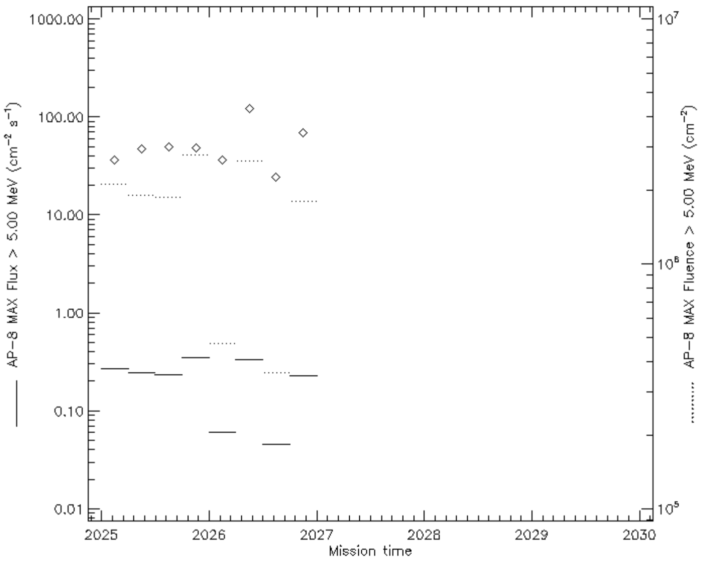
Mission Avg Trapped Particle Spectra



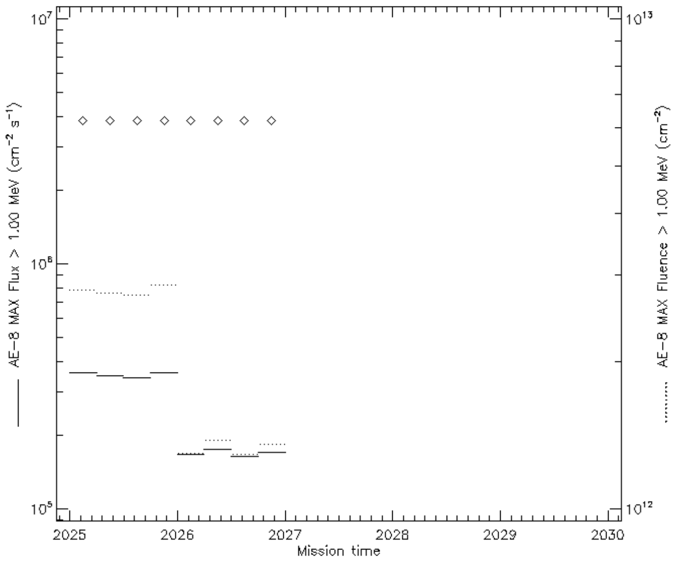


Trapped Particle Evolution

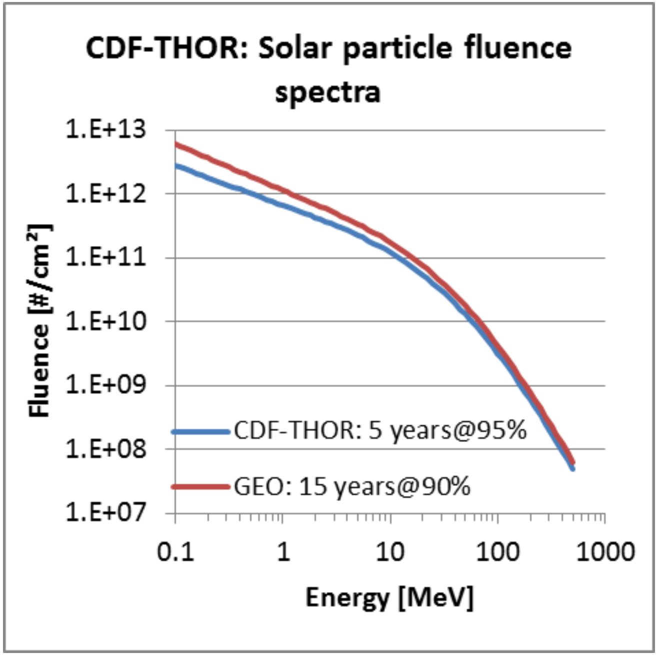
> 5 MeV Protons

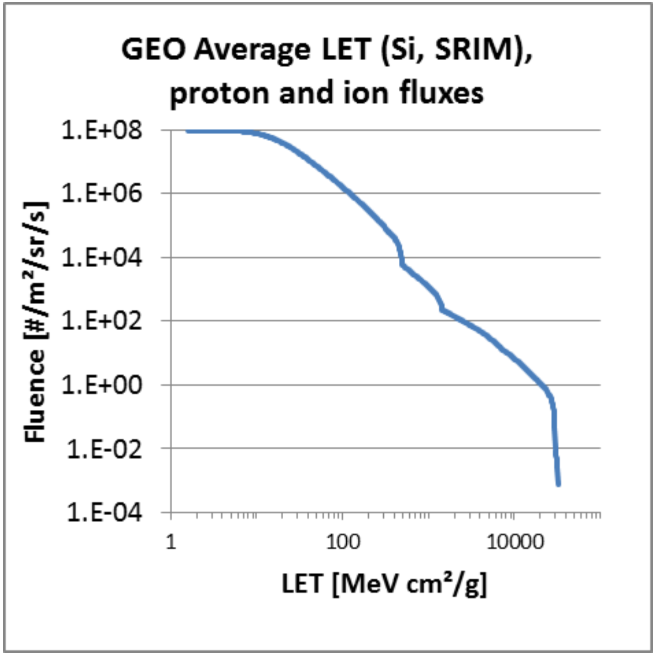


> 1 MeV Electrons



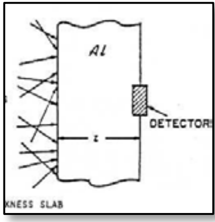
Solar Proton & GCR Spectra

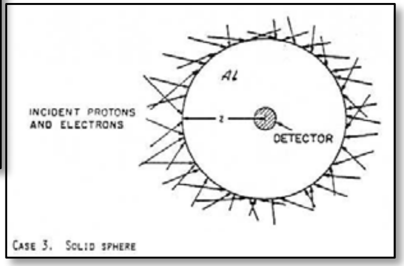


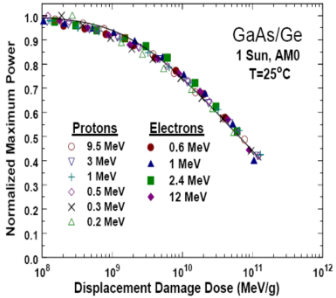


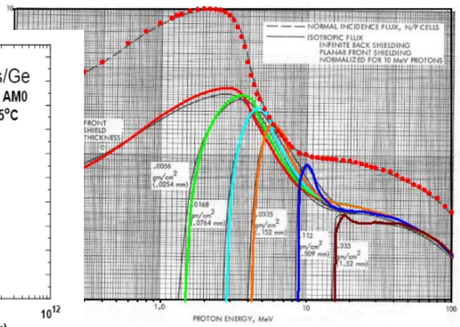
Radiation Effects

- Total Ionising Dose (TID)
  - Results from e^- & γ, p^+
  - Calculated using SHIELDOSE-2
  - Dose as a function of simple shields
  - units: rads(Si)
- Total Non-Ionising Dose (TNID)
  - Mostly from protons
  - Calculated from NIEL curve
  - units: MeV cm²/g
  - Affects opto-electronics and Bi-polar devices
- Solar Cell Degradation
  - A variant of TNID degradation
  - Calculated using EQFLUX or MC-SCREAM
  - Units: equivalent 1 MeV e^- or TNID

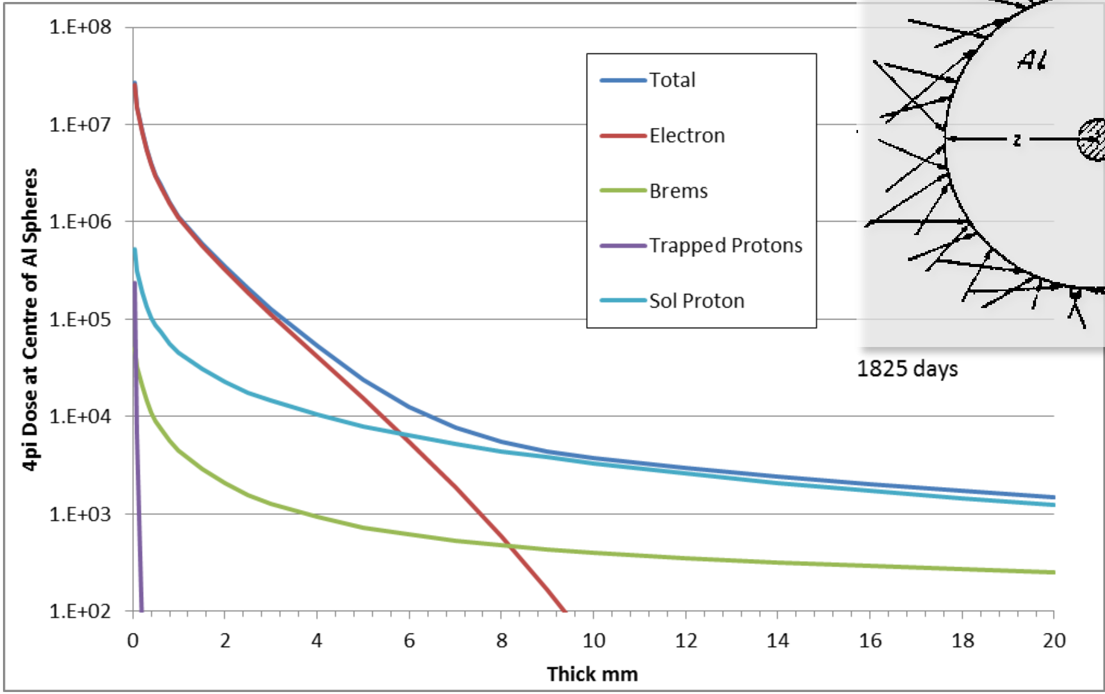


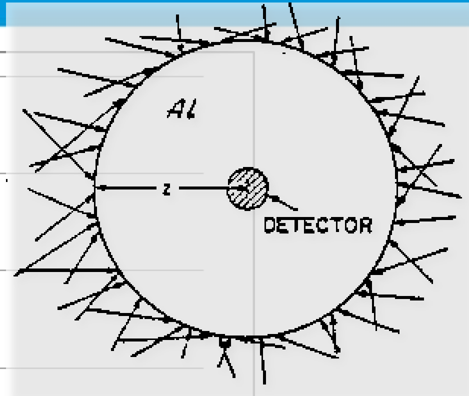






TID as a Function of Shielding Thickness – 4 Re Perigee





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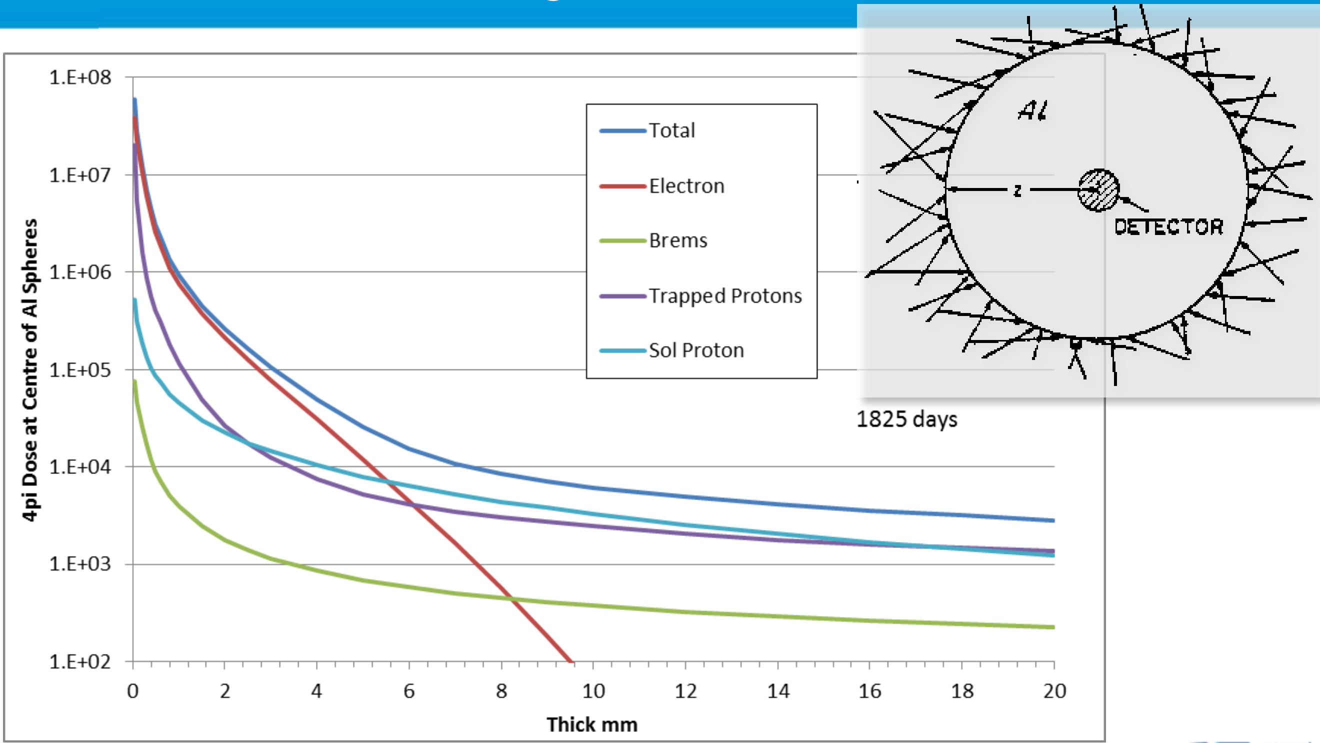
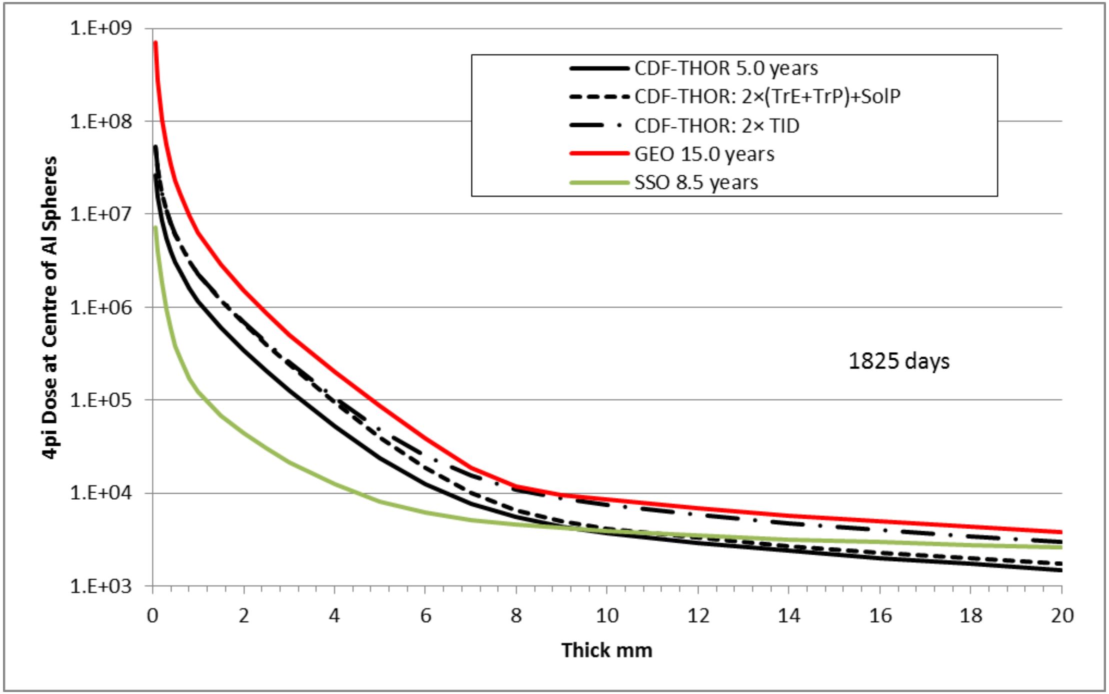
TID as a Function of Shielding Thickness – 2000 km Perigee



THOR TID compared to GEO (4 Re Per)



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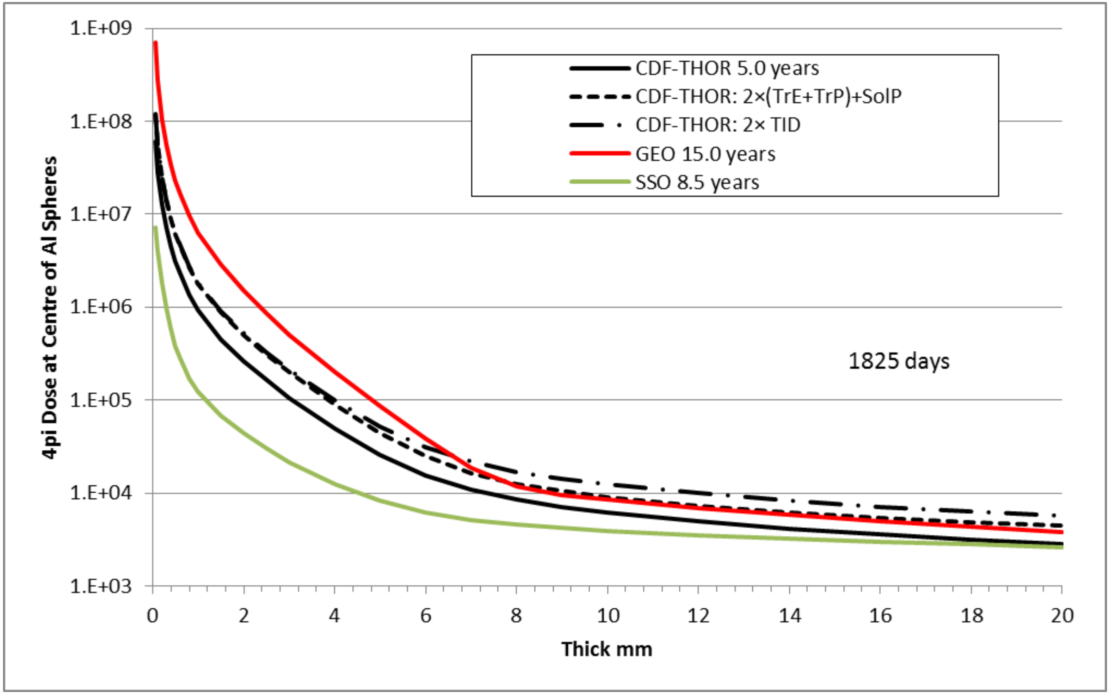
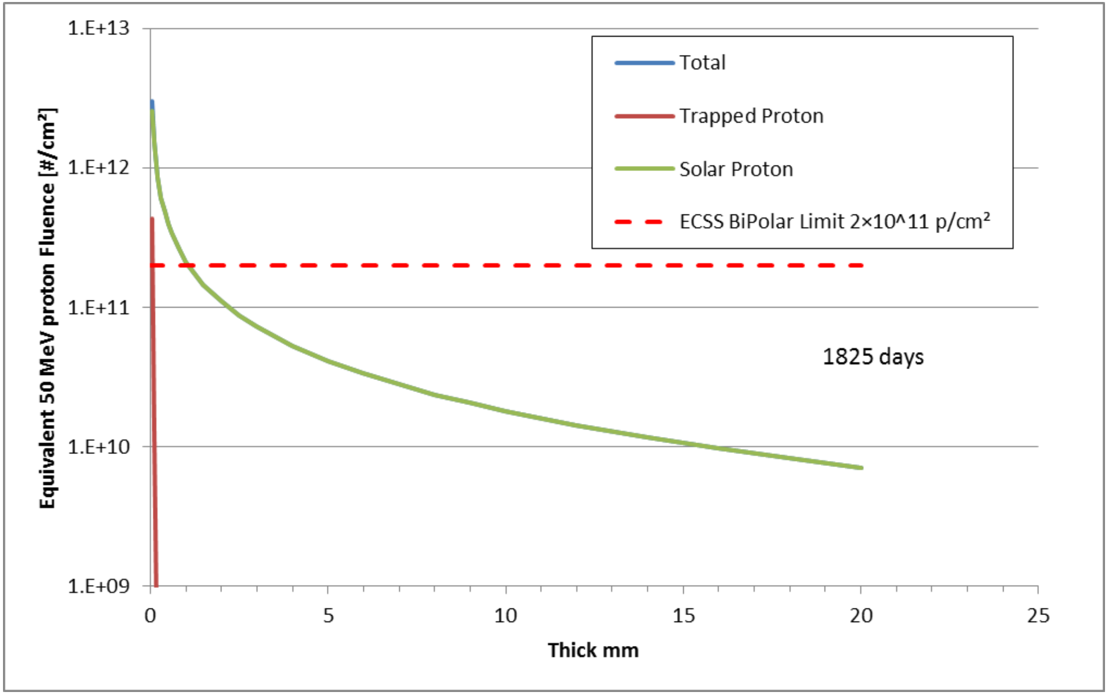
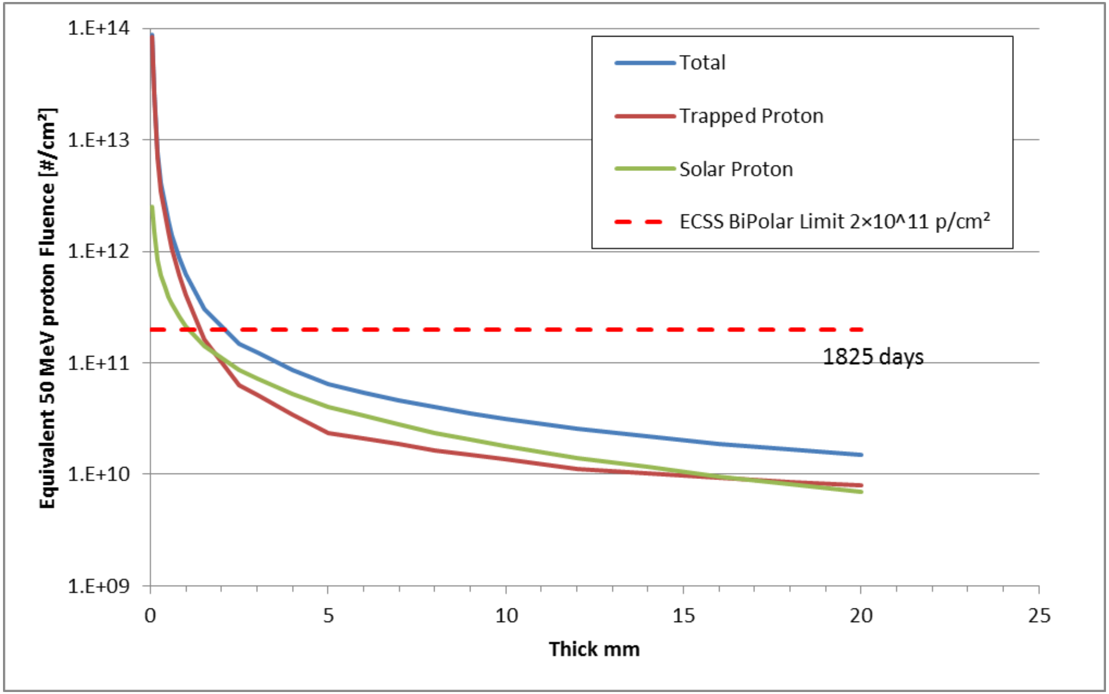


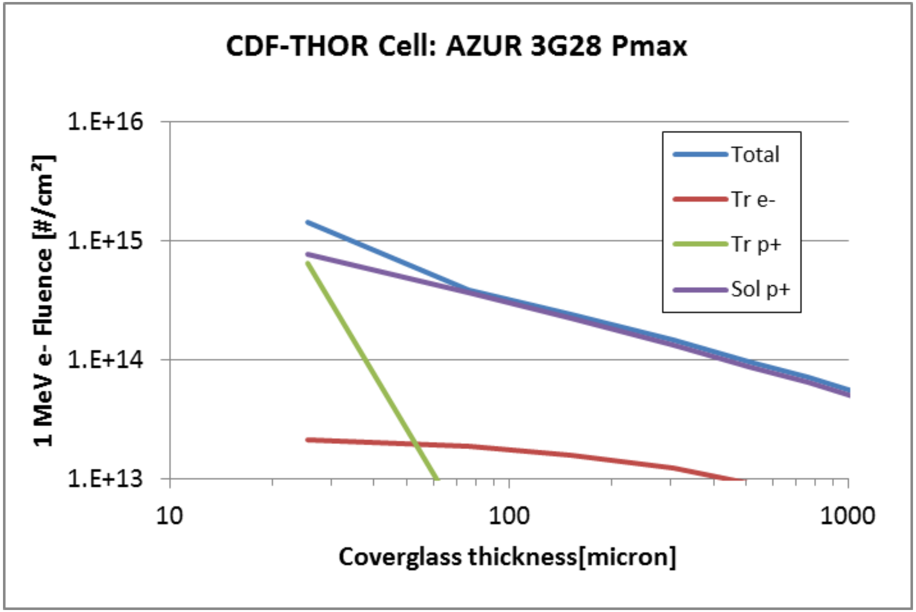
Total Non-Ionising Dose (4 Re Per)



Total Non-Ionising Dose (2000 km Per)



Solar Cell Degradation (4 Re Per)



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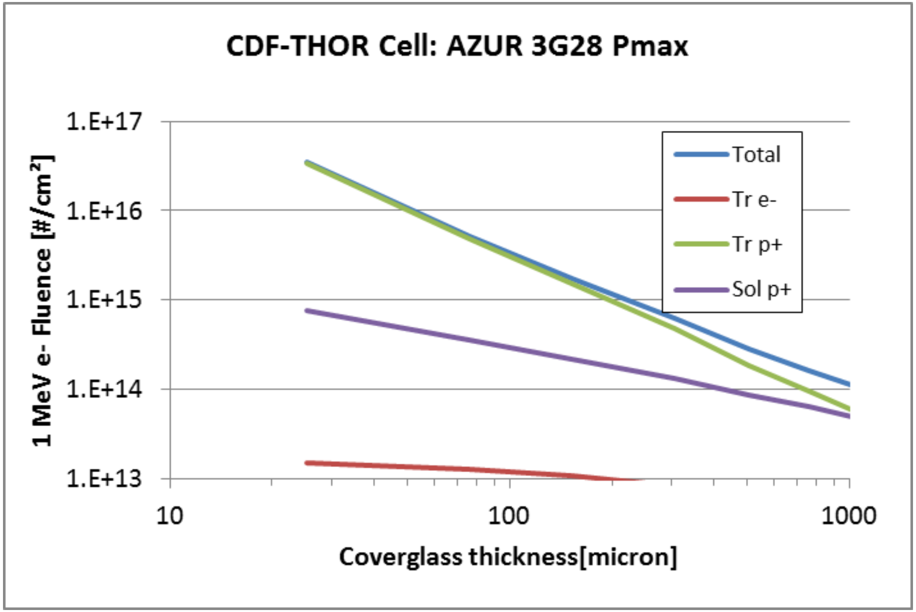
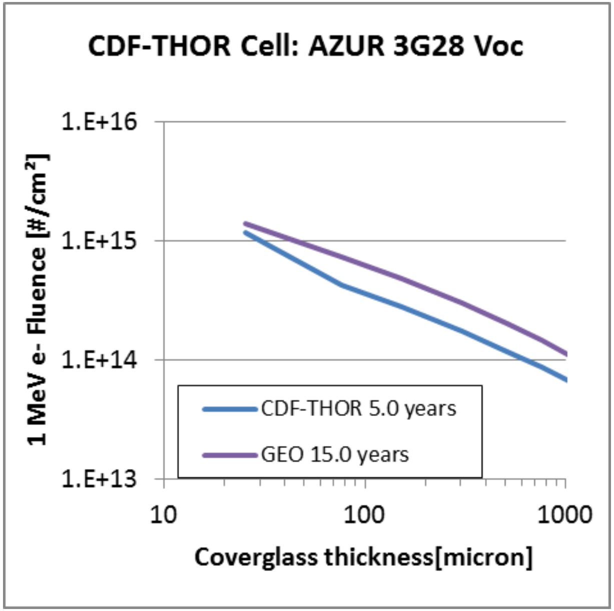
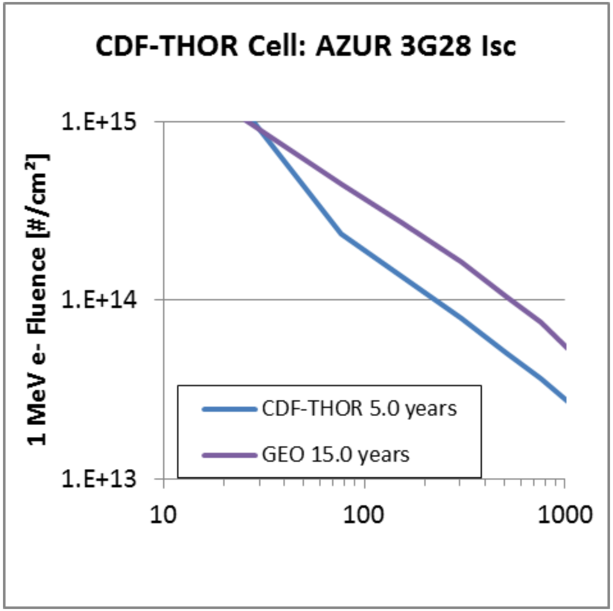
Solar Cell Degradation (2000 km Per)

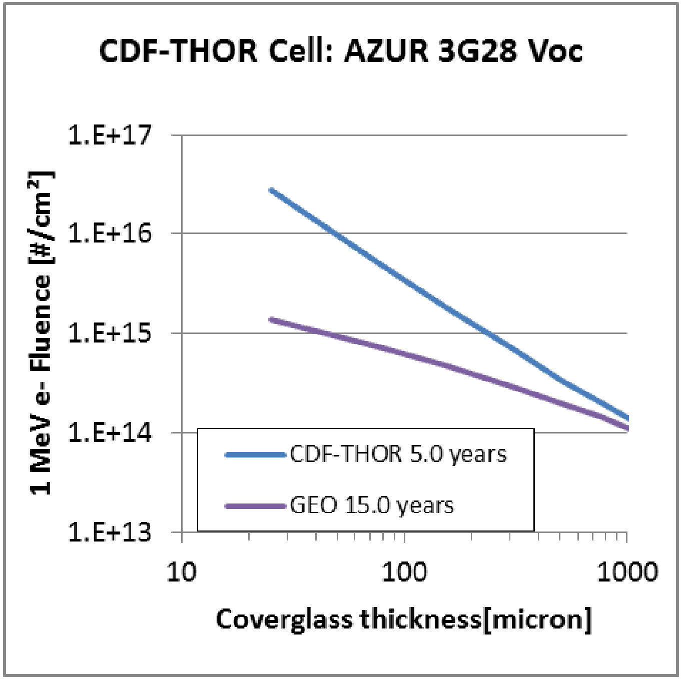


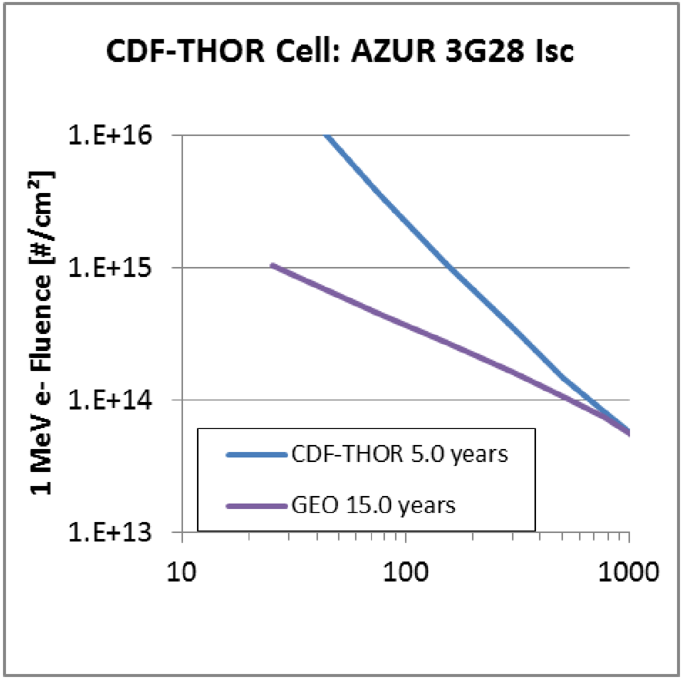
Solar Cell Degradation (4 Re Per)





Solar Cell Degradation (2000 km Per)





Conclusions

- First two years the mission dips into the trapped proton and electron belt; then the mission is effectively in "interplanetary" space, i.e. only SEP and GCR radiation sources.
- Margin recommendation: 2× trapped particle doses + solar energetic particle doses. (Trapped particle doses are "average" values and Solar particle doses are from a "worst-case" 95% confidence).
- Total Ionising dose is dominated by electrons for shields < 6 mm and Solar Energetic Particles at > 6mm shielding thicknesses.
- Total Non-Ionising dose is below the ECSS bi-polar device limit for shielding > 1 mm.
- Solar cell degradation is dominated entirely by solar particles, EXCEPT for 2000 km option!
- **THOR baseline mission is generally less harsh than a 15 year GEO mission → TRL is high.**

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Systems

Internal Final Presentation
ESTEC, 9th July

Prepared by the CDF* Team

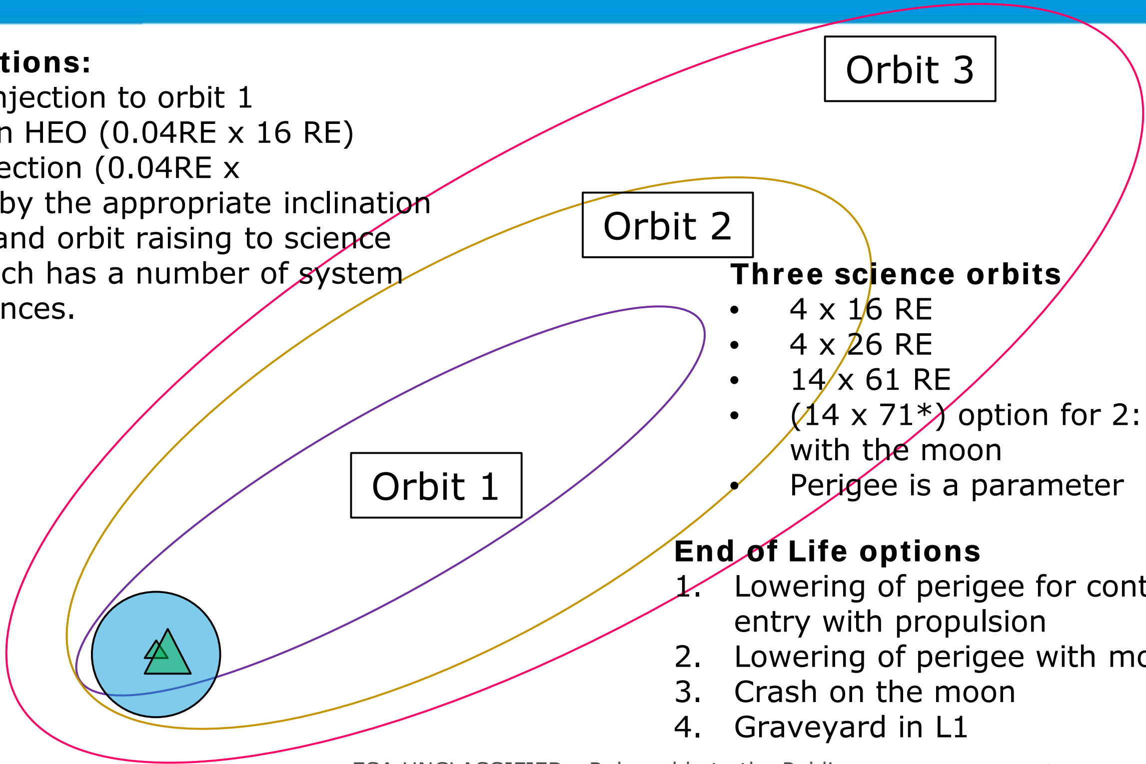
(*) ESTEC Concurrent Design Facility

Content

- Mission/ System requirements
- Design drivers
- Assumptions
- Trade off – justifications
- Baseline description
- Mass budget

Mission Scenario

Launch Options:
- Direct injection to orbit 1
- Injection HEO (0.04RE x 16 RE)
- GTO injection (0.04RE x
- Followed by the appropriate inclination changes and orbit raising to science orbits. Each has a number of system consequences.



Three science orbits
- 4 x 16 RE
- 4 x 26 RE
- 14 x 61 RE
- (14 x 71*) option for 2:1 resonance with the moon
- Perigee is a parameter

End of Life options
1. Lowering of perigee for controlled re-entry with propulsion
2. Lowering of perigee with moon fly-bys
3. Crash on the moon
4. Graveyard in L1

Mission description

- Direct injection to O1
- 1 year in Orbit 1
- 1 year in Orbit 2
- 1 year in Orbit 3
- 2 years extended lifetime in Orbit 3
- Transfer to L1
- Control stability at L1 (Earth – Sun L1)
- Disposal from L1

Mission Requirements

Highlighted requirements

***MIS-R-035**	**EMC**	**The space segment EM generated fields must be below the payload measurement resolution and thresholds.**
MIS-R-010,	Measurement Survey Data	The mission shall allow the collection of survey data continuously during nominal science phase (extended science phase)
MIS-R-015,	**Measurement Burst Data**	**The mission shall allow the collection of burst data with a historical availability of at least 13 days during nominal science phase in the key regions of interest.**
MIS-R-020,	Measurement High Resolution Waveform Data	The mission shall allow the collection of High Resolution Waveform HRWF Data with an availability of at least 1 min twice per orbit during nominal science phase in the key regions of interest.
MIS-R-025,	**Mission Lifetime**	**The mission shall be designed for a lifetime of 3 years.**
MIS-G-030,	Mission Extension	The mission should be designed for a lifetime of 5 (TBC) years.
*MIS-R-045,	Data dissemination	The science team shall be able to review survey stored on board the spacecraft ad select which burst and HRWF data to be downloaded limited by the data rate available at that time.
MIS-R-050,	**Launcher**	**The mission shall be compatible with a launch on Ariane 6.2 from Kourou.**
MIS-R-055,	**Back-up Launcher**	**The mission shall be compatible with a launch on Soyuz from Kourou.**
***MIS-R-130,**	**TRL**	**Technology Readiness Level shall be TRL 5-6 at the end of Phase B1 (2018).**

System Requirements (1)

Highlighted requirements derived from the mission requirements

SC-SYS-R-010,	Spacecraft lifetime	The lifetime of the space segment shall be 3 years.
SC-SYS-G-015,	Space Segment lifetime EXTENSION	The lifetime of the space segment should be extendable up to be 5 years.
SC-SYS-R-025,	Spacecraft Launcher	The space segment shall be compatible with a Ariane 6.2 and Soyuz launcher.
SC-SYS-R-030,	**Radiation**	**A factor 2 shall be applied to the radiation environment.**
SC-SYS-R-035,	**System Mass Margin**	**A 20% maturity margin shall be applied to the total estimated dry mass.**
SC-SYS-R-040,	System Power Margin	A 20% maturity margin shall be applied to the estimated power consumption in each spacecraft mode.
SC-SYS-R-055,	Orbit Maintenance Propellant Mass Margin	The spacecraft shall apply a margin of 100% in addition to the nominal estimated stochastic Delta-V for orbit maintenance.
SC-SYS-R-060,	Orbit Manouvres Propellant Mass Margin	The spacecraft shall apply a margin of 5% in addition to the nominal estimated deterministic Delta-V for orbit raising maneovres.
SC-SYS-R-065,	Space Debris Mitigation	The spacecraft shall be compliant with the space debris mitigation guidelines given in ESA/ADMIN/IPOL(2014)2 (March 2014).

System Requirements (2)

Highlighted requirements derived from the mission requirements

SC-PAY-R-005,	Instrument Configuration	The spacecraft shall accommodate, providing the required FoV, the following instruments as defined in [PDD] ref: - Search Coil Magnetometer - Particle Processing Unit - Fluxgate Magnetometer - Ion Mass Spectrum Analyser - Fields and Waves Processor - Faraday Cup - Electron Spectrum Analyser - Cold Solar Wind Ion Analyser - Energetic Particles Detector - Electric Field Antenna - Active Spacecraft Potential Control (ASC)
SC-PAY-R-015,	**Payload Mass**	**Payload instruments of at least 173.1 kg including margins shall be accommodated on-board the spacecraft.**
SC-SYS-R-080,	**Launch wet mass**	**The spacecraft wet total mass including all applicable margins and constraints shall not exceed Mwet = 1735 kg**
SC-SYS-R-075,	**In-orbit Determination Requirements**	**The spacecraft in-orbit position shall be known to an accuracy of at least 10 km in all directions.**

System Requirements (3)

EMC requirements derived from the Payload requirements

SC-EMC-R-005,	MAG, SCM configuration	The MAG and SCM shall be mounted such that the ambient magnetic field at their location is less than 0.1 nT (TBC).
SC-EMC-R-010,	Slow magnetic field variations	The slow spacecraft magnetic field variations on timescales of more than one hour shall be limited to 0.5 nT peak-to-peak at the location of the MAG and SCM instruments.
SC-EMC-R-015,	Medium magnetic field variations	The medium spacecraft magnetic field variations on timescales of between one second and one hour shall be limited to 10 pT, peak-to-peak.
SC-EMC-R-020,	Electrostatic Cleanliness PD	Differential surface potential between any two points on the spacecraft shall be less than 1 V.
SC-EMC-R-025,	Spacecraft charging	Absolute spacecraft potential shall remain below 10 V (TBC).
SC-EMC-R-030,	AC EM Emissions non-deterministic	Any non-deterministic variations of electromagnetic emissions from the spacecraft in the frequency range of [1, 10^4] Hz shall remain below the noise floor of…: fig 37, 41 in proposal.
SC-EMC-R-035,	AC EM Emissions deterministic	Any deterministic emissions, exceeding the noise floor in R-SEMC-… shall be stable to TBD levels and synchronized to a maximum of TBD frequencies.
SC-EMC-R-040,	Total Magnetic field	The total magnetic field of the spacecraft should be less than 5 nT at the location of the magnetometer sensors.

Assumptions

- Ariane 6.2 is equal or better then Soyuz
- No gravity assist manoeuvers
- No science during the long eclipses (>100 minutes)
- No comms during the long eclipses (>100 minutes)
- Comms subsystem sized for 15m ground station dishes
- Maximum comms duration 8 hours
- Penumbra is considered as an eclipse
- The sun is always within ±39 deg of the spacecraft velocity vector during orbit change
- All manoeuvers can be done with booms and wires deployed
- The harness mass is assumed to be 7% to account for extra EMC related shielding

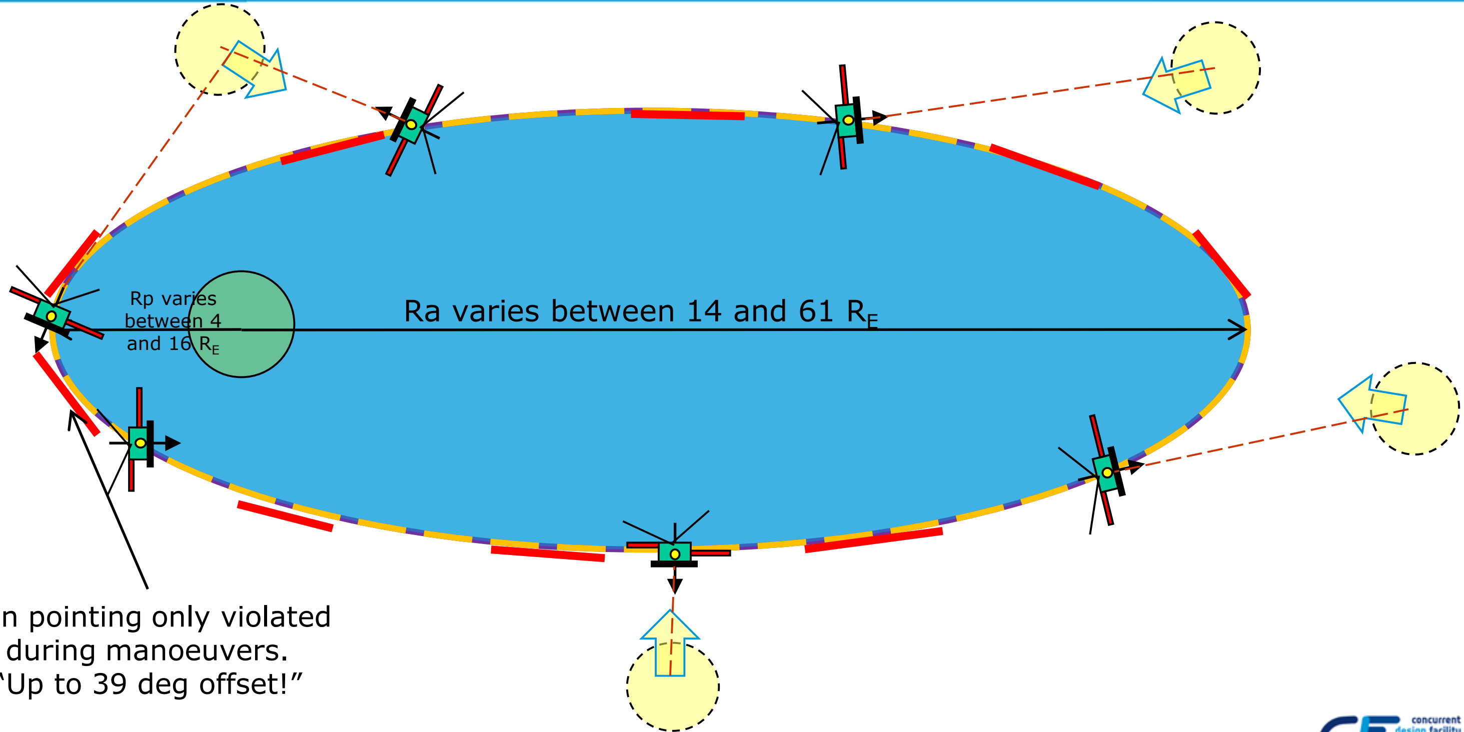
Subsystems Design Drivers (1)

Domain of Expertise	Design drivers
Mission analysis	Minimise delta V, minimise radiation dose, maximise telemetry and scientific data download
Propulsion	Minimise mass (prop ss architecture) Proposal: hydrazine propellant system, Isp 230 s; 20N thruster used for orbital transfers, cluster of 1N thrusters are used for attitude control (spin establishm and maint. + precession control); 225 kg hyd. Delta V 847 m/s incl 25% margin; 8 x 45 l tanks
AOGNC	Comply with spin, pointing and EMC requirements for THOR. Proposal: X-beam sun-sensors, APS star trackers, 1N thrusters
Communications & GS	Achieve positive link margin of at least 2-3 dB. Proposal: X band for uplink and downlink, LGA as in CLUSTER (-1dB gain), 25 W RF power; Data Rates Science Data: 345 (O1) - 155 (O2) - 25 (O3) kpbs. Selective Data Downlink Strategy. Kourou + Perth (availability TBC!) G/T=37.5 dB/K.
DHS	Achieve on-board storage of 5 Tbits (TBC) allowing to store at least 275 hours of Burst data. The payload will generate two science data streams transferred to the spacecraft mass memory: 1) Survey data covering the full time at low time resolution, 2) Burst data covering the full time in the key science target regions at high time resolution Telemetry rate is not suffcient to download the full volume of Burst data on each orbit, and therefore selective data downlink will be used for the Burst data
Power	Comply with EMC requirements; Size battery for long eclipses (assess whether Safe mode could be sizing case) Proposal: non-switching, linear shunted system, with dumping of excess power at several different locations on the spacecraft. Bus voltage 28+/-4V. The grounding concept: Distributed Single Point Ground system.
Thermal	Design for THOR Thermal Environment. Comply with EMC requirements (material selection) Proposal: upper disc bigger than lower for radiative cooling; no side panels, covered with electrically conductive surfaces (ITO Kapton, Black Kapton); MLI on the space facing side

Subsystems Design Drivers (2)

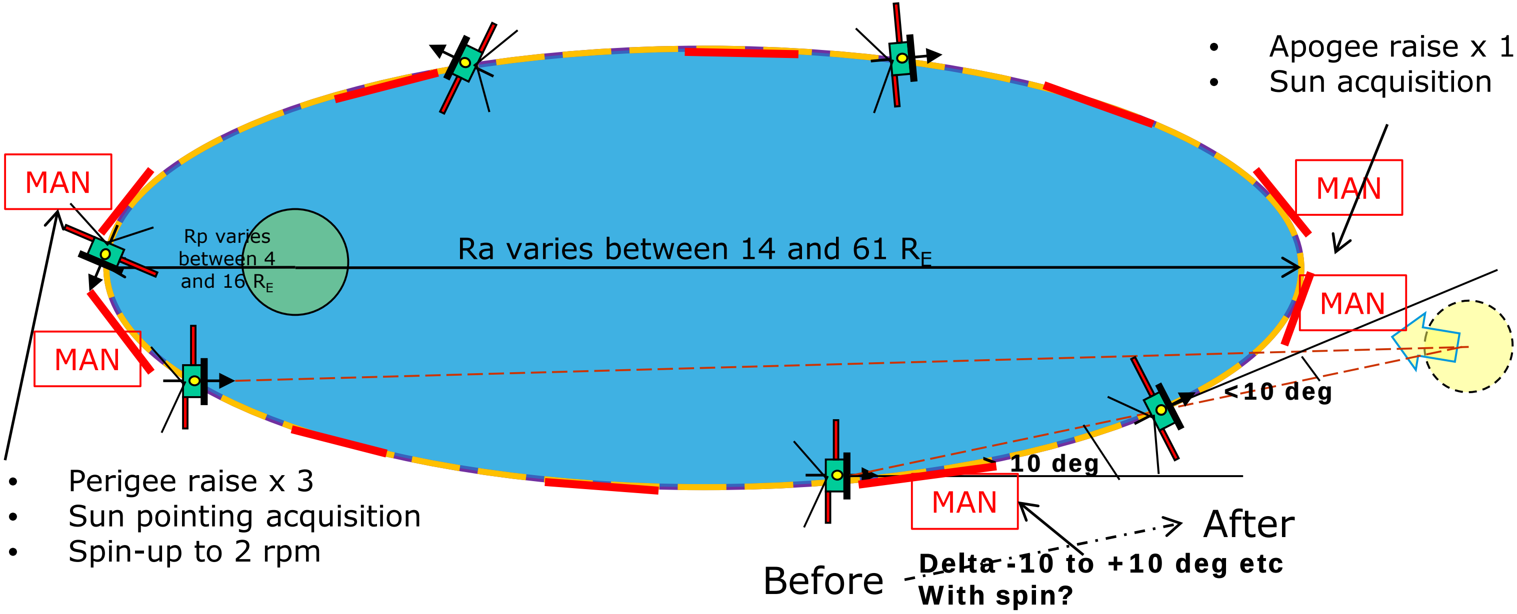
Domain of Expertise	Design drivers
Mechanisms	Comply with EMC Requirements in the Booms design, Minimise mass and complexity Proposal: boom length 5 m might not be sufficient for EMC reqs. Define needs / use Juice developments heritage (6-7m)
Structures and Configuration	Minimise mass, use EMC compatible materials, accommodate PL and equipment coping with EMC and spinning requirements
Radiation	Design shielding concept: judge on required shielding Al thickness. Monitor TIDS of different equipment. Advise on configuration. Proposal:34 krads behind 5 mm Al; 137 krads behind 3 mm Al Note: TIDS: CDMU/CDMU 50 krad - Gyros 70 krad – STR 150 krad
EMC	Advise on design rules to observe (materials, accommodation, harness overshielding, …). Assess need of Active Potential Control (baselined in proposal)
Cost	M4 class Mission (<450 MEUR e.c. 2014). Assess cost impact of EMC requirements. Take geo return constraints into account.
Programmatics	Launch date end 2026. TRL 5/6 by 2018. EMC testing to be considered.
Risk	Advise on minimising development risks (no major technology developments allowed by schedule)

Science Orbit – Sun Variation



Sun pointing only violated during manoeuvers.
"Up to 39 deg offset!"

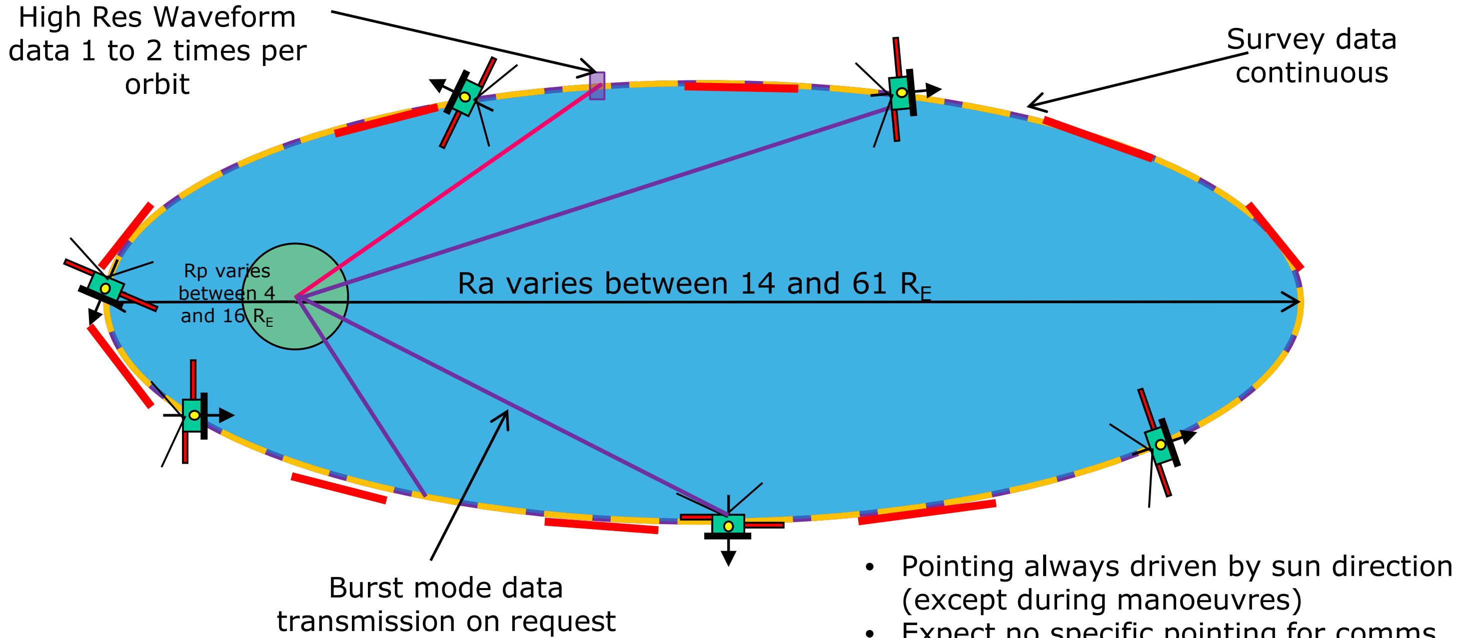
Science Orbit – Manoeuvres



- Apogee raise x 1
- Sun acquisition

- Perigee raise x 3
- Sun pointing acquisition
- Spin-up to 2 rpm

Science Orbit – Data Return



- Pointing always driven by sun direction (except during manoeuvres)
- Expect no specific pointing for comms

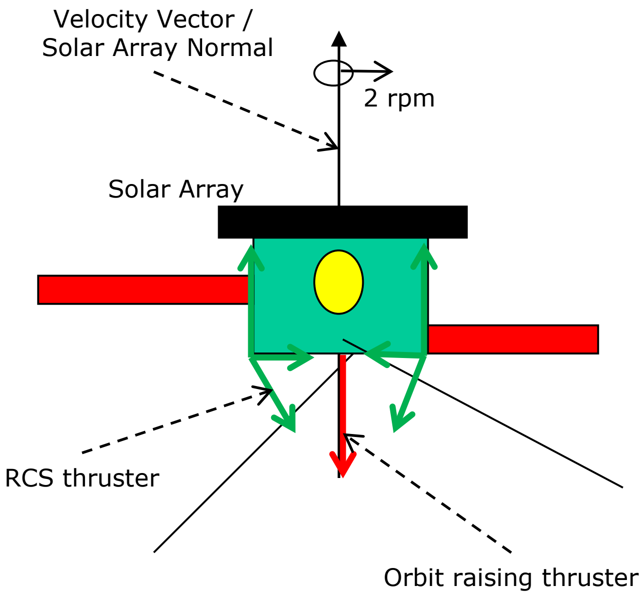
Launch Options Trade Space Results

Option	Vega-C*	Soyuz /Ariane 6	Soyuz /Ariane 6 (50%)	Ariane 5 (25%)	Ariane 5 (50%)	Ariane 5 (75%)	PSLV
GTO	TBD						
Orbit 1 Direct Injection							
HEO Direct Injection	TBD						

*Vega-C could be better performing than PSLV, so if more data were available it could become an option

- Our orbit is not attractive to other passengers
- Our EMC requirements are stringent and could constrain the passenger

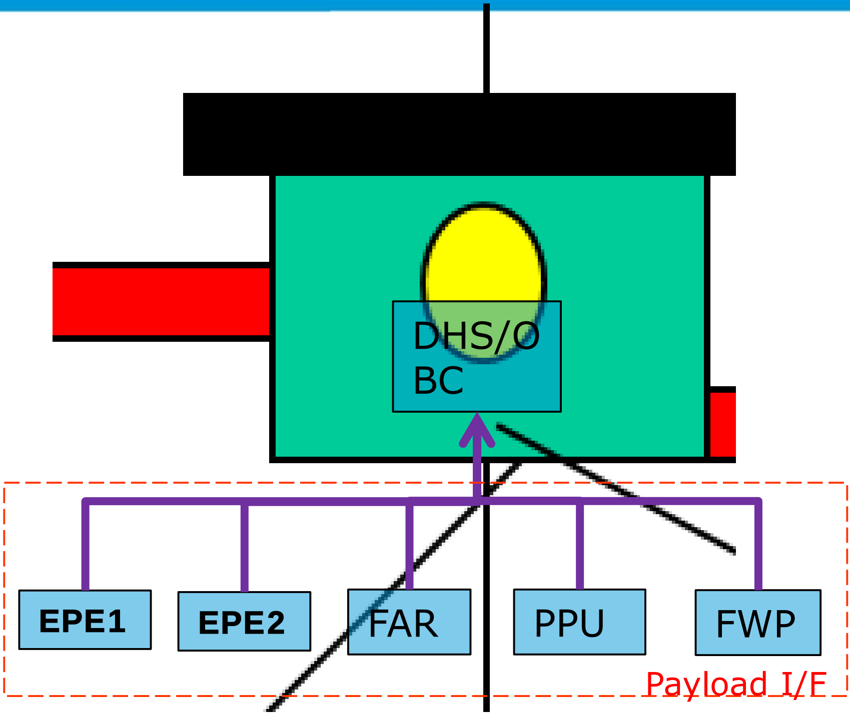
Spacecraft Design (1) – AOCS / Propulsion



Requirements:

- 3-axis control
- Spin around sun direction at 2 rpm
- Conduct slew while spinning at 2 rpm over at least 20 degrees absolute
- Thrust along the spin axis for orbit raising burns
- Spacecraft attitude knowledge of 0.5 deg
- Maintain sun aspect during science mode of within 10 degrees

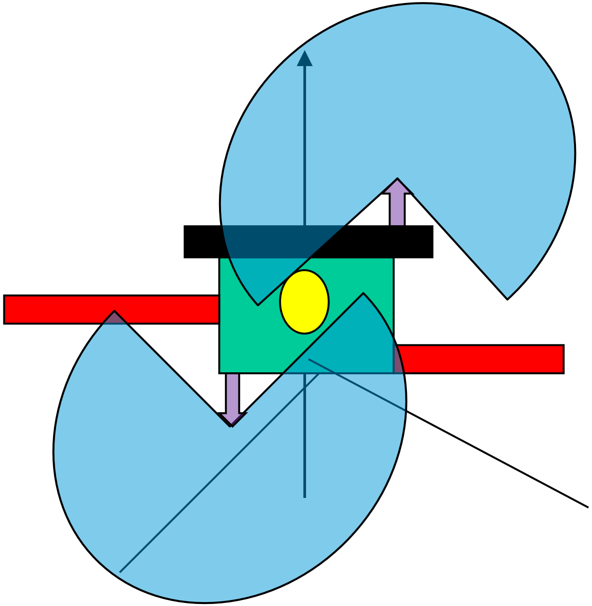
Spacecraft Design (2) – Data Handling



Requirements:

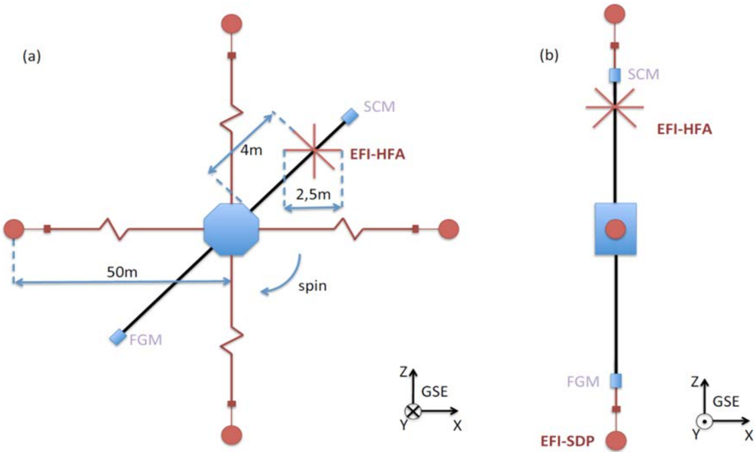
- Provide data interfaces for:
  - FAR instrument
  - EPE instrument 1
  - EPE instrument 2
  - FWP
  - PPU
- Store 13 days of science burst data (Orbit 3 period)
- Burst data shall be selectable from ground
- Store survey data to account for 3 missed passes
- Command and manage spacecraft functions

Spacecraft Design (3) - Comms



Requirements:
- Omni-directional coverage
- Download all survey data in a single pass
- Provide higher data rates for burst science data
- Account for up to three missed passes
- Close a survey data + S/C HK link up to a distance of 61 R_E
- Orbit determination done using ranging, and to be included in the ground pass duration

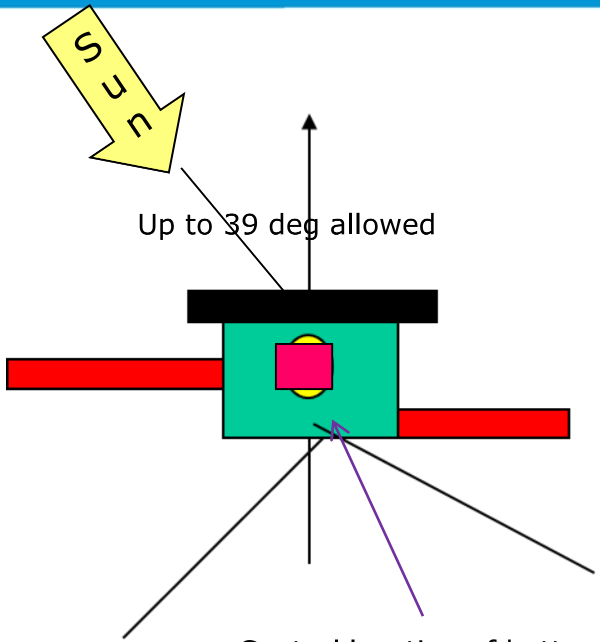
Spacecraft Design (4) - Booms



Requirements:

- Instruments require placement away from S/C implying deployment on booms
- 4 x 50 m boom
- 2 x 6.3 m boom (3 segments in each)
- Rigidity of 50 m booms **TBC**
- Remain deployed during S/C burns
- Expected boom deflection during burns **TBC** deg
- MACS needed to guarantee 0.5 deg positional knowledge

Spacecraft Design (5) – Power

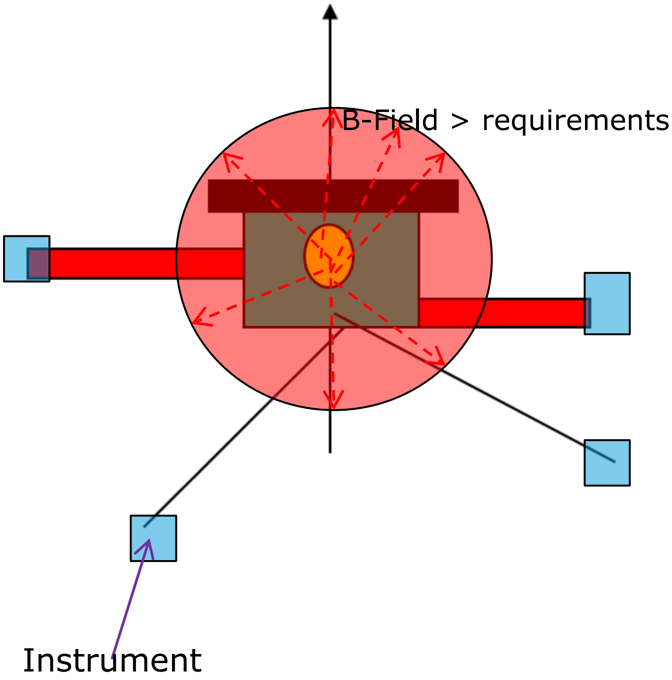


Central location of battery, PCDU

Requirements:

- Sized for MAN mode for up to 39 deg offset from sun
- Minimise EMC signature of PCDU and battery
- Eclipse duration 370 mins worst case
  - No payload or comms in long eclipse (>100 mins)
  - Payload and comms in short eclipse (<100mins)
- No mechanisms recommended
- Excess power dissipation needed

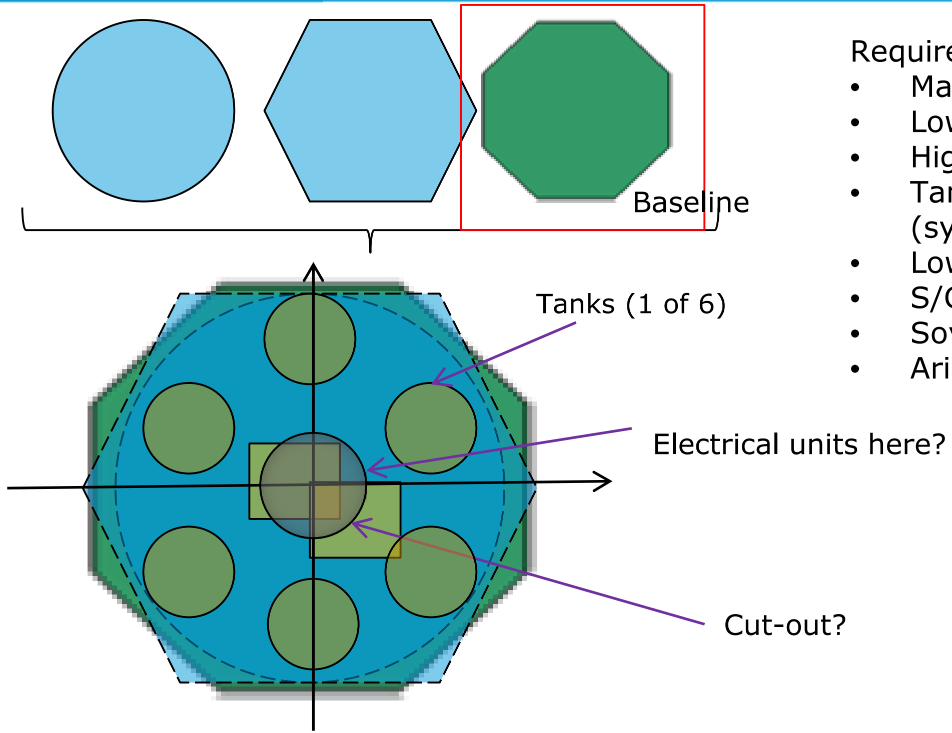
Spacecraft Design (6) –EMC



Requirements:

- Differential surface potential between any two points on the spacecraft shall be less than 1 V
- The medium spacecraft magnetic field variations on timescales of between one second and one hour shall be limited to 10 pT, peak-to-peak.
- The slow spacecraft magnetic field variations on timescales of more than one hour shall be limited to 0.5 nT peak-to-peak at the location of the MAG and SCM instruments.
- Active potential control
- Cancellation of magnetic fields through symmetry where possible.

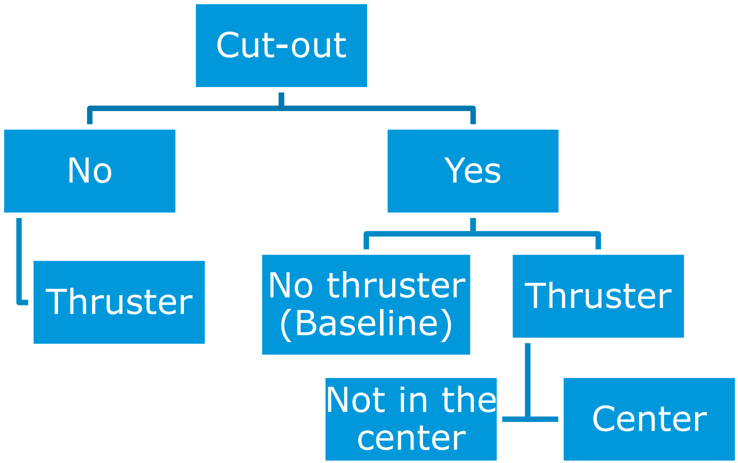
Spacecraft Design (7) – Structures & Config

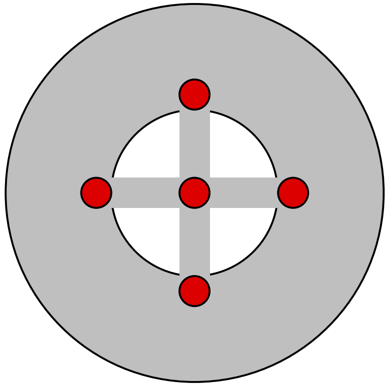


Requirements:

- Magnetic symmetry
- Low magnetic materials
- High EM units close to centre
- Tanks aligned with CoM and rotation axis (symmetric)
- Low height
- S/C Diameter maximised to fairing width
- Soyuz environment assumed
- Ariane 6.2/ Soyuz 115 kg adapter

Spacecraft Design (7) – Structures & Config





Spacecraft Design (7) – Structures & Config

	No cutout	Cut-out No thruster	Cut-out 4 thrusters	Cut-out thruster in center
Contamination	-	++	--	-
EMC	--	++	-	+
AIV	Na	+	+	-
Equipment	--	++	++	+
Orbit changes	+	--	+	+

Spacecraft Design (8) - Shielding

- Shielding
  - Environment factor 2
  - Conservative design
  - -3 mm for case
  - -2 mm for the equipment in the center

- Unit level: 13.3 kg
- Around the central cylinder: 39 kg

Baseline design

Subsystem	Options	
Comms/GS	35 m dish	15 m dish
Propulsion	Monopropulsion (8 tanks)	Bipropulsion (6 tanks)
AOGNC	2 x 10 N THR 8 x 1 N THR	1 (NOM) + 1 (RED) x 22 N THR Isp 300 s 4 (NOM) + 4 (RED) x 4 N THR (8 are enough for pure torque)
Shielding Strategy	Shielding offered by case No need for extra shielding	Need for Extra Shielding
Structure	Hexagonal Shape	Octagonal Shape with cut-out: Diameter 3.7 m, Edge length 1.404 m Central Cylinder: 1.194 m diameter, 0.7m height

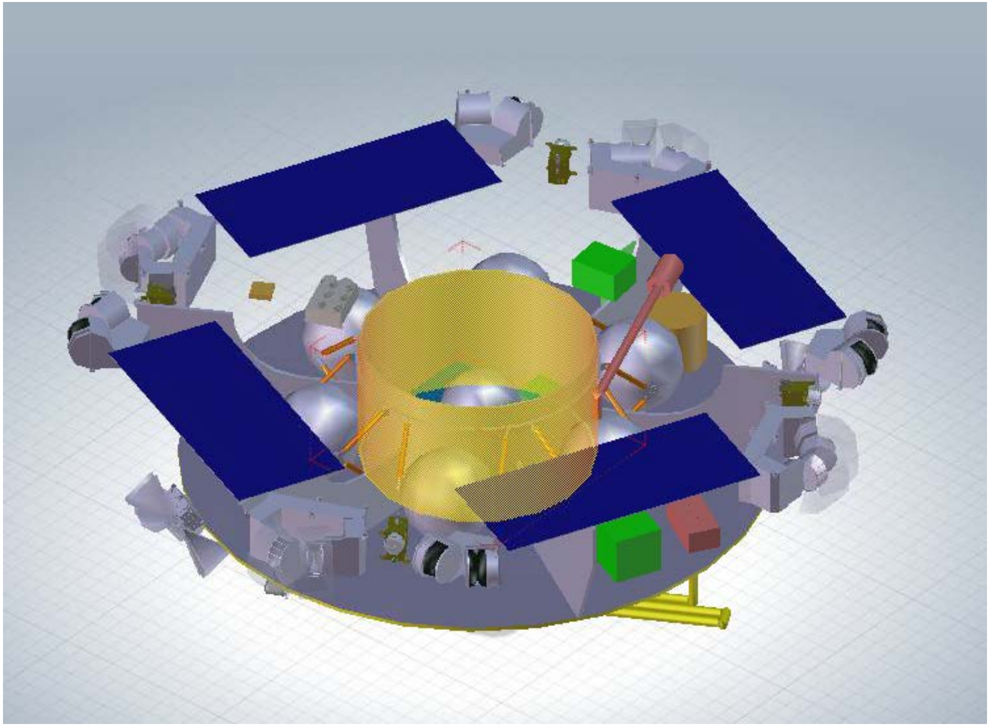
Baseline design

Subsystem	Options		
Mechanisms	6 m boom deployed from top	6.3 m boom deployed from bottom (20 cm inside bottom panel plate)	
		3 segments	2 coilable booms
Mission Analysis	Direct Injection	Shared Launch	
	O3a → O3 without Lunar swing-by	O3a → O3 with Lunar swing-by	
	Phase 4 to L1 without Lunar swing-by	Phase 4 to L1 with Lunar swing-by	

Baseline design

Subsystem	Options		
EMC	Local Synchronization		Global Synchronization Ref. Clock – inside OBC
EMC	Extra Shielding for Harness From 5% (SRE Margin Policy) to 7% of dry mass		No Extra Shielding for Harness
Cost	No EMC measures accounted for	A subset of EMC measures accounted for	All EMC measures accounted for
Radiation	Factor 2 applied on Environment		No factor 2 applied on Environment
Radiation Shielding Strategy	Shielding at unit level Mass: 13.3 kg Instruments: 5% of PL Pack mass		Vault Shielding (Cylinder) Mass: 39 kg Instruments: 5% of PL Pack mass

Baseline Design



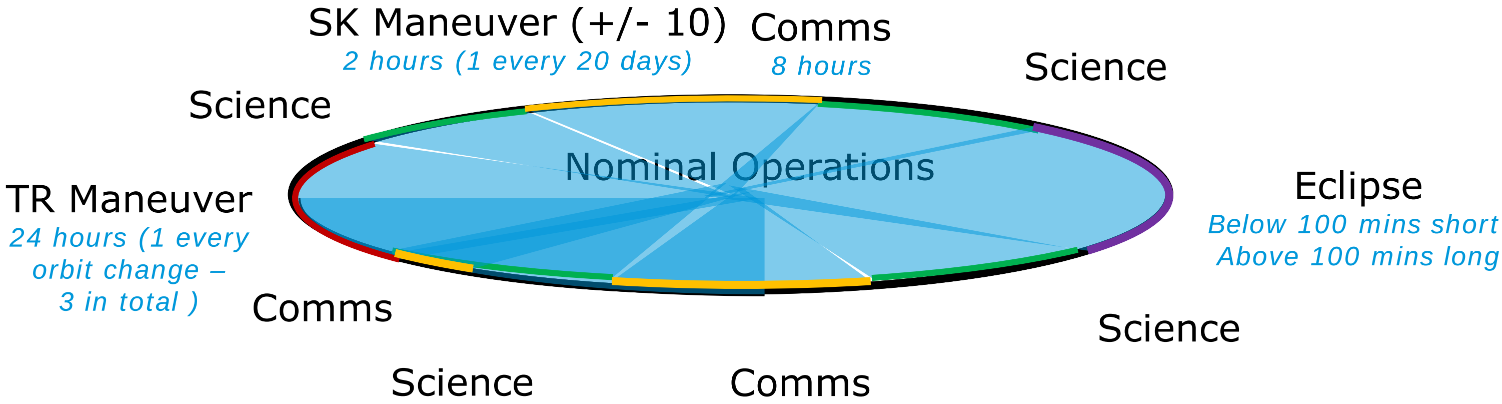
System Modes

System Modes

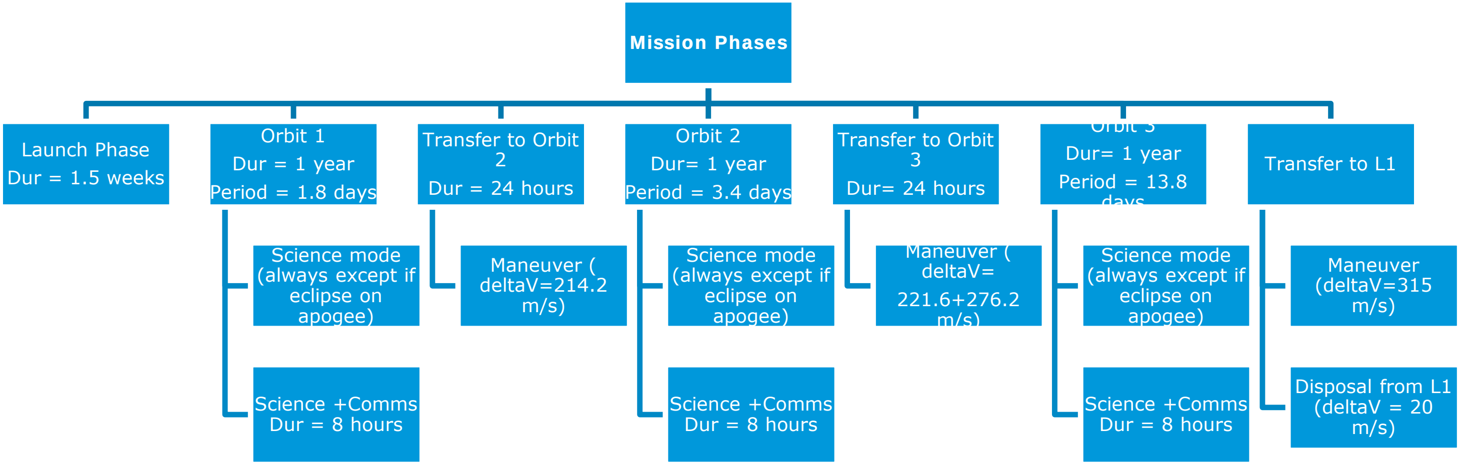
Mode	Description
Launch	S/C in Launch Configuration
Commissioning	S/C performing commissioning activities, including instrument commissioning
Science	S/C with full science capability
Short Eclipse	S/C in short eclipse (mainly close to perigee)
Long Eclipse	S/C in long eclipse (mainly close to apogee)
Science + Communications	S/C with full science capability and comms equipment on for download
Safe	S/C in Safe Mode. Begins with sun acquisition mode. Shut-down of non essential systems, only essential functions such as thermal management, AOCS and minimum Telecom capabilities are active.
Station keeping	S/C is doing station keeping maneouvres
Transfer Maneouvre	S/C is doing the transfer maneouvres to go from one orbit to the next.
Long eclipse+ comms	S/C in long eclipse and transmitting data(mainly close to apogee)
Short eclipse + comms	S/C in short eclipse and transmitting data(mainly close to perigee)

Timeline

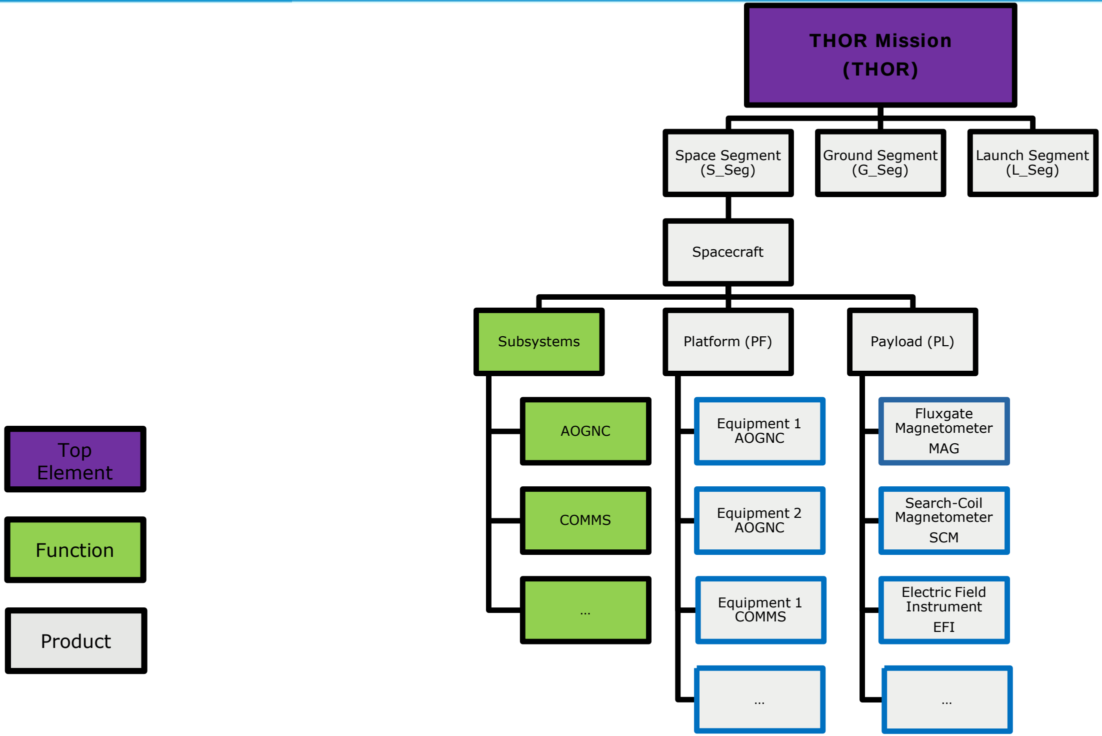
Orbital Period [hours]	Orbital Period [days]	Duration [years]	# Laps
44.5	1.854166667	1	196.8539326
81.8	3.408333333	1	107.0904645
330.4	13.76666667	1	26.64233577



Mission Phases



Model


THOR Mission
(THOR)
Space Segment
(S_Seg)
Ground Segment
(G_Seg)
Launch Segment
(L_Seg)
Spacecraft
Subsystems
Platform (PF)
Payload (PL)
AOGNC
COMMS
...
Equipment 1
AOGNC
Equipment 2
AOGNC
Equipment 1
COMMS
...
Fluxgate
Magnetometer
MAG
Search-Coil
Magnetometer
SCM
Electric Field
Instrument
EFI
...
Top
Element
Function
Product

Mass budget

Row Labels	Product Mass (kg)	Mass margin (%)	Mass with margin (kg)
AOGNC	11.67	2.64	11.98
COM	19.85	9.99	21.83
CPROP	61.53	6.62	65.61
DH	28.00	15.50	32.34
EMC	2.82	0.00	2.82
INS	144.25	20.00	173.10
MEC	48.40	17.44	56.84
PWR	51.12	10.92	56.70
SYE	23.64	8.46	25.64
TC	16.10	5.00	16.91
STR	131.91	16.97	154.29
Grand Total	539.30	14.61	618.07

Instruments Shielding (%)	5.00
Instruments Shielding (kg)	8.66
Harness (%)	7.00
Harness mass (kg)	29.35
System Margin on Platform (%)	20.00
Total Dry Mass (kg)	752.67
Propellant Mass (kg)	370.71
Propellant Margin (%)	2.00
Total Wet Mass (kg)	1130.80
Launcher Adapter (kg)	115.00
Wet Mass + Adapter (kg)	1245.80
Shielding Mass (kg)	**13.64**
Soyuz capacity (kg)	1756
Launch margin (kg)	625.20

- System margin not applied to instruments (payload)
- Harness mass calculated without mass of instruments and systems
  - Instruments provide own harness
  - Systems only contains balancing mass and shielding

THOR

Communications

Internal Final Presentation
ESTEC, 9th July

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Mission / System requirements

The COMM s/s shall be able to transmit Survey, Burst, and HRWF

Hot redundancy shall be provided for telecommand (uplink) and cold redundancy for telemetry (downlink)

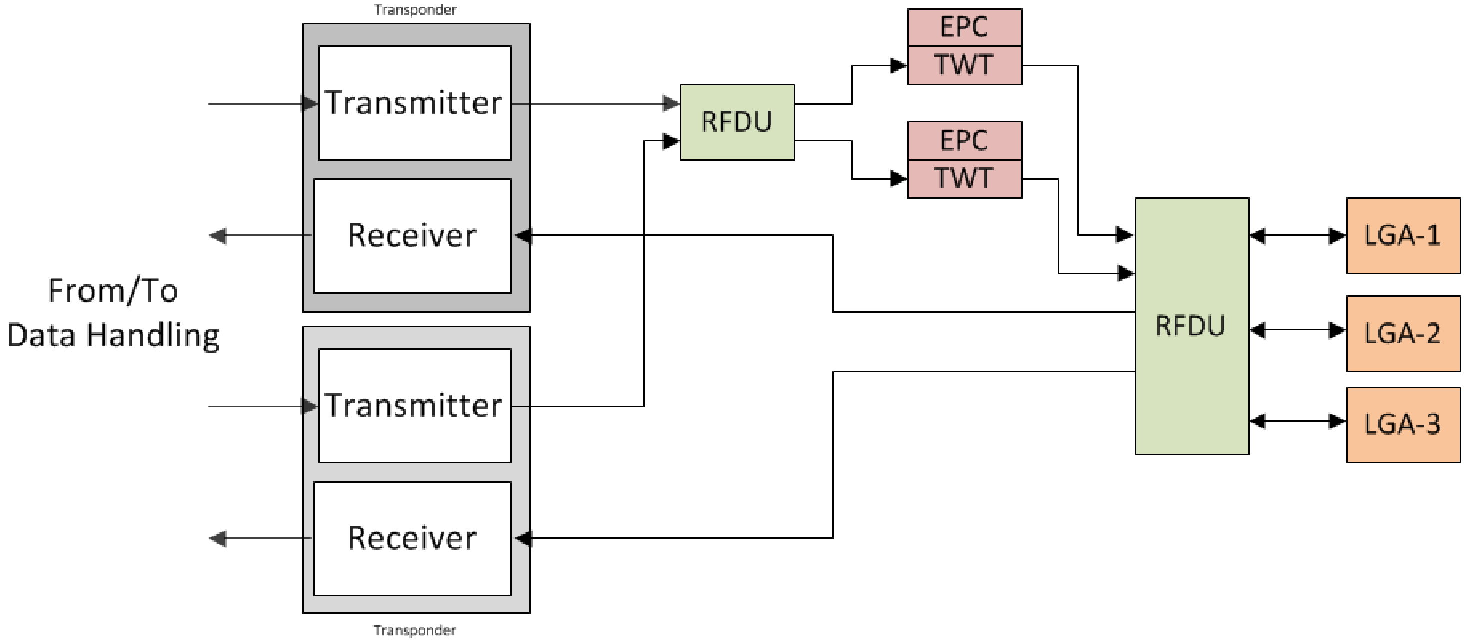
The satellite shall orbit around earth with the following orbits

- 1st year: 4x16 RE
- 2nd year: 4x26 RE
- 3rd year: 14x61 RE

Assumptions & Trade-offs

- X-Band communication link vs S-Band
  - S-Band discarded since is congested and the antenna gains are not sufficient to cover the distance earth-S/C
- 15m G/S antenna vs 35m G/S antenna (discussed later)
  - 35m allows to decrease the power consumption and the mass for the COMM s/s
- Single coded modulation vs multiple coded modulation (discussed later)
  - If we change the modulation (and thus the bitrate) during the mission, we can increase the downloaded data.
- PN Ranging
  - It allows High data rate telemetry and Ranging simultaneously

Baseline design



Baseline design

- The data to be download is

$$D = D_{SURVEY} + D_{BURST} + D_{HRWF} + \frac{3T_{pass} + 4T_{int}}{T_{orbit}} D_{SURVEY}$$

i.e. the one from ARIEL report + Survey data accumulated after three missed passes

- The TM required downlink rate is

$$\frac{D}{T_{GS}}$$

where T_{GS} takes into account G/S visibility, 65% of G/S availability, and the reduction due to ranging.

year	Avg TM Rate [kbps]	Total [Gbit/orbit]
1	2130.38	58.40
2	811.65	52.13
3	99.42	30.23

Baseline design

- Three orbits with three required TM rates → Three link budgets

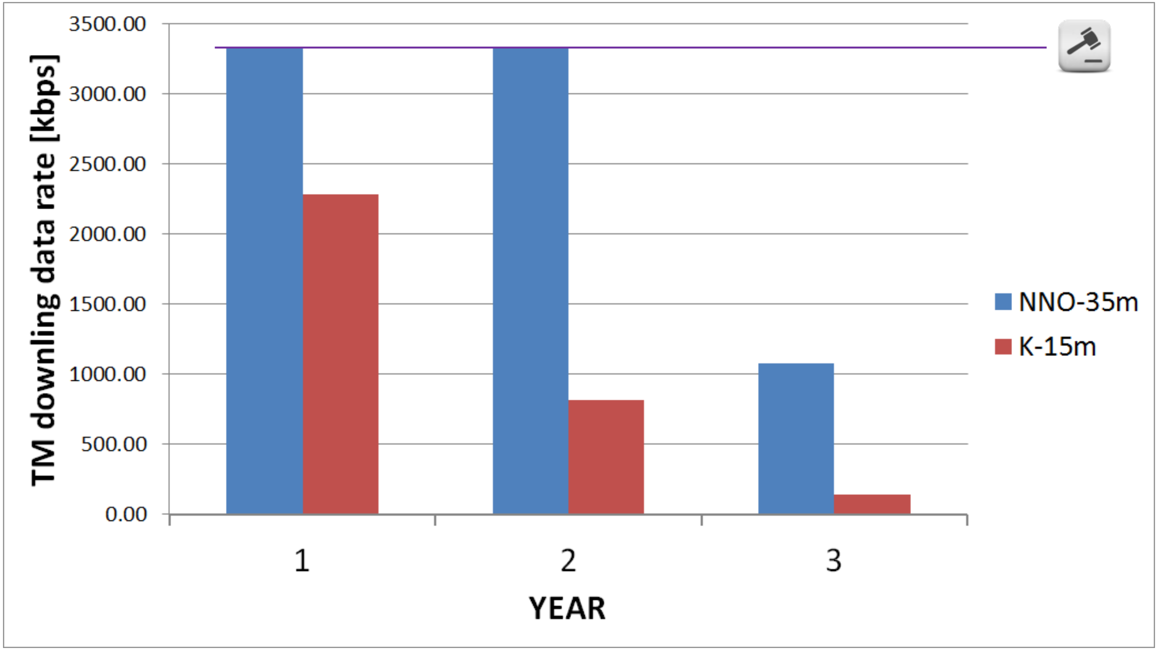
PARAMETER	X-BAND	Notes
ALTITUDE [km]	159275.0	
ELEVATION ANGLE [deg]	10.0	
RANGE [km]	164426.3	
FREQUENCY [MHz]	8500	X-Band - Space-to-Earth Frequency
TX POWER [W]	55	47.4 dBm
TX ANTENNA GAIN [dB]	-4	
TX LOSSES [dB]	2	Preliminary Estimated Value (cables+mech. insertion loss)
TX EIRP [dBW]	**11.40**	**Calculated**
PATH LOSSES [dB]	**215.35**	**Calculated**
ATM+POL LOSS [dB]	1.50	Not accounted yet
RX G/T [dBK]	41.00	Korou 15m
DEMOD. LOSS [dB]	1.50	Estimation
MOD. LOSS [dB]	0.00	
REQIRED Eb/No [dB]	0.55	Turbo 1/3
MINIMUM MARGIN [dB]	3.00	Standard ESA
MAX BIT RATE [dBHz]	59.10	
MAX BIT RATE [kbps]	**814**	

TX Power consumed	**15**	
efficiecy	**0.57**	**TWTA**
RF Power	**55**	
TWTA Power consumed	**96.49122807**	
RX Power Consumed	**10**	
Total Power Consumption	**131.4912281**	

The one deciding the power

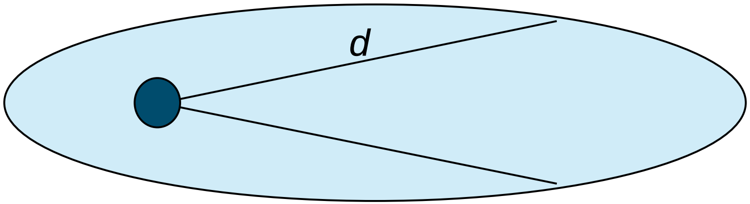
Actual TM rate
2171.67
813.59
146.50

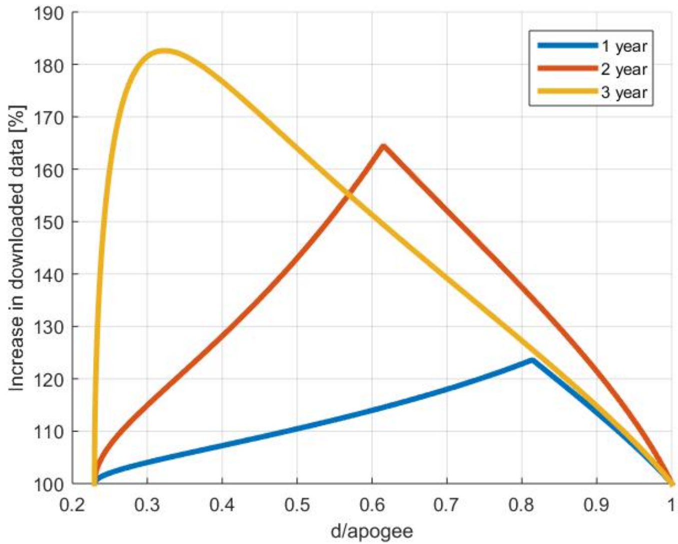
Option 1: 15m vs 35m



Option 2: Variable coding modulations

- Use of two or more data rates during the orbit (first guess)





- G/S availability uniform on ellipse
- No overhead due to switching
- Overhead can be removed by means of CCSDS 131.2-B1

THOR

Data Handling Sub-System

Internal Final Presentation
ESTEC, 9th July

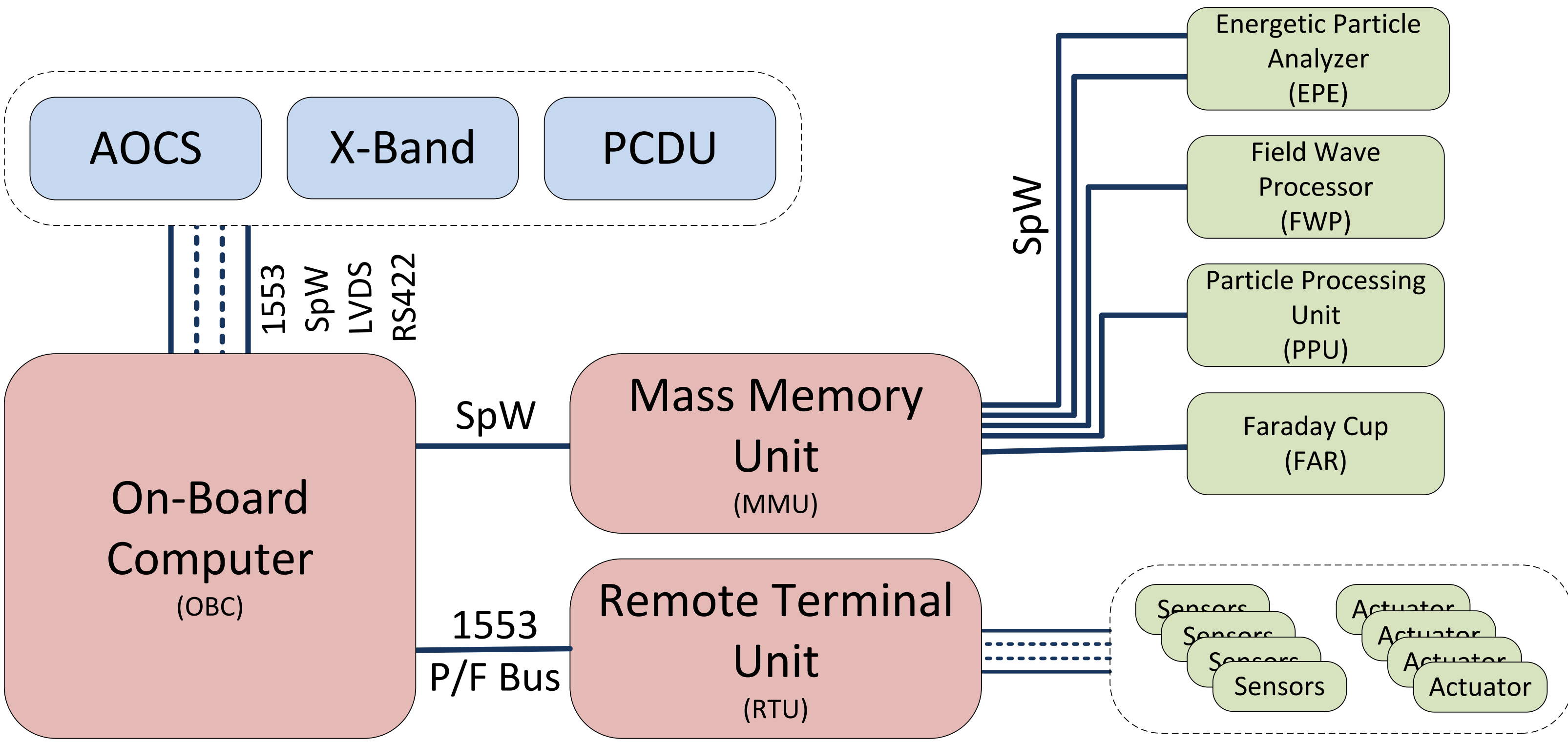
Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

European Space Agency

Data Handling Sub-System Architecture

Components of Data Handling Sub-System:
- Mass Memory Unit (MMU)
- Remote Terminal Unit (RTU)
- On-Board Computer (OBC)



European Space Agency

Mass Memory Unit

Main tasks:

- SpaceWire interface to 5 instruments (PPU,FWP,FAR,2xEPE) + 5 red.
- Total memory: 8Tbits (EOL Req: 5Tbits)
- Performing EDAC function
- CFDP for storing and accessing scientific data

Mass: 13.8 kg (without shielding)

Power: 25W (On mode) / 20W (Data Retention mode)

Dimensions(W x H 5 mm

EUCLID MMU as reference:

Memory size: *2Tbits per module*

Radiation tolerance: *TID >30 kRad*

Expected life-time: *6.25 years on L2 orbit*

Remote Terminal Unit (RTU)

Main tasks:

- Interface to sensors and actuators
- Support for vast number of sensors with different interfaces

Mass: 8.4 kg (without shielding)

Power: 15W

Dimensions(W x H x L): 225x260x275 mm

ExoMars RTU as re

Interfaces: 260 thermal, 16 thermocouple, 8 control lines, 71 bi-level input, 8 high power output, 15 analog inputs, 8 current sensors

TID: 20kRad

On-Board Computer (OBC)

Main tasks:

- Execution of flight software
- On-Board time/synchronization management
- Interface with RTU for actuator use and sensor acquisition
- Interface with MMU for scientific data management
- Interface to other sub-systems (TT&C, AOCS, PCDU)

Mass: 6 kg (without shielding)

Power: 20W (Hot re

Dimensions(W x H x L): 160x200x230 mm

ExoMars OBC as reference:

Performance: *LEON3-FT ASIC (55 MIPS @ 64 MHz)*

TID: *30 kRad*

THOR

AOCS

Session 8
ESTEC, 09-07-2015

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

AOCS HW

- Requirement: The spacecraft shall spin around one axis with a rate of 2 full rotations per minute (0.025 rpm/day).

- **STR** shall be able to acquire and track at 12 deg/s. → SelexGalielo A-STR (CCD sensor) using Time Delay Integration Mode (up to 10 RPM). Used on Plank and Pluto missions.
  - Is the only STR available, APS sensor cannot have TDI mode today. → Risk of detector obsolescence. N.B. Cluster had Star Mapper not star sensor.
  - Radiation on CDD also needs to be studied but problem solvable by shielding.

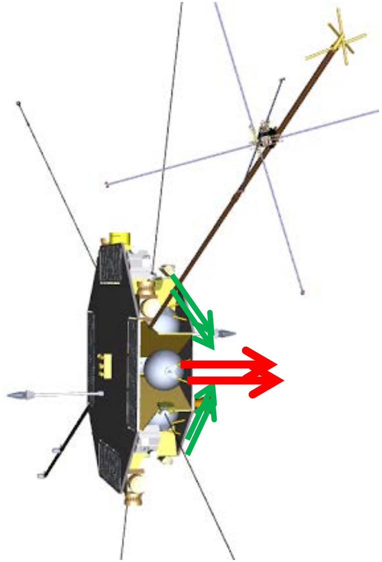
AOCS HW

- **Gyro** shall be able to measure angular rate variation of 0.025 rpm/day (0.15 deg/s/day) → Can be achieved by STR. Gyro needed for safe mode Mems Sireus.
  - Baseline mems Sireus
  - Backup Astrix 1090.

- **Coarse Sun Sensor** for initial acquisition after separation and Safe mode.
- **Nutation Dampers**: two fluid-filled ring nutation dampers along the two SC transverse axes.
- **THR** (Propulsion HW)
  - 8x4N
  - 2x22N

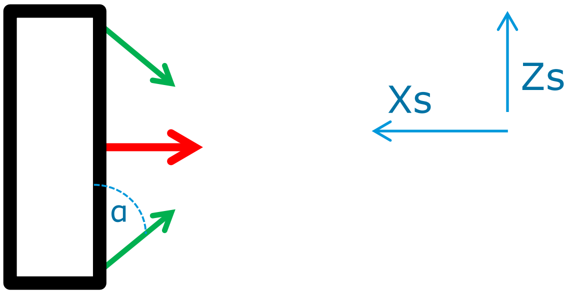
Preliminary THR configuration

- Configuration proposal:
  - 2 x 22 N THR
  - 8 x 4 N THR
  - 22N THR directed long spin axis.
  - Sun power available to platform up to 39deg between rotation axis and Sun direction → Reduces slew rate constrains.
  - →Max Slew angle for ΔV maneuvers = 39deg. Since during slew and maneuvers Sun power shall be always avaliable.

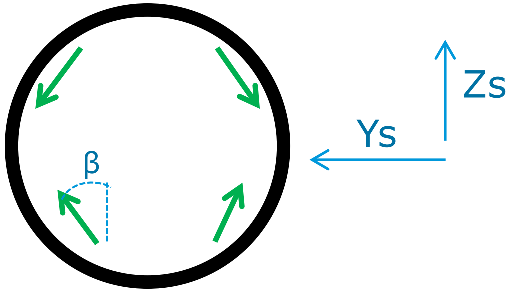


Preliminary HR configuration - Control

- Assumptions:
  - THR - Cog distance ≈ [1;1;1] m
  - α = 45 deg, β = 30 deg
  - F = 4N



- Torque
  - Tx = 7.7Nm (parasitic force Fx = 5.6N)
  - Ty = 10.5Nm (Fx = 5.6N, Fz = 4.8N)
  - Tz = 2.8Nm (Fx = 5.6N, Fy =2.8N)
  - N.B. Parasitic force is assumed to be acceptable by system.



Heritage

	Cluster	MMS	Van Allen
Wire booms Length [m]	44	60	45
Spin Rate [RPM]	15	3	5
THR configuration	10N + 400N (used in stowed configuration)		8x0.9N
Slew Rate [deg/s]	0.032	0.0028	
Nutation frequency Hz	0.19		0.025
ΔV maneuver duration		1 month	
Wire boom deployment	1 month (not continuous)		9 days

Preliminary THR configuration - Consumption

- ΔV efficiency including 4N THR for control:
  - Assuming:
    - CoG max variation on Ys and Zs axis 0.02m
    - 22N THR alignment accuracy 0.5 deg.
    - → maneuver geometric efficiency 99% (no margin included)

Preliminary THR configuration - Consumption

- AOCS propellant consumption in NOM mode:
  - Very difficult to estimate THR duty cycle due to the complexity of the dynamics.
  - Sun pointing requirement 10 deg towards Sun directions moves 1 deg/day. → one precession maneuver per week (Van Allen probe 1 every 3 week).
  - Assuming same average Slew rate than Cluster = 0.032 deg/s.
  - Assuming Inertia difference = 2000Kg m2
  - → Average torque 0.23Nm

Preliminary THR configuration - Consumption

- Consumption for Spin axis orientation→ Preliminary assumption 30 sec of 1x4N THR ON each 20 days.

- Consumption for spin rate control → (TBD), should be less than Spin axis orientation.

Preliminary THR configuration – Slew maneuver duration

- Very difficult to estimate slew rates due to complex dynamics, assumption = cluster (0.032 deg/s).
  - 39 deg in <1500 sec.
  - Settling time after slew should be added (0.7h on Van Allen).
  - Consumption for a single slew of 39 deg = 1x4N ON for 60 sec (no margin).

Design robustness

- Cluster angular rate is an optimistic assumption since Cluster spin is 15 RPM.
- However:
  - If Mission analysis ensures ΔV thrust vector is either ≤ 39 deg from Sun.
  - If SA is capable of providing enough power for platform up to 39 deg from SUN

→ This design should be fairly robust to significant reduction in achievable Slew rate that can occur in future phases of the program.

THOR

Power

IFP
ESTEC, 9th July 2015

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

THOR Power – Design Drivers

- Top mounted array – sun pointed within ± 10° during ops.
- Eclipses of highly variable length, 0 min<>370 min. Operation of science payload and/or comms transmit during eclipse is open to system trade-off…………
  - System trade-off decision:
    - Eclipses < 100 min: Science payload AND comms **ON**.
    - Eclipses 100min <> 370min: Science payload AND comms transmit **OFF**.

THOR Power – Design Drivers (2)

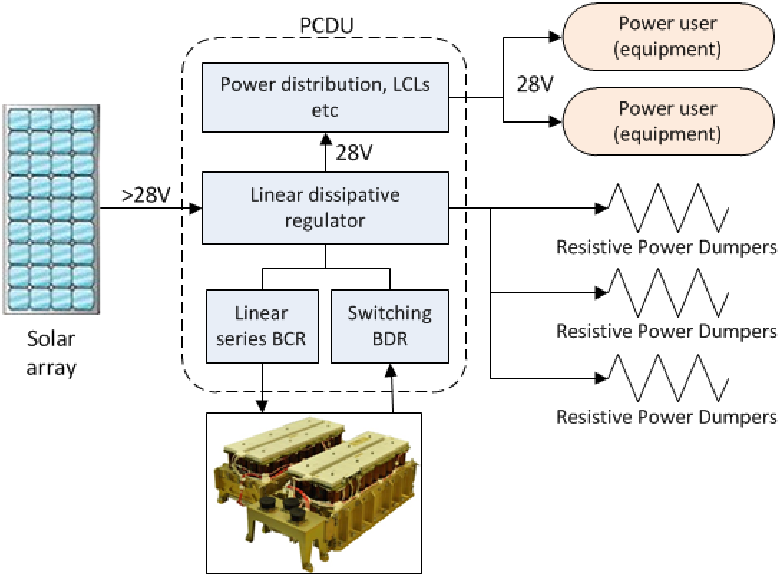
- Very high EMC & magnetic cleanliness required.
  - Affects design of:
    - solar array
    - battery
    - PCDU & power bus concept
  - But no need to panic! Solutions are well understood in principle and have been successfully applied in e.g. CLUSTER

THOR Power – Power bus topology and SA regulation concept

- Follow the successful example of CLUSTER:
- Regulate the solar array by a LINEAR DISSIPATIVE SHUNT system.
  - This is very EMC-quiet, and VERY efficient if SA and bus voltages can be well-matched (i.e. stable illumination conditions and regulated bus).
  - as compared to S^3R, which relies on hard-short switching (at e.g. ~ 3kHz) of entire solar array sections, or an MPPT which uses DC-DC converters (100s kHz) between the SA and bus).

- Use a 28V regulated bus, **because**:
  - It is the usual ESA solution for science S/C with good reason: Gives simplified interface conditions to the secondary power converters (instruments etc.)
  - In the THOR case, the secondary power converters will have extra complications for EMC requirements, e.g. distributed single point grounding, galvanic isolations, synchronisation, etc. Seems wise not to make them deal also with a variable input voltage.
  - For THOR, eclipses are few in number. *Long* eclipses are *very* few in number. This means that battery cycle-degradation is insignificant, and allows the battery size and mass to be kept as small as possible by use of deep discharges (very deep for the extreme long eclipse cases). Therefore, an unregulated bus would be subject to very wide voltage variations.
  - The BCR (battery charge regulator) required for the regulated bus can be implemented by a quiet linear series topology (a low efficiency BCR is not a problem – we have plenty of time between eclipses to recharge!)
  - The BDR (battery discharge regulator) will have to be a DC-DC converter, but this can be implemented in an EMC-quiet way (as it was on CLUSTER!)

THOR Power – Power bus topology and SA regulation concept

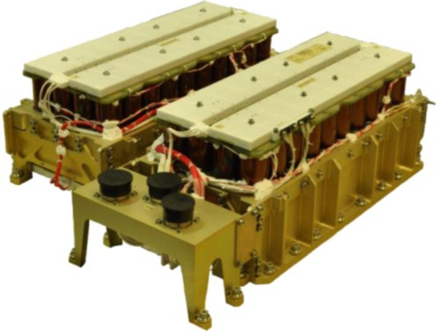


Load requirements per mode (Average power in Watts)

	SCI	Sh_ECL	SAFE	LAU	Lo_ECL	COMMIS	SCI_COMMS	Sh_ECL_COMMS	Lo_ECL_COMMS	SK_MAN	Transf_MAN
CSW (Cold solar wind ion instrument)	10.0	10.0	0.0	0.0	0.0	10.0	10.0	10.0	0.0	0.0	0.0
EFI (Electric field instrument)	3.0	3.0	0.0	0.0	0.0	3.0	3.0	3.0	0.0	3.0	0.3
FAR (Faraday cup)	4.0	4.0	0.0	0.0	0.0	4.0	4.0	4.0	0.0	0.0	0.0
FWP (Field and wave receiver)	20.0	20.0	0.0	0.0	0.0	20.0	20.0	20.0	0.0	20.0	2.0
PPU (Particle Processing Unit)	25.0	25.0	0.0	0.0	0.0	25.0	25.0	25.0	0.0	25.0	2.5
SCM (Search Coil Magnetometer)	1.0	1.0	0.0	0.0	0.0	1.0	1.0	1.0	0.0	1.0	0.1
MMU (Mass Memory Unit)	25.0	25.0	20.0	20.0	20.0	20.0	25.0	25.0	20.0	20.0	20.0
Orb_Thr_1 (THOR_Orbit_Thruster)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.3
Orb_Thr_2 (THOR_Orbit_Thruster)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.3
RTU (Remote Terminal Unit)	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
STR_ASTR_1 (STR Selex Galileo A-STR)	8.9	8.9	0.0	0.0	8.9	8.9	8.9	8.9	8.9	8.9	8.9
STR_ASTR_2 (STR Selex Galileo A-STR)	8.9	8.9	0.0	0.0	8.9	8.9	8.9	8.9	8.9	8.9	8.9
X_TWTA_THOR_N (X-Band TWTA Nominal)	0.0	0.0	9.6	0.0	0.0	96.3	96.3	96.3	0.0	9.6	9.6
X_XPND_THOR_N (X-Band Transponder Nominal)	10.0	10.0	11.5	10.0	10.0	25.0	25.0	25.0	25.0	11.5	11.5
X_XPND_THOR_R (X-Band Transponder Redundant)	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
EPE (Energetic Particle Instrument)	5.0	5.0	0.0	0.0	0.0	5.0	5.0	5.0	0.0	0.0	0.0
EPE2 (Energetic Particle Instrument 2)	5.0	5.0	0.0	0.0	0.0	5.0	5.0	5.0	0.0	0.0	0.0
ESA (Electron spectrometer)	8.5	8.5	0.0	0.0	0.0	8.5	8.5	8.5	0.0	0.0	0.0
ESA2 (Electron spectrometer 2)	8.5	8.5	0.0	0.0	0.0	8.5	8.5	8.5	0.0	0.0	0.0
ESA3 (Electron spectrometer 3)	8.5	8.5	0.0	0.0	0.0	8.5	8.5	8.5	0.0	0.0	0.0
ESA4 (Electron spectrometer 4)	8.5	8.5	0.0	0.0	0.0	8.5	8.5	8.5	0.0	0.0	0.0
IMS (Ion spectrometer)	10.3	10.3	0.0	0.0	0.0	10.3	10.3	10.3	0.0	0.0	0.0
IMS2 (Ion spectrometer 2)	10.3	10.3	0.0	0.0	0.0	10.3	10.3	10.3	0.0	0.0	0.0
IMS3 (Ion spectrometer 3)	10.3	10.3	0.0	0.0	0.0	10.3	10.3	10.3	0.0	0.0	0.0
IMS4 (Ion spectrometer 4)	10.3	10.3	0.0	0.0	0.0	10.3	10.3	10.3	0.0	0.0	0.0
MagFlux (Fluxgate Magnetometer)	1.5	1.5	0.0	0.0	0.0	1.5	1.5	1.5	0.0	1.5	0.2
MagFlux2 (Fluxgate Magnetometer 2)	1.5	1.5	0.0	0.0	0.0	1.5	1.5	1.5	0.0	1.5	0.2
OBC (On Board Computer)	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
GYRO_Sireus (GYRO Selex Galileo Sireus)	5.5	5.5	5.5	0.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5
GYRO_Sireus2 (GYRO Selex Galileo Sireus 2)	5.5	5.5	5.5	0.0	5.5	5.5	5.5	5.5	5.5	5.5	5.5
ASEPCO-EBOX (Active Spacecraft Electric Potential Controller Electronics Box)	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Att_Thr_1 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_2 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_3 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_4 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_5 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_6 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_7 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Att_Thr_8 (THOR_Attitude_Thuster)	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	6.5	6.5
Htr (Heater)	35.4	35.4	70.8	0.0	70.8	35.4	35.4	35.4	70.8	53.1	70.8
MACS (Magnetometer Alignment Calibration System)	0.3	0.3	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0
Htr_Ins_01 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_02 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_03 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_04 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_05 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_06 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_07 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_08 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_09 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_10 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_11 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_12 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_13 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Htr_Ins_14 (Heater Instruments)	2.5	2.5	2.5	0.0	4.2	2.5	2.5	2.5	4.2	2.5	4.8
Grand Total	**335**	**335**	**208**	**79**	**238**	**442**	**447**	**446**	**253**	**311**	**334**
Including 20% margin	**403**	**403**	**249**	**94**	**286**	**530**	**536**	**536**	**304**	**373**	**401**

THOR Power - Battery

- SAFT VES16 battery is baselined (non-magnetic stainless steel cell can material).
- The battery is split into two identical units to improve magnetic cleanliness by orienting the units at 180° to achieve some mag. field opposition / cancellation)



Sized for: LO_ECL for 370 minutes @ 286 W

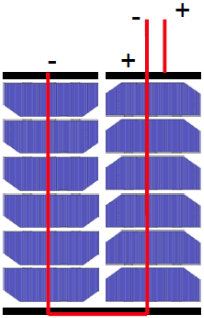
+ SAFE for 15 minutes sun acquisition (after e.g. loss-of-attitude anomaly) @ 249 W.

Results in : **2 × {** 6s-12p, 54 Ah, 1.2 kWh, 10.4 kg, 368 × 190 × 180 mm **}**

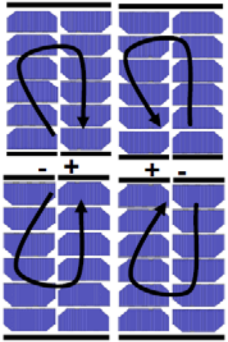
THOR Power – Solar Array

- Azur "next-generation" cells can be assumed (~10% better than 3G30).
- Grounded electrically conductive coating is required to eliminate electrostatic charging.
  - e.g. indium tin oxide.
  - Light attenuation by the coating and area lost (shadowing) for grounding connections gives ~10% performance loss w.r.t non-grounded array.

- Backwiring (to cancel currents) and grounding connections/wiring for the conductive coating together add ~15% to the PVA mass.



Back-wiring



Compensation method

THOR Power – Solar Array

Sized for: SCI_COMMS mode @ 536 W. Approximately sun pointed (modelled at 6° off-point).

EOL total NID (1MeV electron equivalent fluence): 6.2E14 for V_{OC}. 4.3E14 for I_{SC}.

Resulting in: 18s 43p in total (inc. one redundant string).

2.91 m^2 in total*. Can still be arranged in 4 rectangular panels as per the proposal if this is convenient.

Total PVA + wiring (but not including panel substrate) mass = 5.6 kg

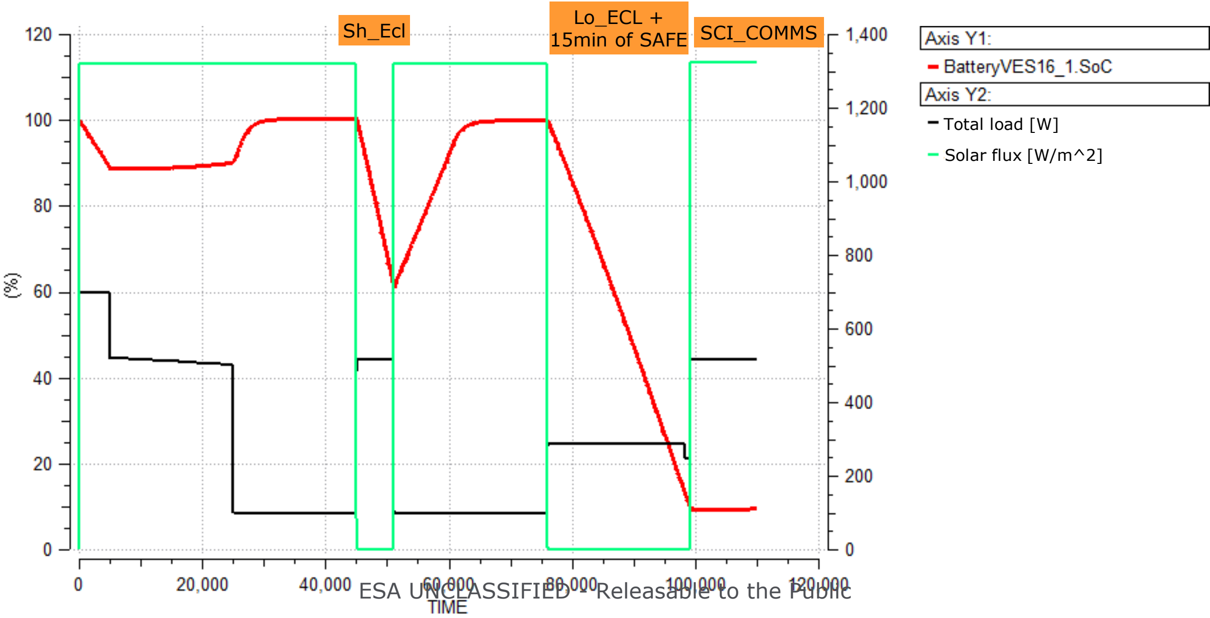
* This is minimum area for current budget – a larger area is assumed in the configuration, to demonstrate design robustness – e.g. for Transf_MAN off-pointing (see next slide)….

THOR Power – Solar Array

- The SA is currently sized to support SCI_COMMS mode (536 W).

- However, Transf_MAN mode (401 W) is also **long in duration**, and must therefore have a positive power budget (i.e. supported by solar power without battery discharge).
  - **Question**: How much off-pointing can be tolerated in Transf_MAN mode?
  - **Answer:** Transf_MAN mode power budget remains positive (no battery discharge) up to **42°** off-pointing from the sun **(SA normal to sun direction = 42°).**
  - **IF** this 42° constraint is unacceptable from a mission analysis point-of-view, then the SA size could be increased, with relatively minor mass implications up to e.g. ~60° **(COSINE law!)**.

PEPS power simulation



Equipment Summary

	mass (kg)	mass incl. margin (kg)
SC (Spacecraft)	**51.12**	**56.70**
PF (Platform)	**51.12**	**56.70**
Bat (Battery_general)	10.40	11.44
PCDU (Power Conditioning & Distribution Unit)	20.00	22.00
ResPwrDmp_01 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_02 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_03 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_04 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_05 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_06 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_07 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_08 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_09 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_10 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_11 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_12 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_13 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_14 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_15 (Resistive Power Dump)	0.22	0.26
ResPwrDmp_16 (Resistive Power Dump)	0.22	0.26
SA (SolarArray)	5.60	6.16
ExtResPwrDmp_1 (External Resistive Power Dump)	0.30	0.36
ExtResPwrDmp_2 (External Resistive Power Dump)	0.30	0.36
ExtResPwrDmp_3 (External Resistive Power Dump)	0.30	0.36
ExtResPwrDmp_4 (External Resistive Power Dump)	0.30	0.36
Bat2 (Battery_general 2)	10.40	11.44
Grand Total	**51.12**	**56.70**

THOR

Risk

Internal Final Presentation
ESTEC, 9 July 2015

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Outline

- Reliability & Fault Management Requirements
- Risk Policy
  - Mission Success Criteria
  - Risk Categorization (Severity/Likelihood Scales) and Acceptance Policy
- Top Risks
- Risk Conclusions

Reliability and Fault Management Requirements

R-REL-010	The overall reliability of the mission, from after launch vehicle separation until the end of the nominal lifetime, shall be ≥ 85%.
R-REL-020	Single-point failures with a severity of catastrophic or critical (as defined in ECSS-Q-ST-30C) shall be eliminated or prevented by design.
R-REL-030	Retention in the design of single-point failures of any severity rating is subject to formal approval by ESA on a case-by-case basis with a detailed retention rationale.
R-REL-040	A failure of one component (unit level) shall not cause failure of, or damage to, another component or subsystem.
R-REL-050	The failure of an instrument channel shall not lead to a safe mode of the S/C.
R-REL-060	Any hazardous situation, which will not cause immediate loss of but may develop into the loss of the S/C or instrument, shall be prevented by design or protected against.
R-REL-070	The design shall allow the identification of on-board failures and their recovery by autonomously switching to a redundant functional path. Where this can be accomplished without risk to spacecraft and instrument safety, such switching shall enable the continuity of the mission timeline and performance.
R-REL-080	Where redundancy is employed, the design shall allow operation and verification of the redundant item/function, independent of nominal use.
R-REL-090	For design and analysis purposes (e.g. verification of operational availability), an average of 3 safe mode events of 3 days each (plus recovery time) per year shall be considered.

Risk Policy: Mission Success Criteria

Science	***SCI01-*** The mission accomplishes all of the key science goals
Technical	***TEC01-*** The spacecraft performs successfully during the nominal mission lifetime (3 years, goal 5 years). ***TEC02-*** No major performance degradation owing to single point failures ***TEC03-*** No failure propagation
Schedule	***SCH01-*** The mission launch date is no later than 2026 ***SCH02-*** All mission related units reach a TRL of at least 5-6 by the end phase A/B1 (estimated end 2018)
Cost	***COS01-*** The mission is compatible with the ESA M4 cost at completion boundary (450 M€ e.c. 2014)

Risk Policy: Severity-Likelihood Scale

Score	Schedule	Science	Technical (ECSS-Q-30 and ECSS-Q-40)	Cost
5	Launch delay results in project cancellation	Failure leading to the impossibility of fulfilling the mission's scientific objectives	Safety : Loss of system, launcher or launch facilities. Loss of life, life-threatening or permanently disabling injury or occupational illness; Severe detrimental environmental effects.	Cost increase result in project cancellation
4	Launch delayed 24-48 months	Failure results in a major reduction (70-90%) of mission's science return	Dependability: Loss of mission. Safety: Major damage to flight systems, major damage to ground facilities; Major damage to public or private property; Temporarily disabling but not life- threatening injury, or temporary occupational illness; Major detrimental environmental effects.	Critical increase in estimated cost (50-100M€)
3	Launch delayed 6-24 months	Failure results in an important reduction (30-70%) of the mission's science return	Dependability: Major degradation of the system. Safety: Minor injury, minor disability, minor occupational illness. Minor system or environmental damage.	Major increase in estimated cost (25-50€)
2	Launch delayed 3-6 months	Failure results in a substantial reduction (<30%) of the mission's science return	Dependability: Minor degradation of system (e.g.: system is still able to control the consequences) Safety: Impact less than minor	Significant increase in estimated cost (5-25 M€)
1	No/ minimal consequences	No/ minimal consequences	No/ minimal consequences	No/ minimal consequences

Severity

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

Likelihood

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

Index

Risk Index	Risk Magnitude	Proposed Actions (during assessment phase)
3E, 4D, 4E, 5C, 5D, 5E	High Risk	Unacceptable risk: implement mitigation actions (either likelihood reduction or severity reduction through new baseline) with responsible party.
1D, 1E, 2C, 2D, 2E, 3B, 3C, 3D, 4A, 4B, 4C, 5A, 5B	Medium Risk	Acceptable risk: Monitor and control. Optional reduction.
1A, 1B, 1C, 2A, 2B, 3A	Low Risk	Acceptable risk

Policy

Risk Log

- Highlighted mission/spacecraft risks
  - Launcher uncertainties
  - Radiation environment
  - EMC: S/C charging, magnetic interference, electromagnetic noise
  - Operational availability
  - Dynamic behavior of 4x50m wires during orbital transfer maneuvers
  - Thruster plume impingement on solar array/instruments→ removed
  - Unavailability of 15m Kourou ground station → mitigated

- Low technology development risk

Selected due to their magnitude with focus on high severity/likelihood risk items.

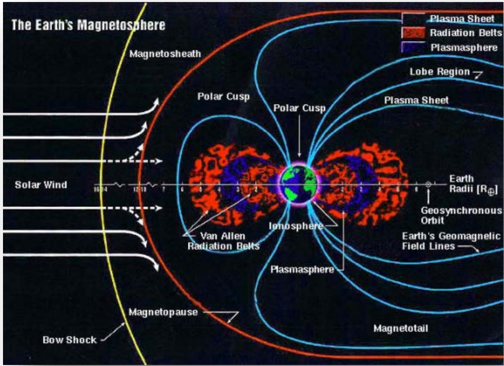
Launcher Uncertainties

- **Risk** (ID# MIS_01): Re-definition of the mission due to uncertainties related to the baseline launch vehicle A6.2 which is a concept design.
- **Cause:** A6.2 launch vehicle uncertainties in:
  - Launch capability (Kg)
  - Usable volume for S/C
  - Interface adaptor
  - Launch environment (loads)
- **Mitigation**:
  - Use best available predictions for A6.2 launch vehicle specifications until official release.
  - Consider worst case margins in terms of performance to phase 1 orbit or transfer orbit , payload fairing volume, and environmental loads to ensure compatibility.
  - Determine as soon as possible the actual capabilities of the A6.2 launch vehicle.
- **Risk Index**: **4D (Technical)**

Ariane 6.2 Concept
©ESA

Radiation

- **Risk** (ID# MIS_02)**:** Extreme radiation environment impact on spacecraft and science return.
- **Cause**
  - Radiation dose is estimated using SPENVIS (for a 2-year mission) at 34 krad behind 5mm of Al shielding (or 137 krad for 3mm Al shielding).
- **Mitigation**:
  - Short mission duration.
  - Built on lessons learnt from previous missions like Cluster.
  - Operational orbits above proton belt.
  - Provide detailed radiation environment assessment and study mitigation options including shielding , rad-hard component selection, etc.
  - Allocate adequate mass margins for shielding.
  - Do not plan any critical manoeuvres during the Van Allen belt passes.
- **Risk Index**: 3D (Technical)



Inner and Outer Radiation Belts ©NASA

Spacecraft Charging

- **Risk** (ID# MIS_03): Spacecraft charging impact on science return (distortion of DC electric field measurements by EFI instrument) , ESDs, and damage to spacecraft sensors.
- **Cause:**
  - Surface charging (of up to kV negative) in outer magnetosphere.
  - Significant surface charging (up to ~200V) in Magnetosheath.
  - Low level charging (+2 to -10V) in Solar wind.
- **Mitigation**:
  - High electric conductivity of all space-exposed surfaces including solar array. Appropriate surface coatings.
  - Bonding of space-exposed surfaces (avoiding loops)
  - Avoid dielectric materials.
  - Avoid isolated ("floating") metals.
  - Active potential control (e.g. electron/ion gun).
  - Bias plasma instruments to overcome spacecraft potential effects.
  - Mount instruments on long booms away from the main body of the spacecraft.
- **Risk Index**: **3E (Technical, Science)**

Magnetic Interference

- **Risk** (ID# SPA_01): Magnetic interference impact on science return (weak magnetic field measurements).
- **Cause:**
  - Stringent magnetic cleanliness requirements not met.
  - DC magnetic field to stay below 5 nT at the magnetometer; long term variations (longer than 1 hour time scale) below 0.5 nT peak-to-peak; medium term variations (1 s- 1 h) shall not exceed 10 pT (averaged over 1 s) over a period of 1h.
- **Mitigation**:
  - A dedicated magnetic cleanliness program is required which includes special design rules, equipment/material selection, special AIT procedures, and appropriate magnetic verification at a calibration facility.
  - Avoid magnetic materials if possible.
  - Minimize magnetic field magnitude
  - Respect distances from known magnetic equipment such as the batteries or PCDU.
  - Ensure high stability of low magnetic disturbances accurately characterized on ground.
- **Risk Index**: **3E (Science)**

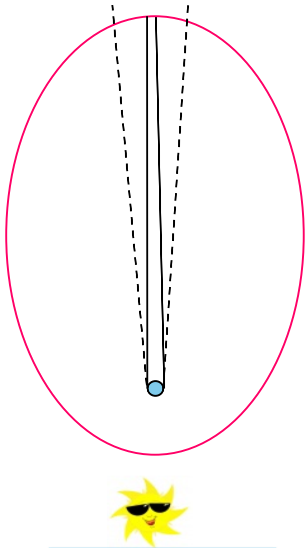
Electromagnetic Noise

- **Risk** (ID# SPA_02): Electromagnetic noise impact on science return (high frequency field measurements).
- **Cause:**
  - Spacecraft generated AC fields (electric and magnetic) during the main science data phase disturb the high-frequency field measurements.
- **Mitigation**:
  - Stable power consumption on relevant time scales. The power system can be implemented as a non-switching, linear shunted system, with dumping of excess power at different locations on the spacecraft.
  - The grounding concept should be a distributed single point ground system (star point) at local (unit) and system level.
  - Harness routing must be optimized to minimize current loops and/or achieve self-compensation.
  - Frequency control for active units during science acquisition.
  - Avoid mechanisms, especially motors, relays, valves.

- **Risk Index**: **3E (Science)**

Operational Availability

- **Risk** (ID# MIS_04): Limited operational availability during phase 3 with impact on science return.
- **Cause:**
  - Significant variations in the orbital elements are to be expected (e.g. orbit inclination).
  - Eclipse durations are likely to be a major concern.
- **Mitigation**:
  - Potentially a much more complex strategy for phase 3 is required, with a series of targeted lunar swing-bys to adjust the orbital parameters periodically.
  - Operational availability requirement to take into consideration multiple unavailability contributors such as ΔV manoeuvres, eclipses, failure recovery, etc.
- **Risk Index**: **2E (Science)**



Orbit 3: Umbra and Penumbra Regions

Oscillations of 50m wires

- **Risk** (ID# SPA_04): Oscillations of EFI 50m antennas during orbit change manoeuvres. Impact on spacecraft controllability, possible wire entanglement, etc.
- **Cause:**
  - Performing a slew while maintaining an angular rate of 2RPM creates strong gyroscopic effects.
  - High ΔV manoeuvres required for orbit changes (+200m/s)
  - Uncertain dynamic behaviour of 50m wire antennas.
- **Mitigation**:
  - Design robust to variation in slew (angular) rate.
  - Increase Thor spin rate?
  - Heritage from previous missions (e.g. Cluster, MMS, etc.)
  - Low thrust manoeuvres (longer manoeuvre duration, impact on propellant mass due to gravity losses and science return).
  - Perform manoeuvres only when Sun direction is close to manoeuvre direction (may place a significant constraint on mission analysis).
  - **Detailed dynamic analysis is required.**

- **Risk Index**: **4D (Technical)**

Plume Impingement (risk removed with baseline configuration)

- **Risk** (ID# SPA_05)**:** Plume impingement from AOCS thrusters on solar array and/or instruments.
- **Cause:**
  - AOCS thrusters are located in the vicinity of sensitive surfaces (e.g. solar array).
- **Mitigation**:
  - Detailed plume impingement analysis required.
  - Study the possibility of placing thrusters on less critical locations or make use of dedicated mounting structures that separate the thrusters from the main body of the spacecraft.
  - Alternative configuration with the spin axis perpendicular to the orbital plane and solar arrays on the side of the spacecraft (i.e. cluster, MMS, etc.)

- **Risk Index**: **3E (Technical)**

Cluster Spacecraft with Fregat upper stage ©ESA

Ground Station Unavailability (mitigated)

- **Risk** (ID# MIS_05): Unavailability of 15m Kourou ground station network.
- **Cause:**
  - Conflict with other ESA missions in the same timeframe.
- **Mitigation**:
  - Design compatible with all 15 m antennas in the ESA network.
  - Design compatible with the 35m ESA DSA network (e.g. NNO station).
  - Shorter daily passes.
  - Larger on-board data storage.
- **Risk Index**: 2E (Science)

15 m Kourou
Ground Station
©ESA

Risk Index Chart

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

Index Chart

Severity					
5					
4			SPA_03	MIS_01, SPA_04	
3				MIS_02, PAY_01, PAY_02	SPA_01, SPA_02, MIS_03
2					MIS_04, MIS_05
1					
	A	B	C	D	E
					Likelihood

THOR

GS&Ops

Internal Final Presentation
ESTEC, 9th July

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Requirements and Design Drivers

- 3+2 years lifetime
- An orbit change at the end of year one and two
- One SK manoeuvre every 20 days in the first year
- Final transition to L1 and disposal
- 100% return of Survey data
- Input from Scientists for the dumping of Burst data
- X-Band only comms
  - S-band licenses are now very limited under pressure from commercial phone companies

More drivers

- 10km orbit knowledge requirement (lower than the 1km of Cluster)
  - Cluster ranging rules are
    - 5m measurement every 15m, if altitude < 35kkm
    - 5m measurement every hour, if altitude between 35kkm and 80 kkm
    - 5m measurement every 2 hours, if altitude > 80kkm
  - But ranging measurements can't be grouped together or they suffer from the same potential noise source, or below 15deg elevation

Assumptions and Trade-Offs

- SOC will collate the Burst data requests from the scientists and deliver a consolidated and validated daily activities file to the MOC
- ESTRACK Perth will be decommissioned at the end of the year
- Kourou and Maspalomas are currently reliant on the Cluster and XMM missions
  - Without new demand, they may no longer be available in 2026
- In general, a data return model should:
  - Be ground station agnostic but compatible with the three DSA locations
  - Not require more than 16hrs of total daily coverage or the mission becomes vulnerable to station down times
  - Be capable of being split up into shorter passes
  - Maximise on-board resources to reduce load on the ground
- A single pass per day and no requirements on when it should be in the day – an offline mission

Baseline

- Routine office-hours only engineering support (MOC and SOC)
- SOC delivers a daily timeline for Payload operations and Burst data requests
  - MOC Mission Planning System automatically incorporates this into the MTL for the next pass
- The data link has a reserved capacity for the Burst and HRWF data whether or not it is used
  - Plus capacity to allow for the recovery of Survey data in the event of 3 missed passes
- An 8hrs pass with a 15m ground station is the Study baseline
  - MSP has a 2 Mbps link to Europe: ~4.5hrs to transfer a pass of data during Orbit 1
  - KRU has a 512 kbps link to Europe: 4x longer is too long

Options

- A 35m ground station coupled with the maximum possible level of on-board transmitter power
  - Each DSA has a 2 Mbps link to Europe
  - They can track at the lowest perigee
  - The daily pass would be less than 8hrs long
  - More flexibility in the allocation of passes around eclipses and manoeuvres
  - Ensure TTC subsystem is compatible with DSN (NASA) and they can be requested to support when there is an anomaly
  - PN ranging in parallel with TM (GMSK) will definitely be possible

THOR

Propulsion Subsystem

internal Final Presentation
ESTEC, 09-07-2015

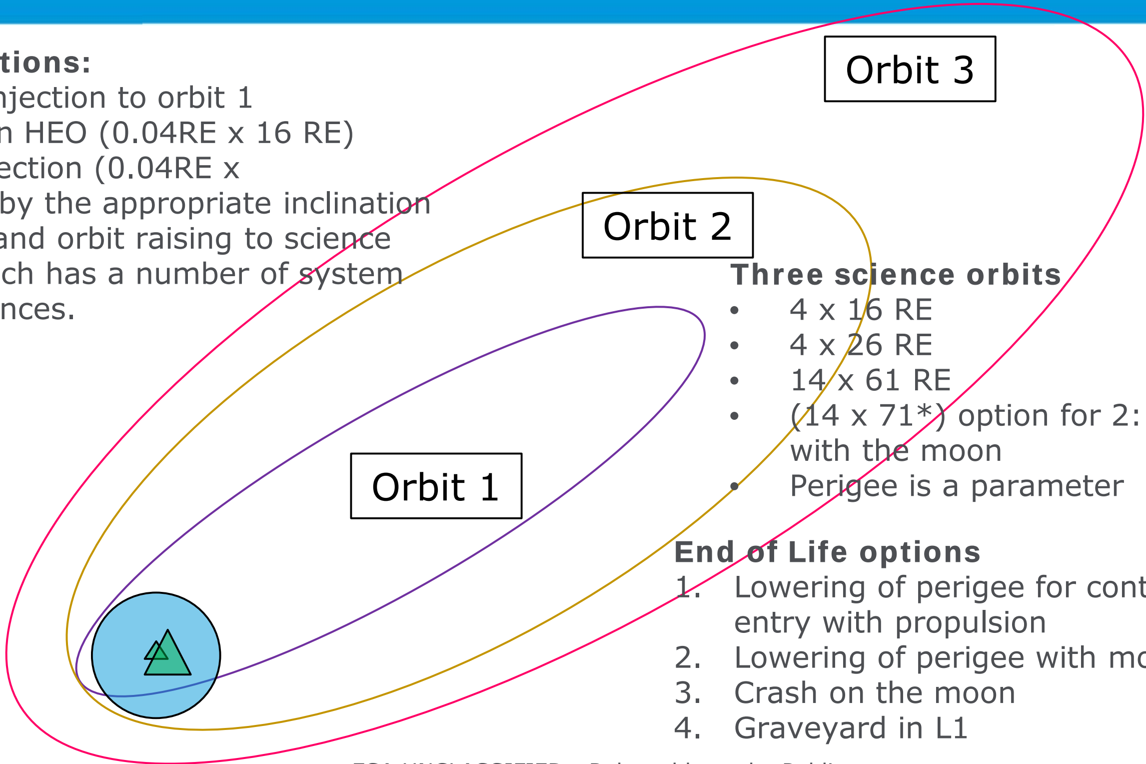
Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Mission Scenario

Launch Options:

- Direct injection to orbit 1
- Injection HEO (0.04RE x 16 RE)
- GTO injection (0.04RE x
- Followed by the appropriate inclination changes and orbit raising to science orbits. Each has a number of system consequences.



Three science orbits

- 4 x 16 RE
- 4 x 26 RE
- 14 x 61 RE
- (14 x 71*) option for 2:1 resonance with the moon
- Perigee is a parameter

End of Life options

1. Lowering of perigee for controlled re-entry with propulsion
2. Lowering of perigee with moon fly-bys
3. Crash on the moon
4. Graveyard in L1

Requirements

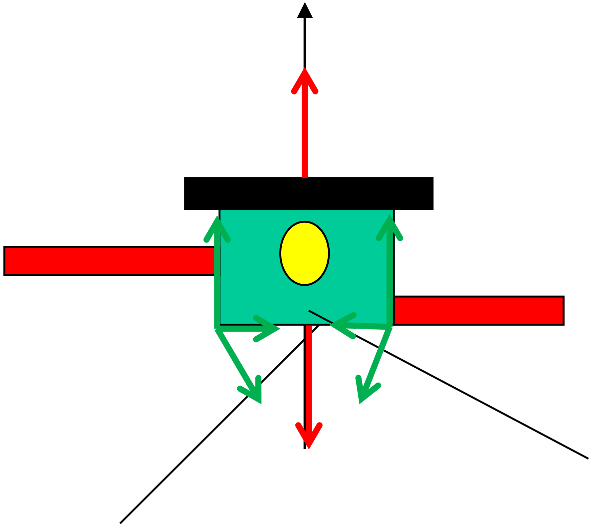
Provide delta V sufficient to perform:

- 3 orbit changes
- 3 years AOCS manoeuvres
- 2 more years (with a total of 5) mission lifetime
- Disposal in L-1

Store enough propellant in order to:

- Reach the 3 different orbits
- Perform all AOCS required manoeuvres
- Include margins

Design drivers / Requirements



Requirements:

- 3-axis control
- Spin around sun direction at 2 rpm
- Conduct slew while spinning at 2 rpm over at least 20 degrees absolute
- Thrust along the spin axis for orbit raising burns

Design drivers

- Dry mass
- Thrust level must be minimised due to presence of wires
- Total propellant throughput
- Total duration burn time

Assumptions from Mission Analysis

Transfer	Delta V [m/s]	Propellant [kg]
1st year		2.5
O1 → O2	214.2	
Transfer AOCS O1 → O2		0.01
2nd year		2.5
O2 → O3a	221.6	
Transfer AOCS O2 → O3a		0.01
O3a → O3	276.2	
Transfer AOCS O3a → O3		0.01
3rd year		2.5
Phase 4 (to L1)	~315	
Transfer AOCS L1		0.01
4th year		2.5
5th year		2.5
Navigation	(40)	
Disposal from L1	20	

DV Depending on launcher insertion orbit

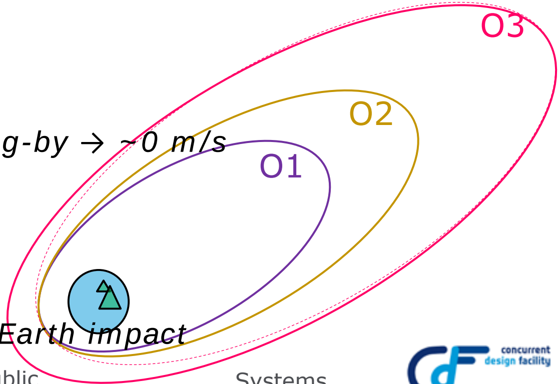
Iterative calculation used to achieve final dry mass specified in the proposal ~637 kg

Option for lunar swing-by → ~0 m/s

Option for lunar swing-by → ~0 m/s

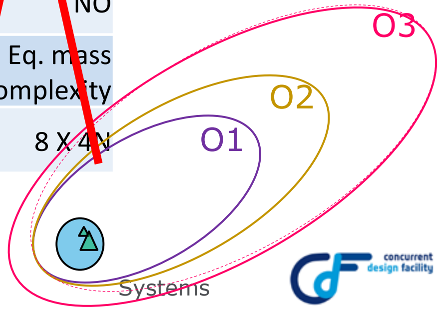
Default is 0 m/s

Heliocentric Orbit or Earth impact



Apogee Thruster Selection

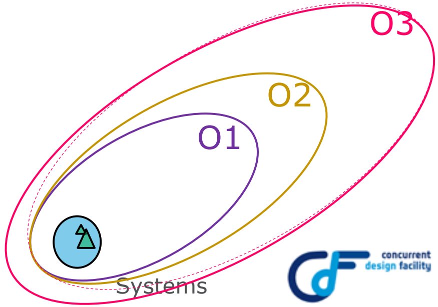
	CHT-20	MR-106L	MR-107V	MONARC-90	S22-2	ATV
Propellant	Hydrazine	Hydrazine	Hydrazine	Hydrazine	MMH/NTO	MMH/NTO
Thrust	20 N	22 N	220 N	90 N	20 N	200 N
Propellant Mass	507 kg	489 kg	413 N	407 kg	315 kg	395 kg
Max Firing Time	32906 s	22249 s	1017 s	2481 s	10050 s	1248 s
Single Burn Time	5400 s	4000 s	100 s	??	??	7600 s
Total throughput	290 kg	243.6 kg	152 kg	1537 kg	??	3627 kg
Tank accommodation	6 X 124 litres	6 X 124 litres	8 X 91 litres	8 X 91 litres	6 X 60 litres	6 X 60 litres
ITAR	NO	YES	YES	YES	NO	NO
Comment	2X needed!	2X needed!	3X needed!		Eq. mass Complexity	Eq. mass Complexity
RCS Thrusters	8 X 1N	8 X 1N	8 X 1N	8 X 1N	8 X 4N	8 X 4N



Apogee Thruster Selection

	CHT-20	MR-106L	S10-13	DST-13
Propellant	Hydrazine	Hydrazine	MMH/NTO	MMH/NTO
Thrust	20 N	22 N	10N	22 N
Propellant Mass	460 kg	413 kg	373.5 kg	369 kg
Max Firing Time	30433 s	19280 s	22104 s	10024 s
Single Burn Time	5400 s	4000 s	28800 s	14400 s
Total throughput	219.8 kg	243.6 kg	869.4 kg	904 kg
Tank accommodation	6 X 104 litres	8 X 91 litres	6 X 60 litres	6 X 60 litres
ITAR	NO	YES	NO	YES/NO
Comment	2X needed!	2X needed!	Eq. mass complexity	Eq. mass Complexity
RCS Thrusters	8 X 1N	8 X 1N	8 X 4N	8 X 4N

Monoprop **Biprop !!!**



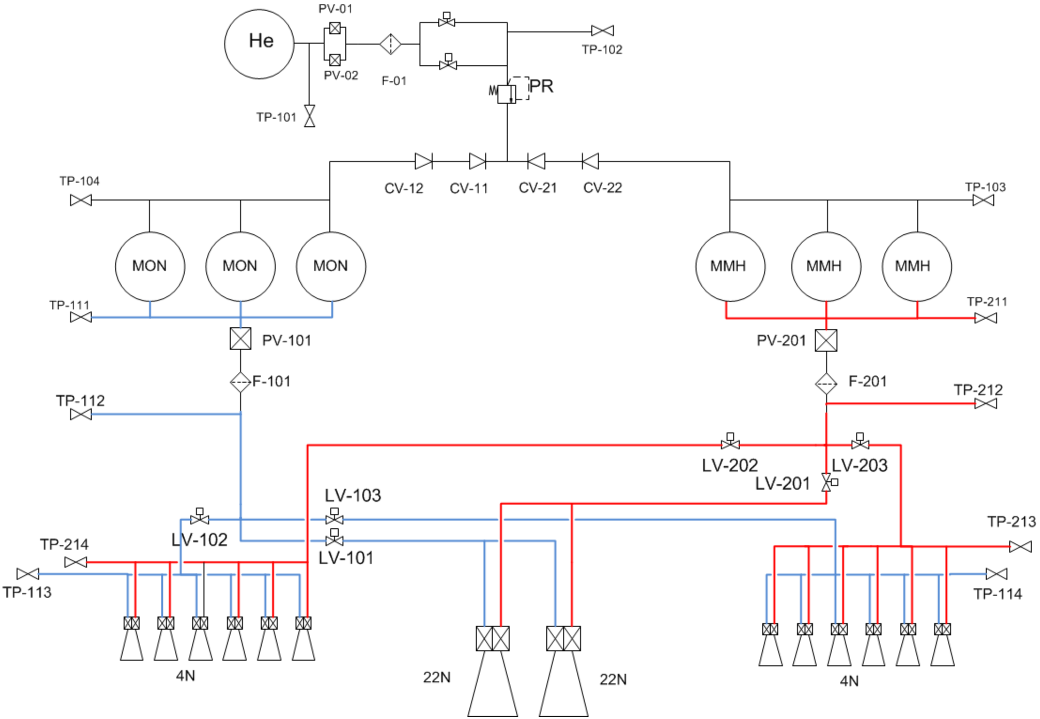
Propulsion Subsystem: trade-off

Based on the Thruster selection a propulsion architecture has been selected as baseline

- Biprop configuration 22N thruster (baseline)
- Biprop configuration 10N thruster (option)
  - Based on M.A. + AOCS + Science constraints a 10N option can be considered
- A Monoprop configuration with 2x20N thrusters firing sequentially can be considered as a third configuration (cons: propellant budget, propellant tanks, additional thrusters (total throughput not sufficient))

- Equipment list is finalised and it is complete for both architectures
  - 65.7 kg for Biprop (margins included: 5% on equipment)
  - 77.6 kg for Monoprop (margins included: 5% on equipment)

Propulsion Subsystem baseline



Equipment:

- #1 He Tank 35 litres
- #6 Tank 59.5 litres
- #2 Thruster 22N
- #8/12 Thruster 4N

- #8 Latch Valves
- #1 Pressure Regulator
- #4 Check Valves
- #4 Pyros
- #3 Filters
- #15 FDVs
- #8 Pressure Transducer
- Feed-lines

Equipment Budget

All the equipment items have been identified among the ones already qualified / flight proven → no development efforts

- 22N Thruster DST-13 (MOOG-ISP)
- 4N Thruster S4 (Airbus DS)
- Pressurant Tank MTA-35 (MT- Aerospace)
- Propellant Tank ATK 80353-1 (Orbital ATK)
- Pressure Regulator (Stanford Mu)
- Latch Valves (VACCO)
- Pyros (Airbus DS)

Total mass of the (dry) propulsion subsystem is around **65.7 kg** (5% margin on equipment)

Conclusions

A propulsion subsystem architecture for THOR spacecraft has been designed

- Propellant mass → **369.5 kg**
- Propulsion subsystem mass → **65.7 kg**
- Propulsion architecture: Biprop MMH/MON
- 1(+1)x22N thruster for orbit change
- 4(+4)x4N thruster for ACS
- 6 Propellant tanks
- 1 Pressurant tank

THOR

<Mechanisms>

<IFP>
ESTEC, <Meeting Date>

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Assumptions & Design Drivers

- Positional Accuracy: 0.5°(knowledge)
- Length of booms > 5m
- Number of instruments mounted on the booms and dimensions
- Configuration in S/C: need of 3 segments to accommodate aprox. 6.5m of boom in the bottom panel of the S/C (without Search coil instrument)

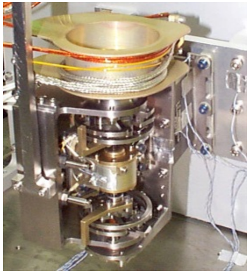
Trade-off

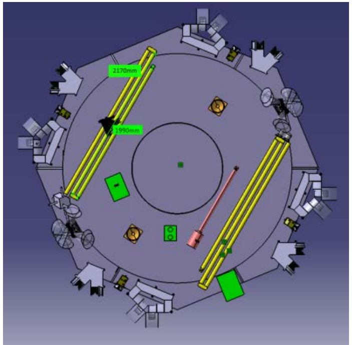
- 3 Segments Boom
  - Heritage of 2 segments booms (Cluster, Rosetta, Solar Orbiter, etc..)
  - Need of development for a 3 segment boom
  - More problematic with configuration
  - Good positional stability

- 2 phase Coilable boom
  - Technology not available in Europe
  - 2 phase booms would need development
  - Good positional stability

Baseline design

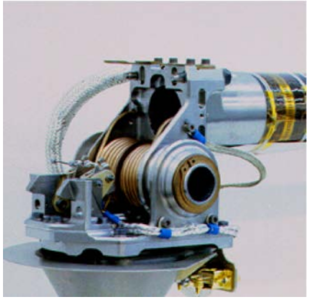
- Magnetometer Boom: Rosetta type boom
  - 6.3 meters length
  - 2 Booms, with 3 segments each
  - No heritage for 3 segment booms
  - Spring based hinges
  - Aprox. 0.45° of positional accuracy without considering other effects
  - The baseline is a radial deployment as in Cluster (spin rate not considered for the torque)
  - DC brushed motor needed for synchronization
  - 3 HDRMs per boom are foreseen





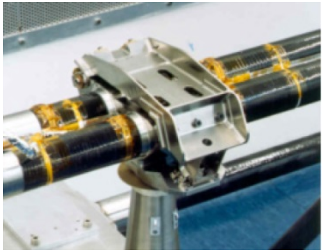
Baseline design

- Antenna Boom: Cluster Heritage
  - 2 Antenna booms, one segment each
  - Hinge based on spring
  - Boom of CFRP
  - One HDRM per Boom



Baseline design

- Boom HDRM
  - Based on Non Explosive Actuator
  - Similar concept as used in Cluster
  - 3 HDRMs per Boom are estimated



- Antenna Boom HDRM
  - Based on Non Explosive actuator
  - Similar concept as used in cluster

Mass Budget

	mass (kg)	mass margin (%)	mass incl. margin (kg)
⊟SC (Spacecraft)	**48.40**	**17.44**	**56.84**
⊟PF (Platform)	**48.40**	**17.44**	**56.84**
ABM_1 (Antenna Boom Mechanism)	3.00	10.00	3.30
ABM_2 (Antenna Boom Mechanism)	3.00	10.00	3.30
BHDRM_1 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_2 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_3 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_4 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_5 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_6 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_7 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
BHDRM_8 (Boom Hold Down and Release Mechanism)	0.80	10.00	0.88
MDB_1 (Magnetometer Deployable Boom)	18.00	20.00	21.60
MDB_2 (Magnetometer Deployable Boom)	18.00	20.00	21.60
Grand Total	**48.40**	**17.44**	**56.84**

THOR

Configuration

IFP
ESTEC, 09/07/2015

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Assumptions & Design Drivers

- Spinning aircraft → Axisymmetric structure
- Equipments by sets of 4 → Octagonal platform
- 6 tanks → 6 shear panels

THOR

Electromagnetic Compatibility (EMC) Design Features

Session 8
ESTEC, 09-JUL-2105

Prepared by A. Junge (TEC-EEE*)

(*) Electromagnetic Compatibility Section

Payload Instruments - Magnetometers

FGMs

- Boom length 6.3 m with MAG-O (outer fluxgate) and SCM at tips
- total S/C magnetic moments equivalent to the req.:
  Basic rule: 1 m & 1 $Am^2 \rightarrow$ 200 nT; cubic distance law

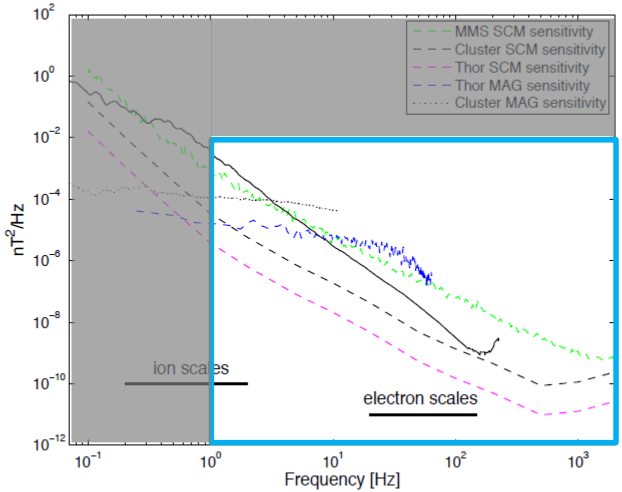
a. DC: 5 nT req. (factor 5/200=1/40) $\Rightarrow$ 25 mAm^2; ca. *6.3 m* (factor $6.3^3 \approx 250$)
   $\Rightarrow$ 6.25 Am^2

b. AC >1h: 0.5 nT_{pp} req. $\triangleq$ 250 pT_p (factor 5/0.25=20) — *using dual magnetometers ?*
   $\Rightarrow$ 312.5 mAm^2

c. AC 1s – 1h: 10 pT_{pp} req. $\triangleq$ 5 pT_p(factor 250/5=50) — *relaxation from SST ?*
   $\Rightarrow$ ca. 6.25 mAm^2

Payload Instruments - Magnetometers

SCM



d. AC 1Hz – 200 kHz:
~ 10^{-6} – 10^{-11} nT^2/Hz req.

$\Rightarrow$ ca. 10^{-3} – $3 \cdot 10^{-5}$ $nT/\sqrt{Hz}$

Bandwidth 1 Hz
$\Rightarrow$ 1 pT – 0.01 pT (TBC)
(1.25 mAm^2 – 0.001… mAm^2 = 1 μAm^2)

req. to be clarified (under discussion)

Payload Instruments – Electric Field and Particles

- EFI-SDP and –HFA
  - Req.: Frequency management below 250 kHz
    - Limited no. of frequencies (value TBD)
    - Stable frequencies (value TBD)

  ⇒ Central OBC reference clock; synchronization of DC/DC converters
- EFI-SDP and Particle Sensors
  - Req.: Voltage between any two points on spacecraft surface below 1 V.

  ⇒ Spacecraft charging simulation required → TEC-EES
- Particle Sensors:
  - Low magnetic fields

  ⇒ Magnetic field simulation required → TEC-EEE/-EES

Platform Equipment

- Active Spacecraft Potential Control (ASPOC)
  → Neutralize spacecraft potential by ion emission

- Magnetic Alignment Calibration System (MACS)
  → Allows increased boom length despite more hinges
  (i.e. less alignment accuracy)

- TT&C RF system
  - X-Band COMMs
    → natural attenuation of EMI generated below 1 GHz
  - Static antenna → no risk of illuminating S/C body with main lobe
  - Emissions: High power 55 W ≙ 47.4 dBm
    → Side- and backlobe field levels to be assessed (accommodation depended)
  - Susceptibility TBD

Platform Equipment

- EPS
  - PCDU at central position (inner tube) → star point
  - BAT at central position (inner tube) → maximizing distance to MAG + SCM
  - 2 BAT modules for mutual cancellation of magnetic moment
  - Linear regulation scheme with distributed power dumps
    → limiting variations in power consumption and related currents
    → LF AC electric and magnetic fields
    - OPTIONAL: power dumps inside payload instruments and platform equipment
  - Solar cell cover glass ITO coating
    → minimizes potential differences on spacecraft surface
  - Solar array back-wiring in mass estimate
    → reduction of magnetic fields

Platform Equipment

- Thermal
  - Conductive external materials
    → minimizes potential differences on spacecraft surface
- Propulsion
  - Tank bearing axes in ring (or star) configuration
    → Magnetic moments cancel out
  - Thrusters in pairs but cancelling of magnetic moments unlikely
- Structure
  - Aluminum panels → high conductivity → good ground plane
  - No “ring” → avoidance of eddy current induced by S/C spin
- Harness
  - Shielding and backshells (2% extra mass allocation)
    → reduction of emissions and susceptibilities via I/Fs

Platform Equipment

- OBC
  - Central position → star point routing of "signal" (data) harnesses
  - Central reference clock included
    → frequency control and selection
    → principle possibility for phase control (TBD; OPTIONAL)

- Other
  - "No" mechanisms (only HDRMs → static after S/C commissioning)
    → no related LF AC magnetic variations

System AIV/AIT (preliminary)

Unit AIV/AIT

- Conducted EMC on E(Q)M, PFM, FS
- Magnetic tests on parts, E(Q)M, PFM, FS
- Radiated EMC Tests on (E)QM, PFM, FS
- ESD on (E)QM

System AIV/AIT

- Conducted EMC on EQM/*EFM* & PFM
- Radiated EMC & RF auto-compatibility on PFM
- Magnetic Test in large coil facility on PFM
- Solar array magnetic model (Biot-Savart) -> TDA ?
- S/C magnetic model starting at preliminary design stage
- Charging simulation starting at preliminary design stage

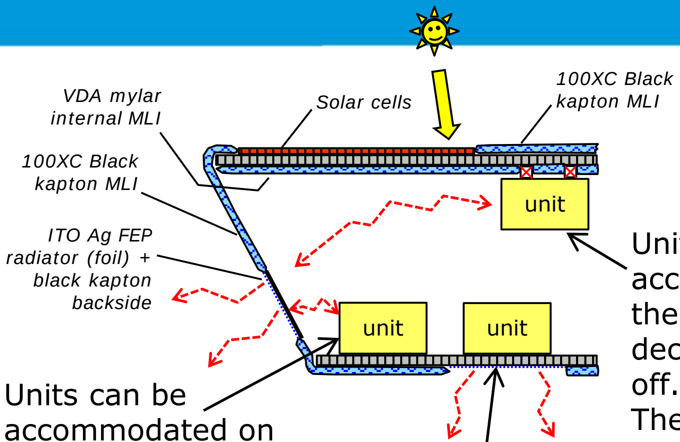
THOR

Thermal

Internal Final Presentation
ESTEC, 9th July 2015

Prepared by
Romain Peyrou-Lauga

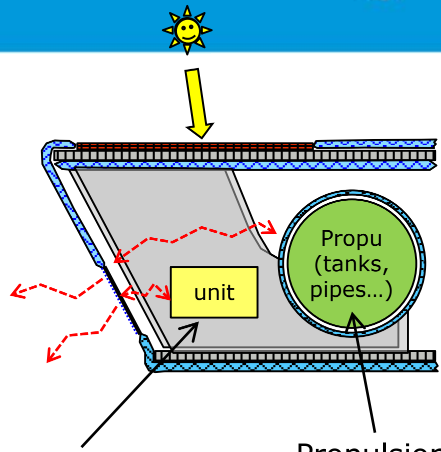
Units thermal control



Units can be accommodated on the top floor with decoupling stand-off.
The may radiate inside the S/C and benefit of a warm environment.
(low dissipative unit)

Units can be accommodated on the bottom floor (thermally coupled or decoupled) and radiate their heat towards a lateral radiative window.
(low/medium dissipative units)

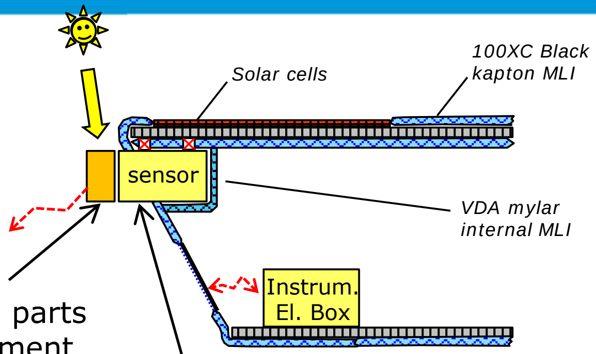
Units can be accommodated on the bottom and benefit of a dedicated radiator.
(high/medium dissipative units)



Units can be accommodated on a shear wall and radiate their heat towards a lateral radiative window.
(low/medium dissipative units)

Propulsion subsystem benefit of a warm radiative environment and requires a minimum of heating power

Instrument thermal control



Sun exposed instruments can be accommodated under the top floor with the needed FoV with the Sun.

External surface of the instrument is used to reflect the Sun and to radiate the excess of absorbed heat and internal dissipation.

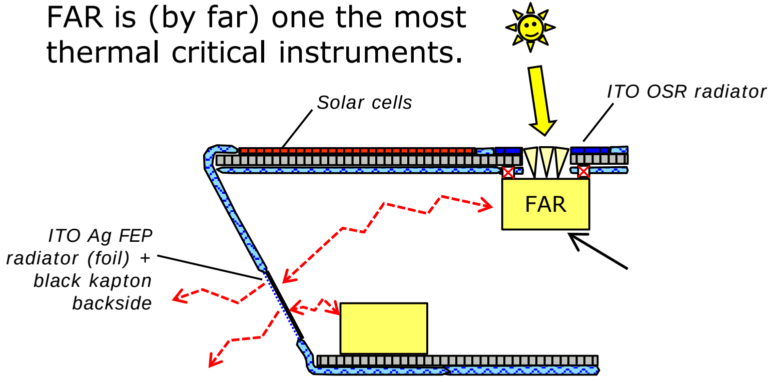
Sun exposed parts of the Instrument are passively thermally controlled with appropriate coating.
They are conductively decoupled from the rest of the instrument.

Dissipative parts of the instrument may have their own radiator (opposite to Sun direction) or radiate inside the satellite cavity.

To facilitate interface and independent development and verification of both instruments and platform, it is strongly recommended thermally decouple the instrument sensor from the S/C.

FAR instrument thermal control

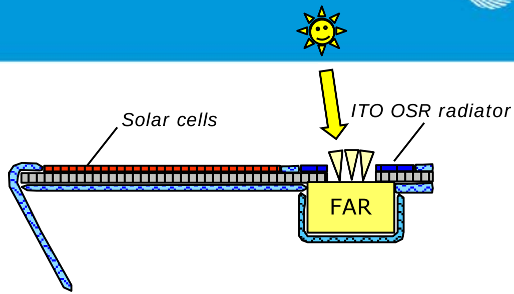
FAR is (by far) one the most thermal critical instruments.



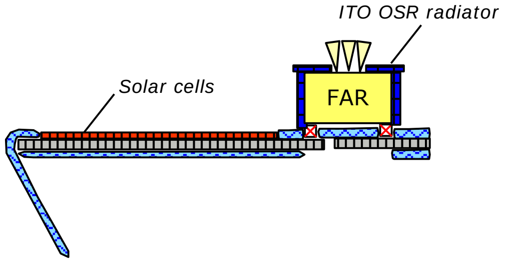
Several configuration are possible:

1. The instrument is mounted behind the front wall, as much thermally decoupled from the wall. The wall is locally passively cooled with OSR (Sun reflective tiles / high emissivity).

(*drawback: inter-dependability between S/C and instrument*)

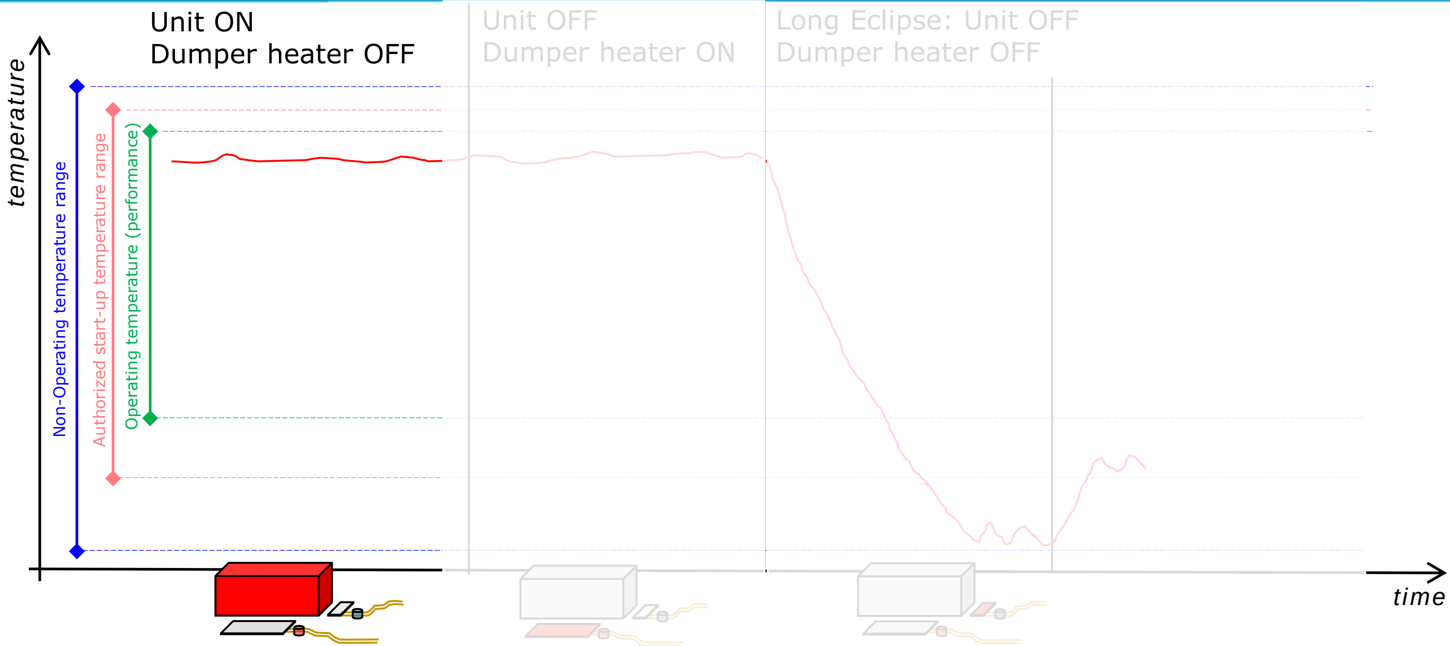


2. The instrument is mounted behind the front wall, directly coupled to an OSR radiator.



3. The instrument is decoupled from the S/C and has its own OSR radiator.

Heating lines / Dumper heaters management



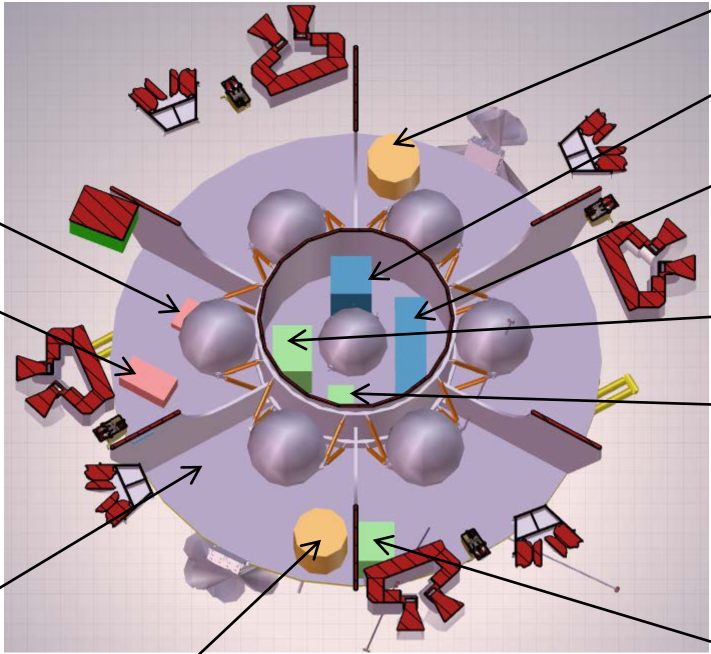
Dumper heater is located close to unit baseplate, and has a security thermostat

Non-op heater is located close to unit baseplate. Software or thermostat is used to control the temperature

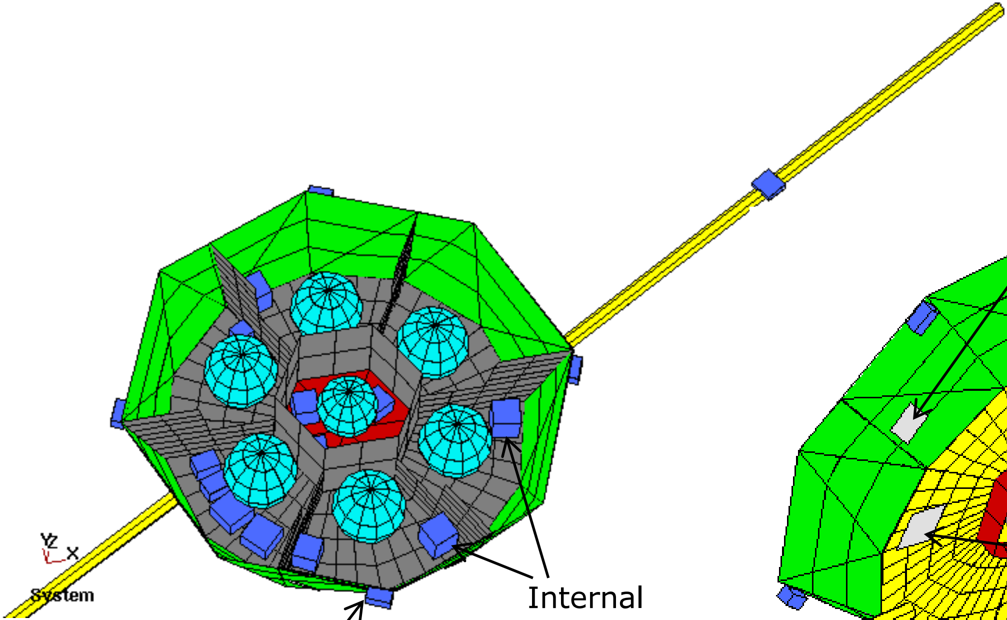
Thermal design / thermal analysis

Science Mode

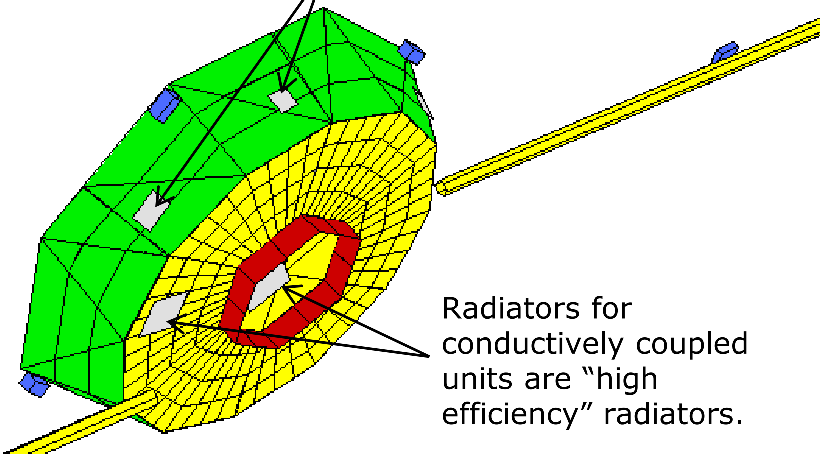
Safe



Thermal model overview



The radiative windows constitute "low efficiency" radiators (as they work only radiatively). This is good enough in operating mode and present great advantage during eclipse / safe mode)

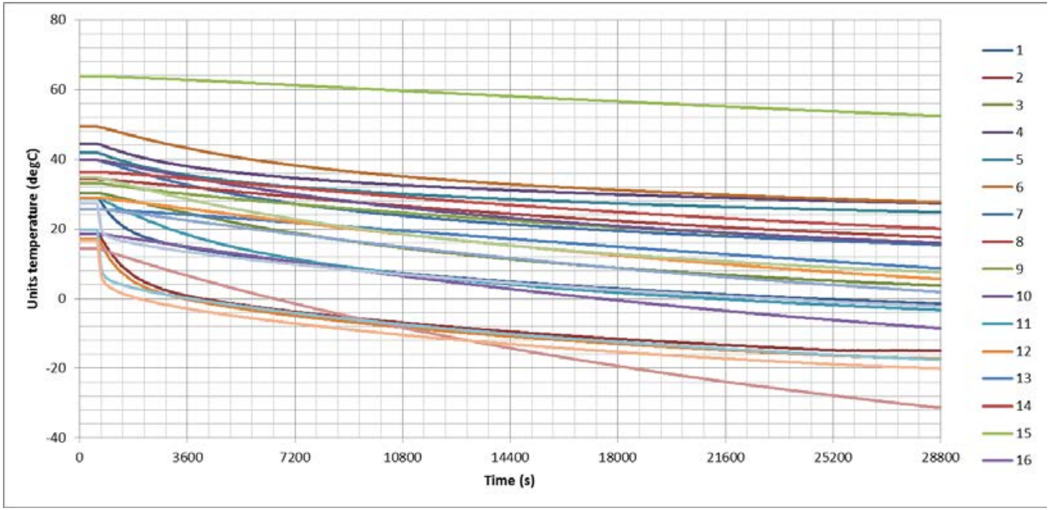


Radiators for conductively coupled units are "high efficiency" radiators.

Simulation of long eclipse

The long eclipse has been simulated and shows all internal units do not require specific heating power, thanks to:

- their thermal inertia,
- the remaining dissipation in safe mode,
- the “low efficiency” radiators which slow down most of the internal units cooling.



External instrument (particularly the Sun exposed ones) need heating power to maintain them in their non-op temperature range after about 1 hour of eclipse.

Typical heating power is about 50 % of their dissipation.

Propulsion subsystem requires as well additional heating power during eclipse.

THOR

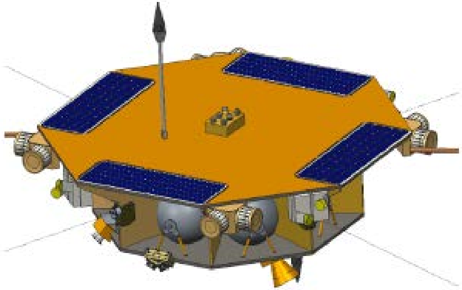
Structure

Internal Final Presentation
ESTEC, 9th July 2015

Prepared by the CDF* Team

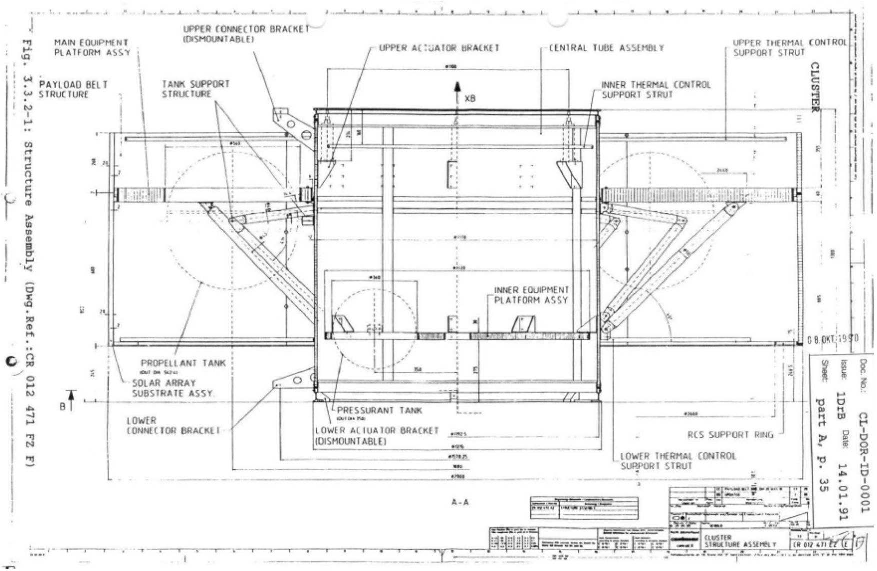
(*) ESTEC Concurrent Design Facility

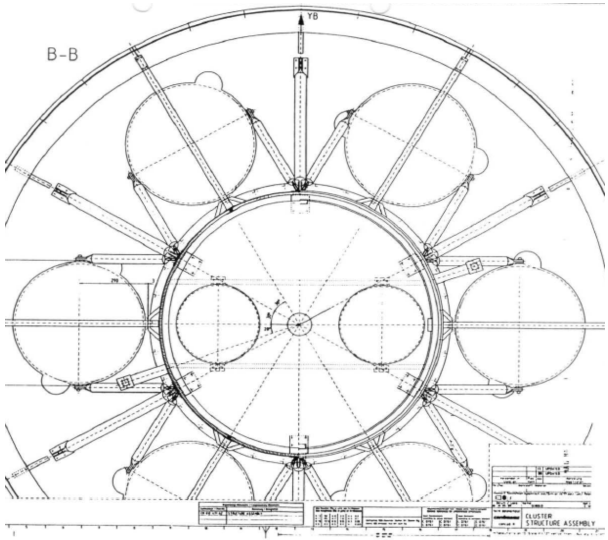
Structure Updated Baseline



- initial baseline: proposal
- updates
  - look at Cluster
  - attach tanks to central cylinder
  - reduce panel surface to what is required for instruments & equipment and keeping stiffness (less mass)
    - less shear panels, plus cut-outs
    - remove inner part of upper platform
- keep
  - lower platform diameter less than upper platform
  - EMC compatibility (alu/alu panels except central cylinder cfrp/alu)
  - spinner (balanced, cog, compact height, …)

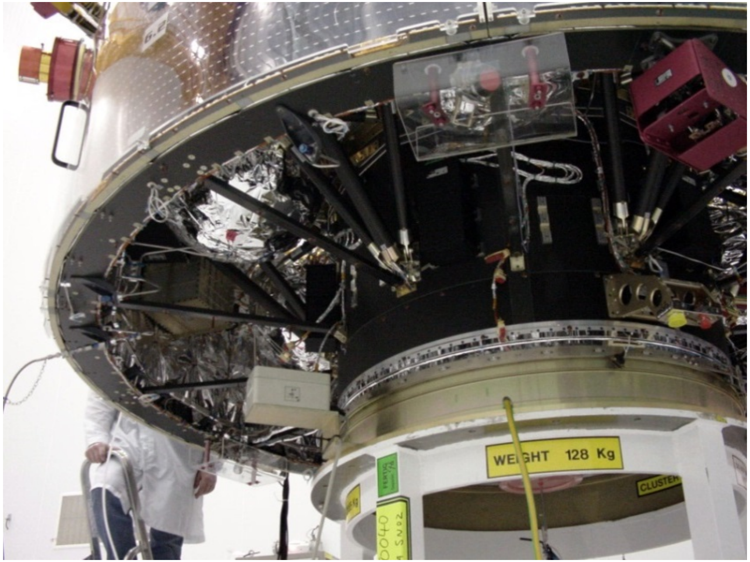
Cluster Structure / Top & Side View





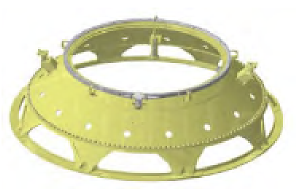
Cluster Primary Structure

- Central cylinder: CFRP facesheets & Aluminium honeycomb core (12 mm)
- MEP: Aluminium facesheets & Aluminium honeycomb core (60 mm)
- IEP: Aluminium facesheets & Aluminium honeycomb core (30 mm)
- MEP support struts: CFRP (ø 50 mm, 1.35 mm), Aluminium fittings
- Tank support struts: CFRP (ø 40 mm, 1.35 mm), Aluminium fittings
- Fittings, panel segment connections, etc: Aluminium



THOR Stiffness Verification

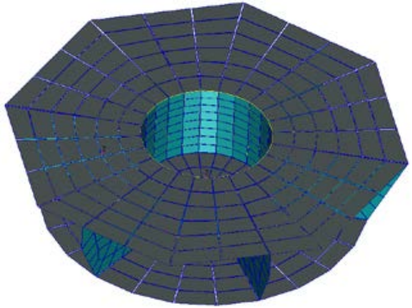
- requirements (15% margin to be added)
  - Soyuz:
    - 1st Lateral Frequency ≥ 15 Hz
    - 1st Longitudinal Frequency ≥ 35 Hz

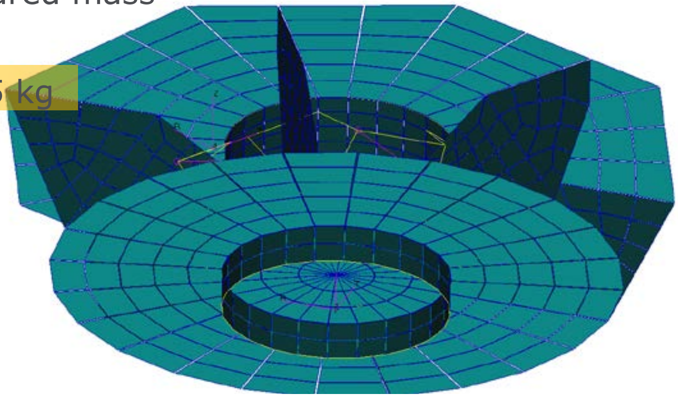
PAS 1194 VS 	PAF 1194 S + LVA-S Total height: 517 mm Total mass: 115 kg	Clamp-band ∅1194 with low shock separation system (CBOD) (RUAG Space AB)

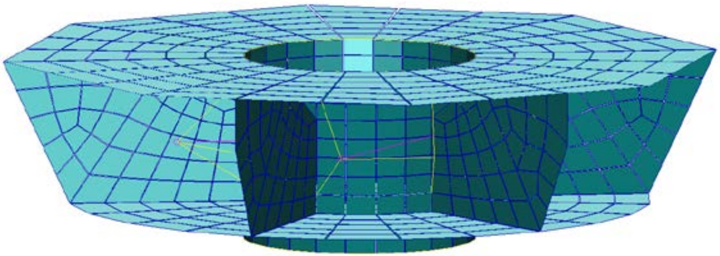
  - Ariane6 (tbd -> use Ariane5):
    - 1st Lateral Frequency ≥ 10 Hz
    - 1st Longitudinal Frequency ≥ 31 Hz

THOR FEM

- geometry
- global stiffness and mass representativeness
- PAF interface clamped
- simple tank model
- equipment & instruments modelled as smeared mass platforms upper/lower/lower-inner/panels
- Baseline mass 935 kg; margin +20 % 1035 kg

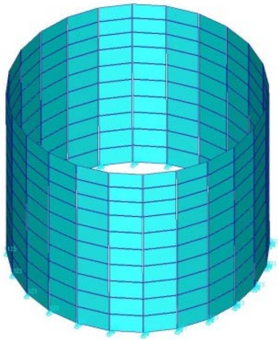


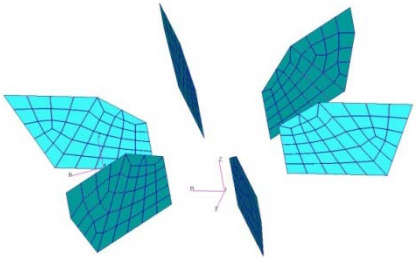


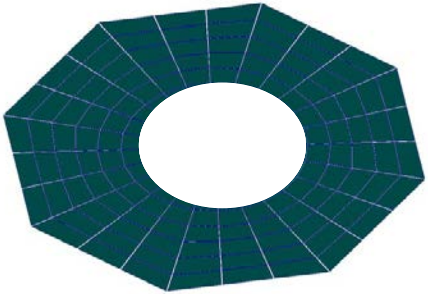


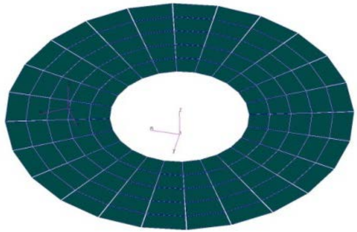
THOR FEM Materials and Properties

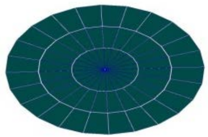
			area	diameter	thickness		material		length
					facesheet / strut	core	facesheet / strut	core	/ height
tank strut	upper - A			40.0 mm	1.350 mm	n.a.	m40 cfrp	n.a.	0.575 m
	lower - B			40.0 mm	1.350 mm	n.a.	m40 cfrp	n.a.	0.575 m
top platfor	outer part	sun panel	9.632 m2	3.700 m	0.500 mm	30.0 mm	alu	alu 3/16-5056-0.0007	
	inner part		1.120 m2		0.500 mm	30.0 mm		alu 3/16-5056-0.0007	
lower platform		nadir panel	5.950 m2	3.000 m	0.635 mm	60.0 mm	alu	alu 3/16-5056-0.0007	
inner equipment platform			1.120 m2	1.194 m	0.500 mm	30.0 mm	alu	alu 3/16-5056-0.0007	
shear panels			0.788 m2		0.500 mm	20.0 mm	alu	alu 1/8-5056-0.001	0.700 m
central cylinder			2.840 m2	1.194 m	0.500 mm	11.0 mm	m40 cfrp	alu 3/16-5056-0.0007	0.757 m
	lower doubler		0.375 m2	1.194 m	1.250 mm	11.0 mm		alu 1/8-5056-0.001	0.100 m
	upper doubler		0.315 m2	1.194 m	1.250 mm	11.0 mm		alu 1/8-5056-0.001	0.084 m
	lower I/F ring		415.0 mm2	1.194 m		n.a.	alu	n.a.	3.751 m
	upper I/F ring		76.8 mm2	1.194 m		n.a.	alu	n.a.	3.751 m











THOR wrt L/V stiffness requirements

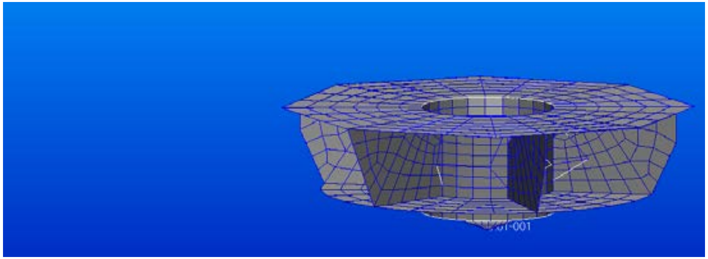
margin +20% mass

- 1st Lateral Frequency = 26.5/27.3 Hz (Z/Y)   24.3/25.1 Hz (+20% Z/Y)
- 1st Longitudinal Frequency = 31.5 Hz   28.7 Hz (+20%)

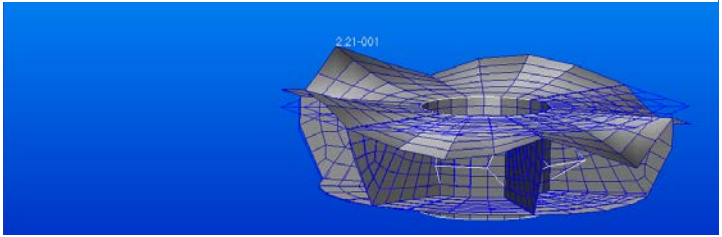
configuration	baseline	baseline *120%		baseline							baseline *120%						
comment																	
mass	935.0 kg	1051.0 kg			axial	lat-y	lat-z					axial	lat-y	lat-z			
Upper Platform flapping	21.6 Hz	19.7 Hz	1	21.62	0.00	0.00	0.14	0.00	5.74	0.00	19.73	0.00	0.00	0.13	0.00	6.47	0.00
Tanks & Inner Lower Platform axial mode	23.1 Hz	21.0 Hz	2	23.06	16.01	0.00	0.00	0.00	0.00	0.00	21.05	19.21	0.00	0.00	0.00	0.00	0.00
Upper Platform flapping	23.2 Hz	21.2 Hz	3	23.22	1.69	0.00	0.00	0.00	0.00	0.00	21.20	2.01	0.00	0.00	0.00	0.00	0.00
Upper Platform flapping	24.9 Hz	22.7 Hz	4	24.91	0.00	0.00	0.00	0.01	0.00	0.00	22.74	0.00	0.00	0.00	0.01	0.00	0.00
First lateral mode (Z) & Upper Platform flapping	26.5 Hz	24.3 Hz	5	26.54	0.00	0.04	26.33	0.00	399.37	0.00	24.30	0.00	0.02	24.65	0.00	438.32	0.00
First lateral mode (Y) & Upper Platform flapping	27.3 Hz	25.1 Hz	6	27.34	0.00	33.32	0.05	0.00	0.00	443.74	25.06	0.00	30.95	0.03	0.00	0.00	483.08
First axial mode (mainly Upper Platform flapping)	31.5 Hz	28.7 Hz	7	31.48	151.23	0.00	0.00	0.00	0.00	0.00	28.74	178.34	0.00	0.00	0.00	0.00	0.00
Inner Lower Platform mode	37.1 Hz	33.9 Hz	8	37.11	0.00	0.00	0.00	0.00	0.18	1.00	33.88	0.00	0.00	0.00	0.00	0.01	1.25
Inner Lower Platform mode	37.1 Hz	33.9 Hz	9	37.11	0.00	0.00	0.00	0.00	1.03	0.17	33.88	0.00	0.00	0.00	0.00	1.26	0.01
Global Torsional mode	37.2 Hz	34.8 Hz	10	37.17	3.33	0.00	0.00	998.56	0.00	0.00	34.83	1.69	0.00	0.00	1130.85	0.00	0.00
Second lateral mode (Z) & Upper Platform flapping	38.0 Hz	35.7 Hz	11	38.00	0.00	2.02	214.76	0.00	498.92	0.13	35.72	0.00	1.81	239.71	0.00	584.20	0.47
Second lateral mode (Y) & Upper Platform flapping	38.1 Hz	35.7 Hz	12	38.08	0.00	204.69	1.94	0.00	0.13	464.86	35.75	0.00	229.37	1.76	0.00	0.49	551.39
Lower Platform flapping	44.9 Hz	41.0 Hz	13	44.93	0.00	0.01	0.23	0.00	0.18	0.00	41.02	0.00	0.00	0.39	0.00	0.40	0.00
	46.6 Hz	43.4 Hz	14	46.62	1.04	0.00	0.00	0.00	0.00	0.00	43.36	1.26	0.00	0.00	0.00	0.00	0.00
	46.8 Hz	43.4 Hz	15	46.85	0.00	0.00	0.00	0.01	0.00	0.00	43.41	2.73	0.00	0.00	0.00	0.00	0.00
	47.6 Hz	43.6 Hz	16	47.56	2.28	0.00	0.00	0.00	0.00	0.00	43.55	0.00	0.00	0.00	0.01	0.00	0.00
	47.7 Hz	43.6 Hz	17	47.72	0.00	0.00	0.00	0.00	0.00	0.00	43.56	0.00	0.00	0.00	0.00	0.00	0.00
	47.7 Hz	43.6 Hz	18	47.72	0.00	0.00	0.00	0.00	0.00	0.00	43.58	0.00	0.00	0.00	0.02	0.00	0.00
	52.7 Hz	50.5 Hz	19	52.73	1.26	0.00	0.00	0.01	0.00	0.00	50.52	0.00	0.00	0.00	0.00	0.00	0.00
	52.8 Hz	50.5 Hz	20	52.78	0.01	0.00	0.00	0.01	0.00	0.00	50.52	0.00	0.00	0.00	0.00	0.00	0.00
			TOTAL		176.84	240.07	243.46	998.61	905.55	909.90		205.24	262.16	266.67	1130.89	1031.13	1036.20

THOR wrt L/V stiffness requirements

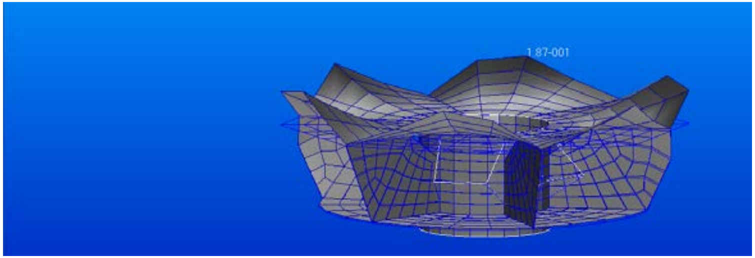
local (lower internal platform) axial 23.1 Hz



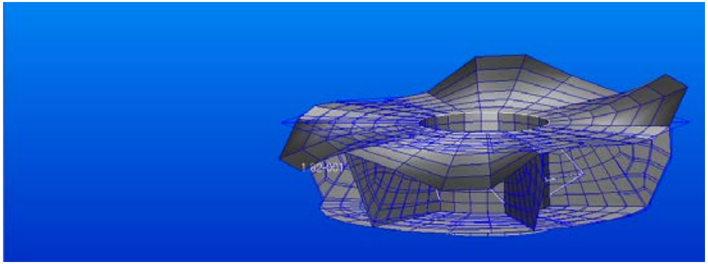
1st lateral-Z & upper platform 26.5 Hz



1st axial & upper platform 31.5 Hz

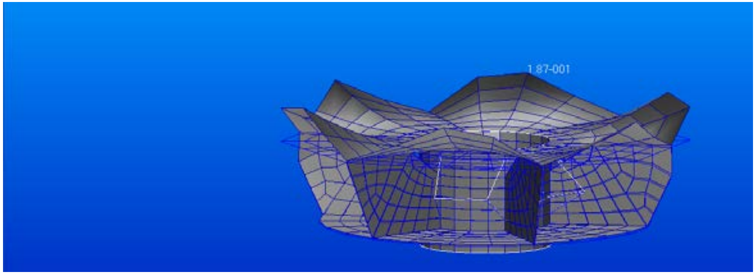


1st lateral-Y & upper platform 27.3 Hz

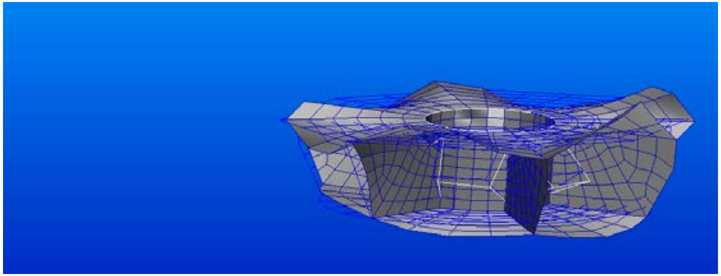


THOR wrt L/V stiffness requirements

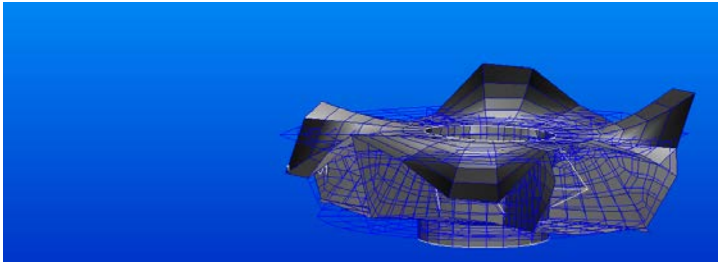
global axial & upper platform 31.5 Hz



2nd lateral-Z & upper platform 38.0 Hz



2nd lateral-Y & upper platform 38.1 Hz



THOR Conclusions

- Lateral frequency requirement (≥ 15 Hz)
  - met
- Axial frequency requirement (≥ 35 Hz)
  - not met
  - mainly due to lower inner platform & upper platform *(& FEM tbc*)

- Improvements
  - increase thickness of upper platform face sheet to "push local modes up", same for lower inner platform
  - diameter (platform upper) could be reduced, additional cut-out
  - place more equipment on shear panels?
- Mass impact minimal

THOR

Conclusions

Internal Final Presentation
ESTEC, 9th July

Prepared by the CDF* Team

(*) ESTEC Concurrent Design Facility

Study Objectives Achievement (1/3)

The CDF study shall serve the following purpose:

- consolidate the science and mission requirements definition
  - *Achieved: MRD and SciRD documents injected into the design and elaborated based on feasibility assessment and CDF design outcome*
- prepare a preliminary design of the S/C supported by dedicated analysis
  - *Achieved: Design based on Swedish Institute of Space Physics Proposal; several trade-offs performed (mission analysis, maneuvers and launch strategies, propulsion architecture, thrusters number and accommodation, deployment mechanisms, comms architecture and data download strategy, ground stations, shielding strategy, units accommodation with EMC considerations in-the-loop, structural optimization), and baseline selection based on plenary analysis and discussion of trade space; budgets supported by OCDT engineering model; domains analysis supported by dedicated tools*

Study Objectives Achievement (2/3)

The CDF study shall serve the following purpose:

- identify any critical technologies, potentially requiring TDAs
  - *Achieved: at the end of last Design Sessions the following TDAs have been highlighted:*
    - *MECHANISMS:*
      - *3 segment booms (current assumption: JUICE booms development is for a 3 segment boom; no further TDA required; however this will have to be confirmed in 1 month from time of writing)*
    - *EMC:*
      - *Solar Array magnetic model (Biot – Savart)*
      - *OBC central reference clock phase control capability*
    - *POWER:*
      - *Battery: not mere TDA but potential Delta qual. if split in 2 modules is still not adequate for EMC 9magnetic field)*

All other technologies fulfill TRL requirement of at least 5-6 by the end of the Phase A/B1 (end 2018)

Study Objectives Achievement (3/3)

The CDF study shall serve the following purpose:

- perform a programmatic analysis (cost, risk and schedule)
  - *Achieved: dedicated presentations and report chapters from Cost, Risk, Programmatics*
- propose P/L accommodation
  - *Achieved: starting point was Swedish Institute of Space Physics Proposal, elaborated during the CDF design sessions based on Instruments FoV considerations, accommodation issues, EMC constraints, …with study scientists, Instruments specialists and Instruments PI participating in all design sessions*

Study Objectives Achievement (2 / 2)

The CDF study shall consider the following design / trade-offs / analyses:

- Launch with A6.2 from Kourou (Soyuz) into initial target orbit, later transfer to 2nd and 3rd target orbits by S/C propulsion
  - *Achieved. A6.2 is the baseline launcher; compatibility with Soyuz is ensured (Launcher performance data and environment are taken from Soyuz UM)*
- Accommodation of P/L suite with consideration of EMC constraints
  - *Achieved. Accommodation of P/L suite and platform equipment have been revisited and amended (when necessary) according to EMC design rules*

Study Objectives Achievement (2/2)

The CDF study shall consider the following design / trade-offs / analyses:

- Radiation environment
  - *Achieved. Environment has been analyzed and appropriate shielding mass has been allocated in the mass budget; degradation of equipment and charging issues have been considered in the design*
- EMC aspects
  - *Achieved. Preliminary evaluation of magnetic moment of the spacecraft has been performed. Design choices have been oriented towards improving EMC behavior of the platform*

Study Objectives Achievement (2/2)

The CDF study shall consider the following design / trade-offs / analyses:

- Ground/Science operations with Scientist-in-the-loop
  - *Achieved. Assumption is that during standard routine science operations SOC submits burst-data dump requests/macros for instruments performance updates 2 hours in advance of the pass and an automated process in the MOC Mission Planning System integrates these requests into the command stack for the next pass.*
- Data download strategy
  - *Achieved. As per proposal: Survey data downloaded from the whole orbital period. Burst data downloaded through selective downlink. Data archiving and distribution at ESA.*

Further Study Areas (1/2)

The CDF study has highlighted the following areas for further study:

- **Wire Booms Dynamic** shall be investigated in later phases to ensure Orbit Transfer Manoeuvres (O1→O2; O2→O3) are performed appropriately (*MMS Heritage 12 degrees in ~1 hour Control thrust strategy on board; Thrust level: from 5 to 20 N; Manoeuvres with SAA 2.5 deg*)
- Bottom-up Magnetic Budget to be produced in order to confirm feasibility to meet the magnetic instrument requirements (top-down estimate for the allowed total magnetic moment of the spacecraft has been performed in the frame of the CDF THOR Study)
- 15m dish GS Availability is at stake: compatibility of the comms equipment to 35m dishes has been guaranteed. GS support in LEOP to be investigated for resource allocation (commercial assets?)

Further Study Areas (2/2)

- Radiation sector analysis to be iterated and refined when configuration will be consolidated and units procured
- 3-segment deployable boom concept baselined for THOR to be revisited based on the selected JUICE boom concept
- Ariane 6.2 performance and environment to be injected in the design as soon as available
- Shared launch was not considered appealing (mostly due to EMC reasons, but also for long eclipses deriving from orbital plane inclination) to be considered should cost become a driver (not the case for this CDF study)

Final Considerations

- THOR design is "**robust**", as based on conservative assumptions:
  - Comms *(and required power)* design based on usage of 15 m GS dish
  - "generous" radiation shielding, based on factor 2 on an environment which is well known
  - no GA maneuvers
  - redundancy scheme applied at subsystem level
- Room for improvement at mass level *(current design leaves ~500kg margin in Soyuz)*
- Few (possibly none) TDAs highlighted
- Mission and Spacecraft Risks identified, classified and mitigation proposed
- Cost well below cap