Gaia Design Considerations & Lessons Learned

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Fundamentals of Gaia: mission objectives

- To create the largest and most precise 3D chart of our Galaxy by providing positional and velocity measurements for about one billion stars:

  - Astrometry and Photometry for at least one billion stars (1% of the stars in the Milky Way)
  - Spectroscopy for about 150 million stars
  - One billion objects observed on the average 70 times over 5 years mission is 40 million stars a day (400 million measurements a day)
  - Orders of magnitude improvement w.r.t. Hipparcos

Fundamentals of Gaia: performance requirements

Astrometric

	B1V	G2V	M6V
$V < 10$	$< 7\ \mu as$	$< 7\ \mu as$	$< 7\ \mu as$
$V = 15$	$< 25\ \mu as$	$< 24\ \mu as$	$< 12\ \mu as$
$V = 20$	$< 300\ \mu as$	$< 300\ \mu as$	$< 100\ \mu as$

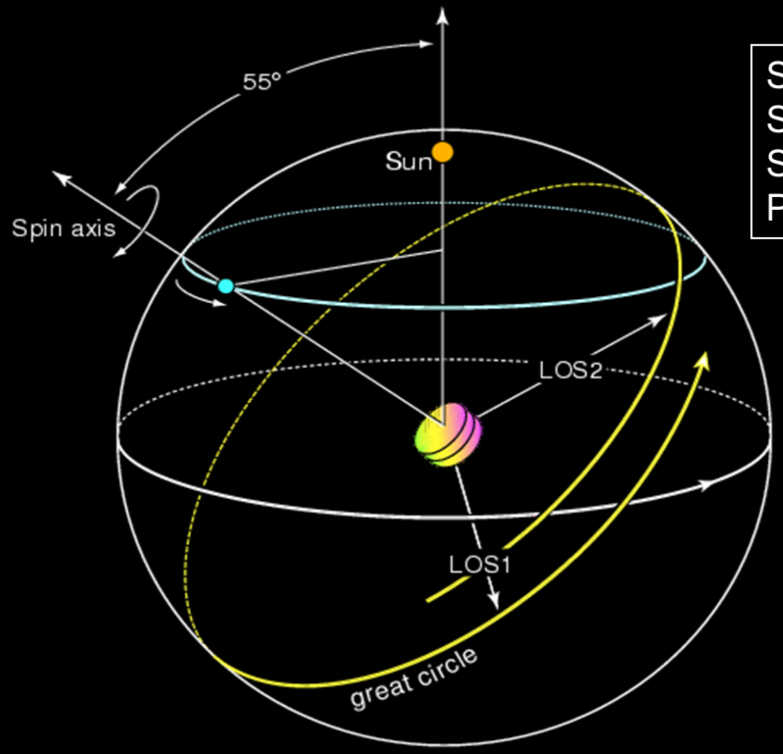
Radial Velocity

Stellar type	V (mag)	RV (km/s)
B1V	12	15
G2V	16.5	15
K1IIIMP	17	15

Photometric

Band	V (mag)	B1V (mmag)	G2V (mmag)	M6V (mmag)
C1M344	15	< 10	< 15	< 100
	20	< 150	< 1000	-
C1M410	15	<10	< 10	< 20
	20	< 60	< 200	<1100
C1M549	15	< 8	< 8	< 8
	20	< 120	< 120	< 120
C1M965	15	< 20	< 10	< 10
	20	< 400	< 150	<10

Fundamentals of Gaia: Sky scanning principle



Spin axis	45° to Sun
Scan rate:	60 arcsec/s
Spin period:	6 hours
Precession:	63 days

This revolving scanning:

- ❑ keeps the viewing directions at a constant angle to the sun (thermal)
- ❑ provides a fairly uniform coverage of the sky
- ❑ allows the details of the star motion to be identified

Gaia S/C Design

General considerations

The design of Gaia is driven by the payload:

- Two separate lines of sight, requiring an extremely accurate basic angle:
    - Basic Angle Monitoring device needed
    - Extremely stable environment (thermal, microvibration and particulate contamination), driving shape and material selection (minimise CTE using same material, avoid any mechanism, etc.)
    - Focal length of two telescopes, dictating S/C dimensions, number of mirrors and folding optics structure (FOS)

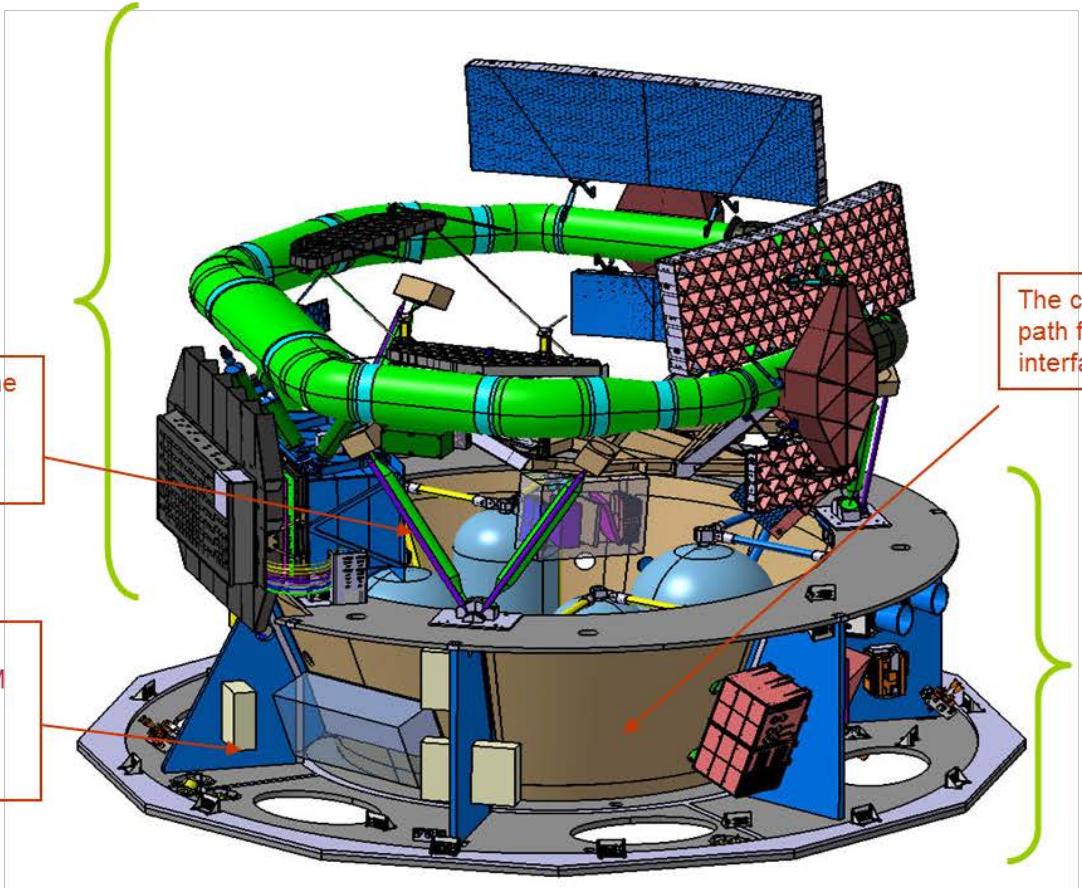
- Scanning law & TDI read out of CCD’s, requiring a spinning spacecraft:
    - Spinner requires spin symmetrical design, impacting all design aspects (e.g. comms, AOCS, propulsion)
    - Spinner and two apertures require large circular sun shield around the entire S/C

Gaia S/C Design: Spacecraft Configuration

Payload Module (PLM)

In-orbit bipods decoupling the PLM from the SVM after release of the launch bipods in parallel

Some PLM electronic units are accomodated in the SVM structure:
Video **P**rocessing **U**nits
Clock **D**istribution **U**nit

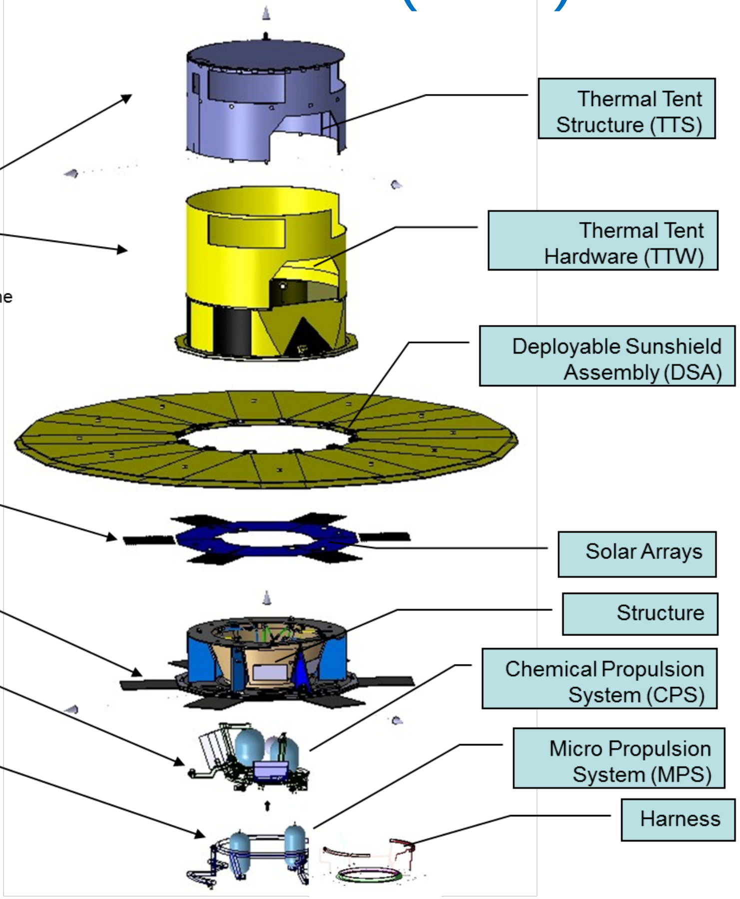


The central cone is the main load path from the launcher ring interface to the PLM bipods

Service Module (SVM)

Gaia S/C Design: The Service Module (SVM)

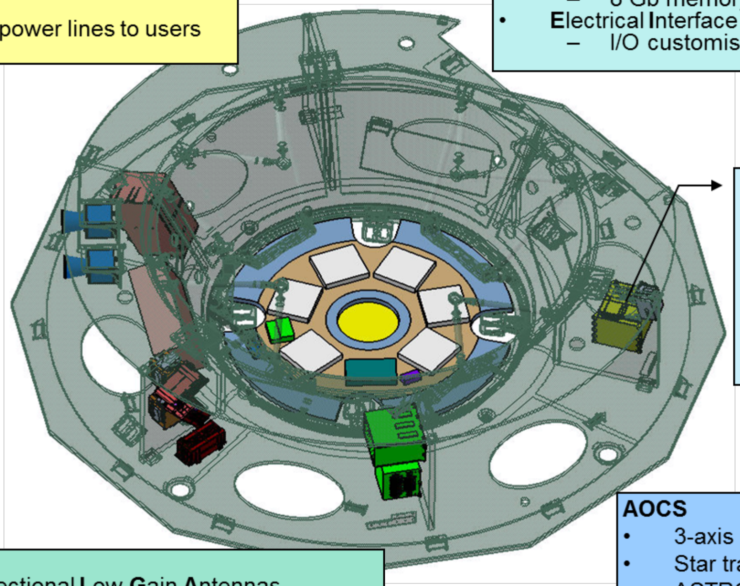
- The thermal tent provides a stable thermal environment and protects against micro-meteoroids ; it has large cut-outs for the instruments FoV and the FPA radiator
- The 10 m dia. sunshield is deployed in orbit to keep the PLM in the shade of the sun ; it has to be very flat and uniform, with an overall 0.2 deg flatness requirement
- The solar array has fixed panels and deployed panels mounted on the sunshield
- The CFRP SVM structure is mainly made of lower & upper floors, a central tube including the LV/IF ring, radial panels and a DSA ring
- Bi-propellant propulsion system with 8 x 10 N thrusters for orbit correction
- Cold gas micro-propulsion to perform stable attitude control
  [1µN – 500µN] thrust range
- The harness provides electrical connection between units for power and data management



Gaia S/C Design: The Electrical SVM

Power
- 73 Ah Lithium battery
- **P**ower **C**onditioning and **D**istribution **U**nit
  - 28 V regulated main bus
  - MPPT regulation of 1.9 kW solar arrays
  - Protected power lines to users

Data management
- **C**ommand & **D**ata **M**anagement **U**nit
  - ERC 32 processor (N+R)
- **P**ayload **D**ata **H**andling **U**nit
  - 8 Gb memory for mission management
- **E**lectrical **I**nterface **U**nit
  - I/O customised with SVM and PLM units

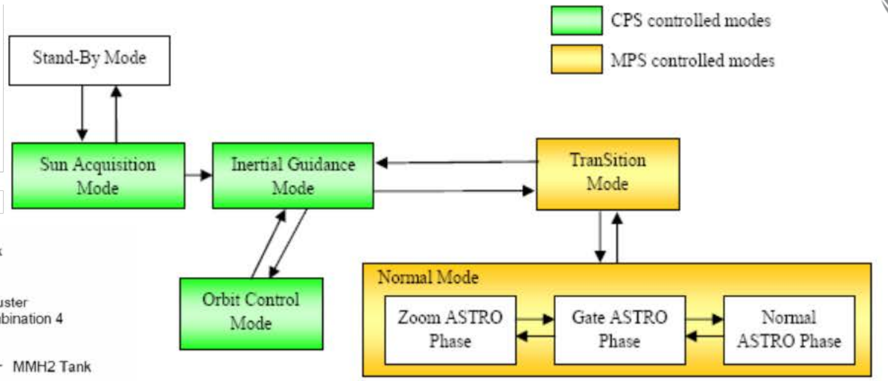


The electronic units are accommodated ortho-radially in the SVM cavities
Very stable power dissipation and avoidance of conductive thermal paths minimises thermoelastic distortion

X-band TT&C
- Three omni directional **L**ow **G**ain **A**ntennas
- **P**hased **A**rray **A**ntenna with up to 28 SSPA
  - No mobile parts, electronically steered beam
  - TM only, 4.8 to 8.5 Mbps
- Two X band TRSP

AOCS
- 3-axis control
- Star trackers/gyro/sun sensors
- ASTRO instrument in the loop for accurate pointing
- Thrusters and micro-thrusters for attitude control

Gaia S/C Design: The AOCS system



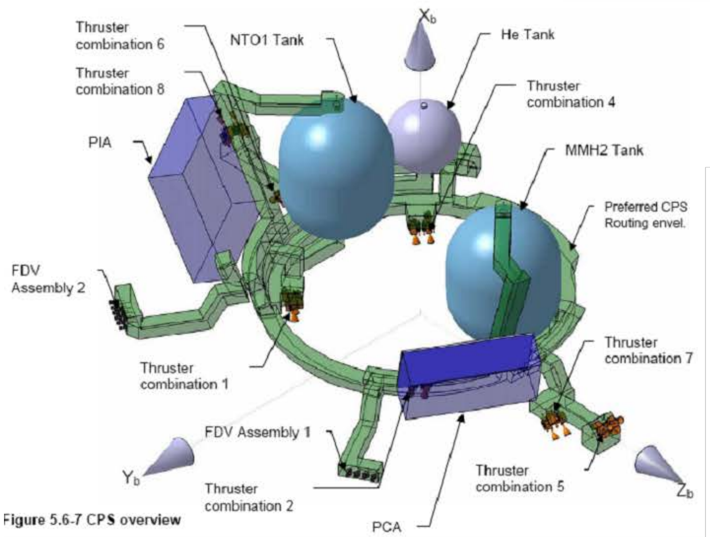
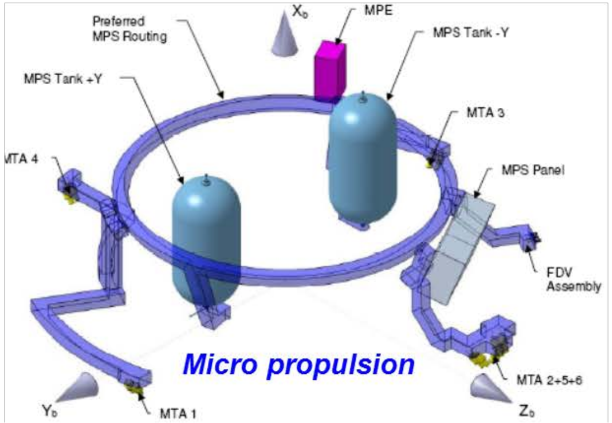


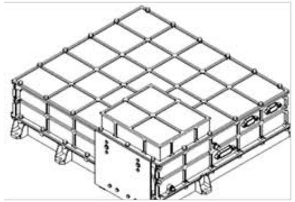
Figure 5.6-7 CPS overview

Chemical propulsion



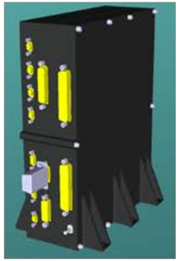
Gaia S/C Design: The Payload Module (PLM) [1]

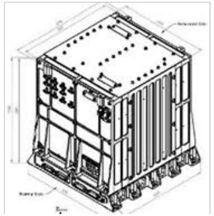
Units in the Service Module:



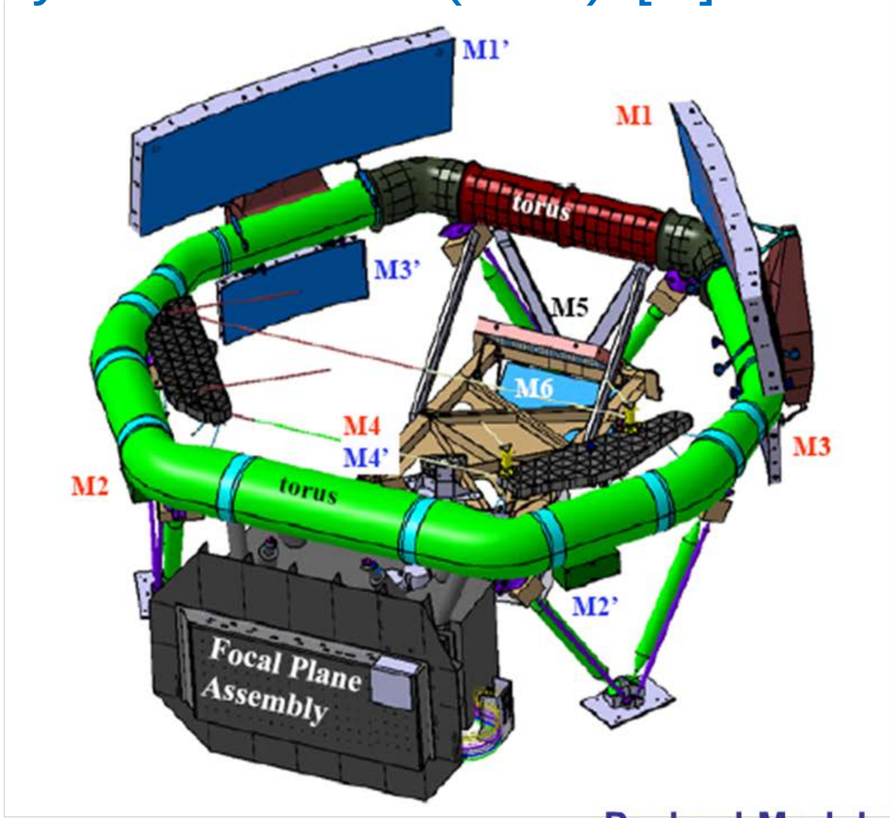
Clock Distribution Unit

Video Processing Unit (7×)





Payload Data Handling Unit

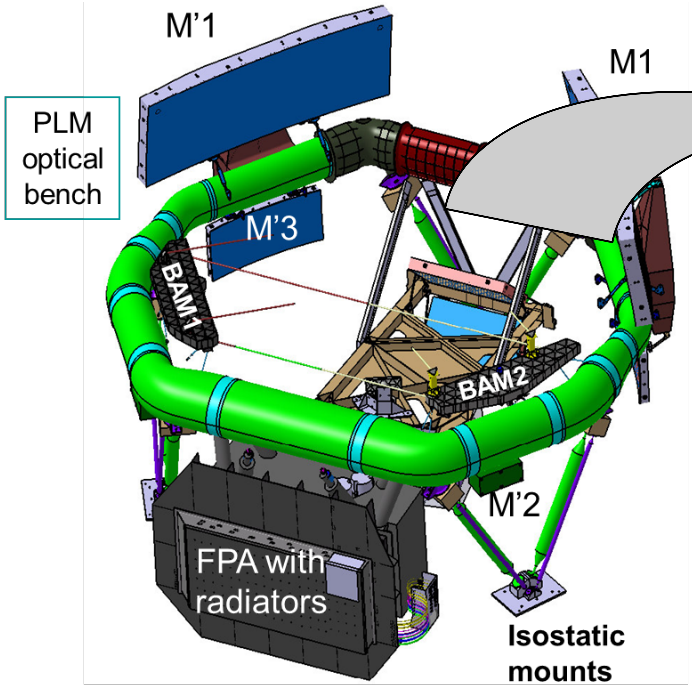


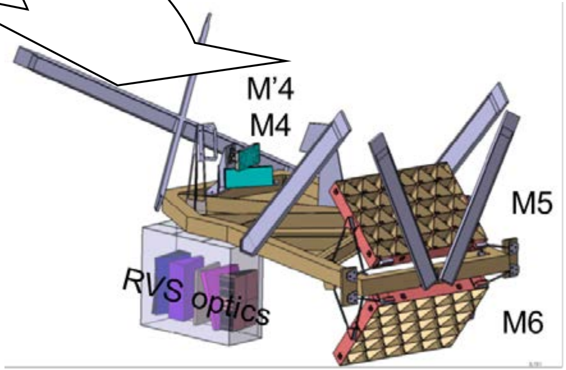
Payload Module

Gaia S/C Design: The Payload Module (PLM) [2]

A stable opto-mechanical design

- **Full silicon carbide architecture**
- **Passive thermal design**
- **Decoupling by release of launch bipods**

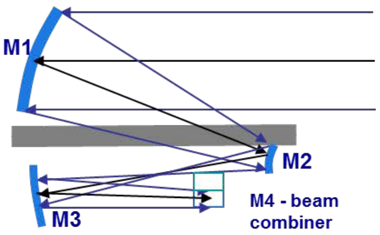




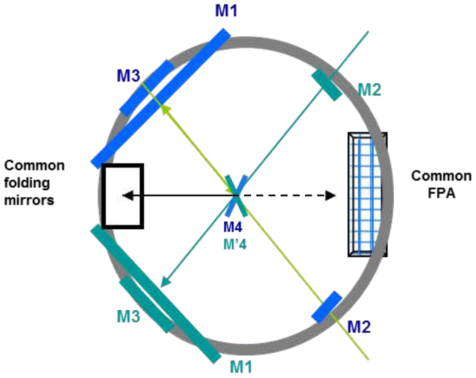
Folding optics structure with RVS optics

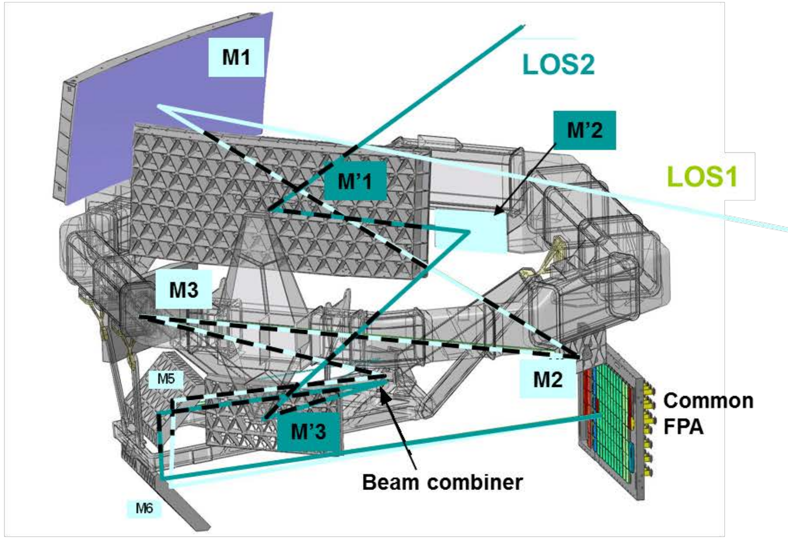
Gaia S/C Design: The Payload Module (PLM) [3]

Two telescopes combined on the same focal plane



- 2 Three Mirror Anastigmat telescopes M1-M3 aperture 1450x500 mm², focal length f = 35 m angular separation = basic angle
- Intermediate image used for field discrimination
- Beam combiner at their exit pupil => common FPA

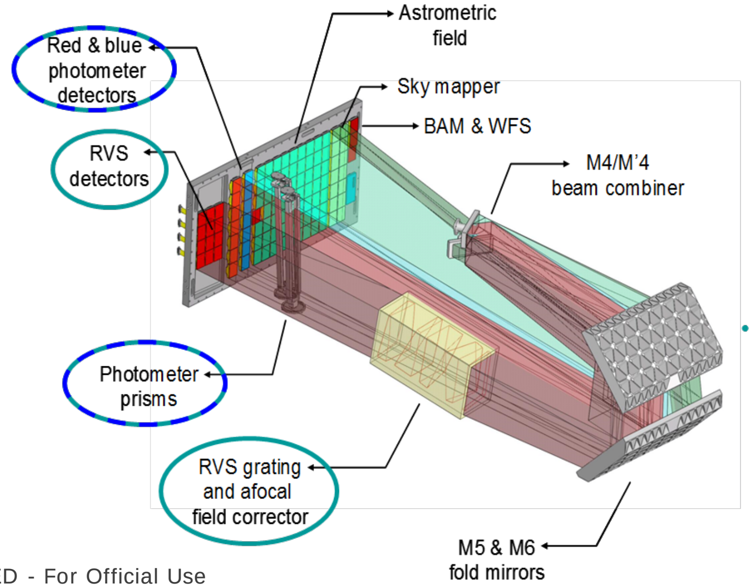




Gaia S/C Design: The Payload Module (PLM) [4]

3 instruments sharing the same Focal Plane

- Photometry & RVS: spectral dispersion is produced in the image space, in front of the focal plane
  => common detection & processing



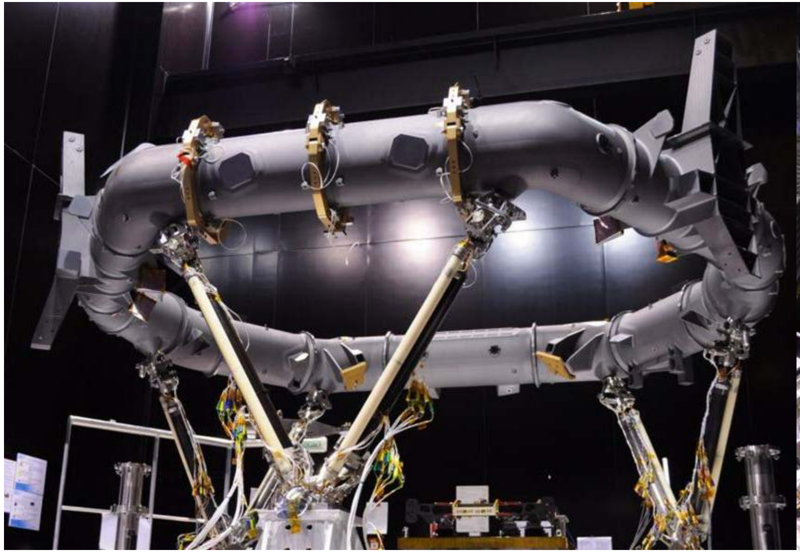
- Blue & red photometry
  with 2 prisms in the FPA
  & dedicated CCDs:
  - Chromaticity correction simultaneous to astrometry
  - Medium Band Photometry [330-1000 nm]
- Radial Velocity Spectrometer
  with grating & afocal corrector
  & 12 dedicated CCDs:
  - Spectrometry in [847-874nm]
  - Radial Velocity measurement

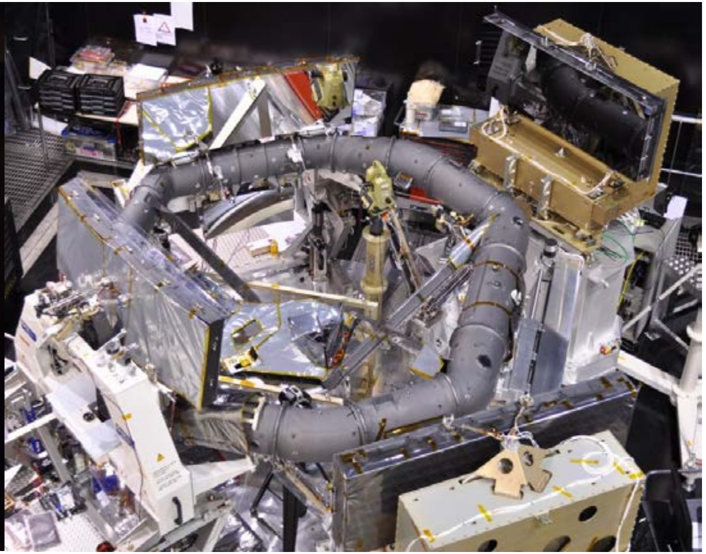
Gaia S/C Design: The Payload Module (PLM) [5]

The torus

- ❑ PLM load carrying structure in SiC:

- 17 segments brazed
- 3.5 meters diameter



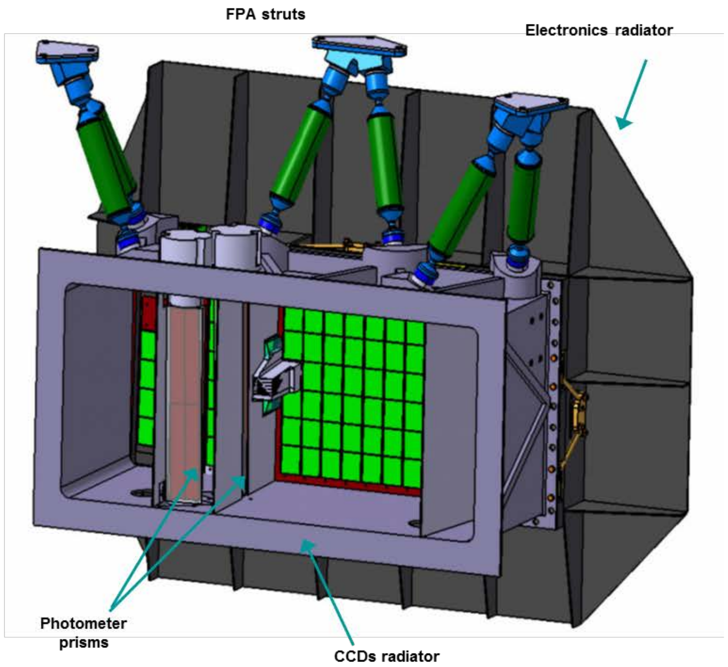


- ❑ Design activity critical due to novelty of material an many iterations required
- ❑ Segment manufacturing critical due to novelty of material and shape
- ❑ Final brazing in one go very critical due to the many interfaces
- ❑ Torus manufacturing was in the Gaia critical path

Gaia S/C Design: The Payload Module (PLM) [6]

Focal Plane Assembly

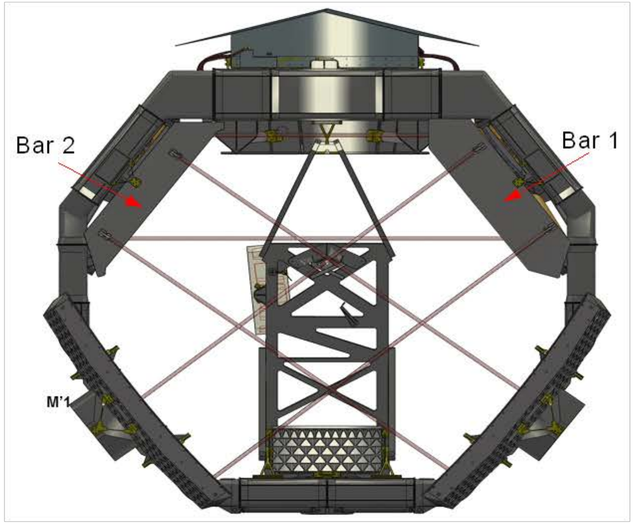
- A cold part at 160K for limiting CCD sensitivity to radiations
  - CCD support structure (CCDs & WFS)
  - CCD radiator supporting the Photometer prisms, shielding CCDs & acting as FPA primary structure
- A warm part for electronics
  - PEM linked with flexi-cables to CCDs
  - 7 IMs mounted on PEM rows
  - M2 Mechanism Drive Electronics
  - BAM & WFS Optical Sources & Electronics with their optical fibres
  - An external electronics radiators
- Bipods for mechanical mounting & thermal decoupling wrt optical bench



Gaia S/C Design: The Payload Module (PLM) [7]

Metrology: WFS, M2M & BAM

- Two Shack Hartman Wave Front Sensors measure the telescopes WFE, enabling their correction thanks to the 5-axes refocusing mechanisms (M2M) placed behind the secondary mirrors.

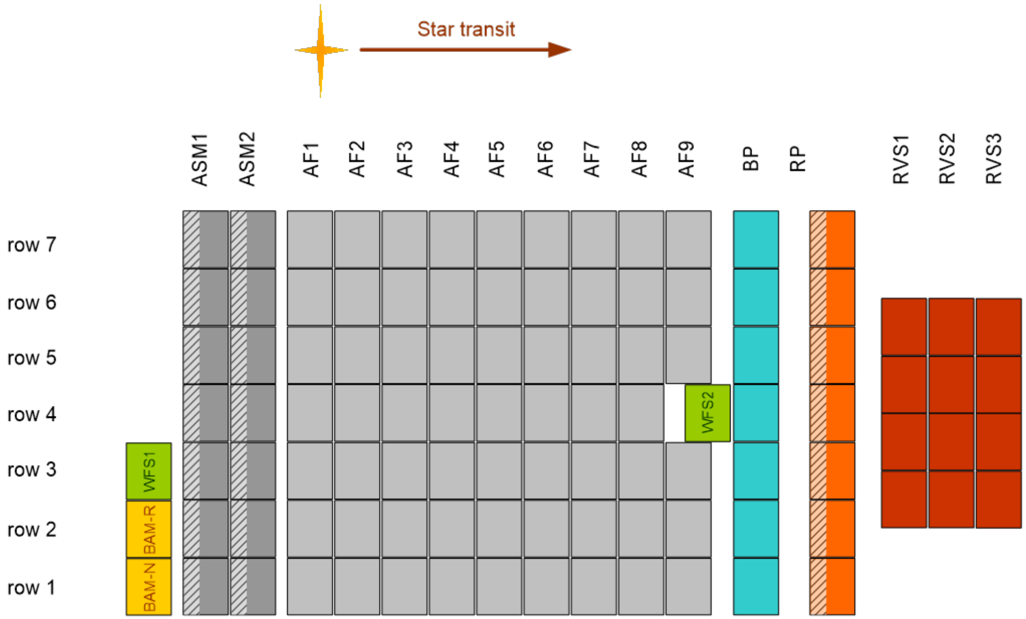


M1

- The Basic Angle Monitoring measures the stability of both telescopes lines of sight with 0.5 µas every 5 min.
  - from each bar: 2 laser beams illuminate each telescope
  - a pattern of fringes is measured on the BAM CCD

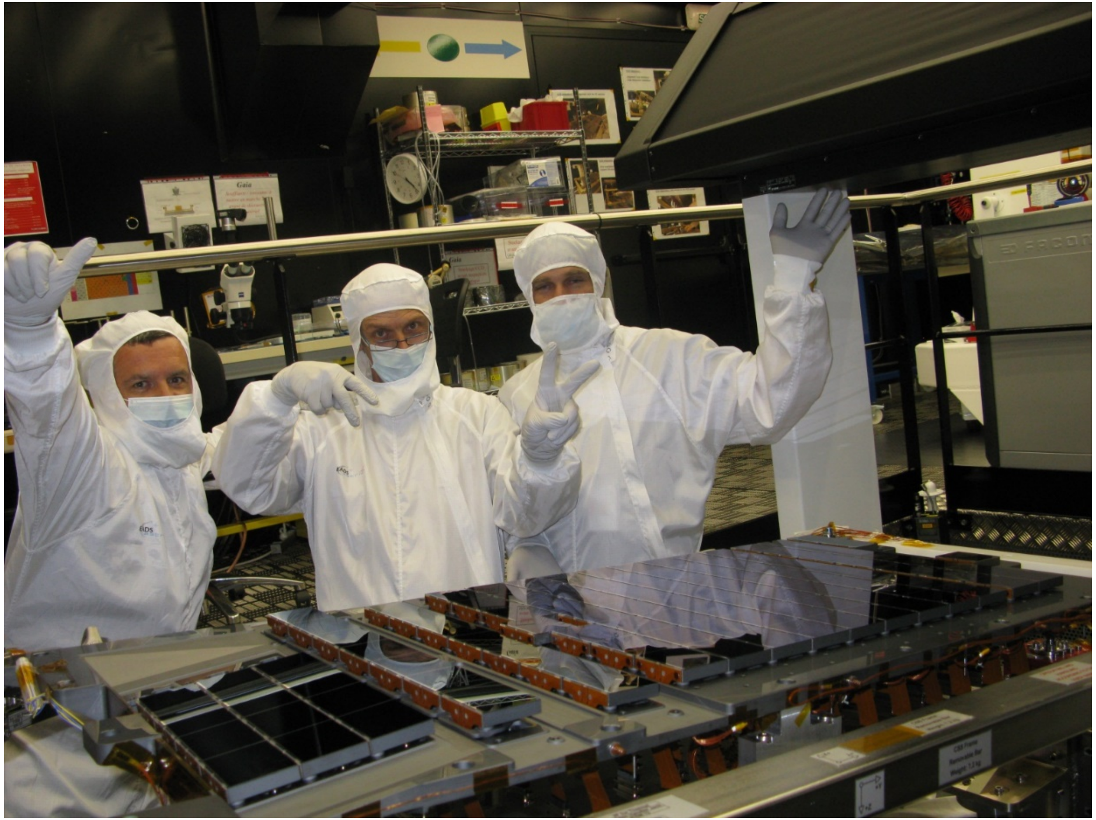
Gaia S/C Design: The Payload Module (PLM) [8]

The focal plane assembly : detection plane



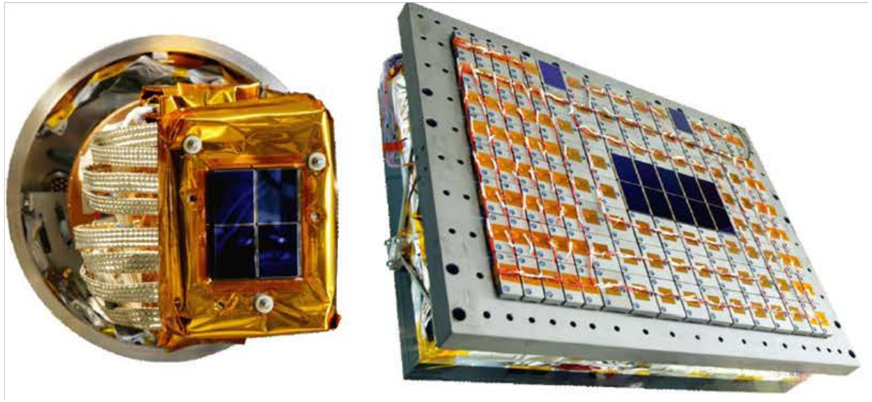
- ❑ Very complex and highly integrated focal plane (1.1 m × 0.58 m)
- ❑ 106 large CCDs of three different types (45 mm, 4500 pixels) × (59 mm, 1966 pixels)

Gaia S/C Design: The Payload Module (PLM) [9]



Technology Readiness: critical technologies

- **Data Handling**
  - compression algorithm
  - large size mass memory (~100 GB)
- **Detectors**
  - CCDs
  - front end electronics
  - radiation effects
  - focal plane demonstrator
- **Optics**
  - primary SiC mirror
  - high stability optical bench
  - radial velocity spectrometer concept
- **Micro-propulsion**
  - electrical
  - cold gas
- **Structure and Mechanisms**
  - deployable sun shield
  - precision focusing mechanism
- **Communication**
  - phased array antenna



Critical technologies: Mirrors

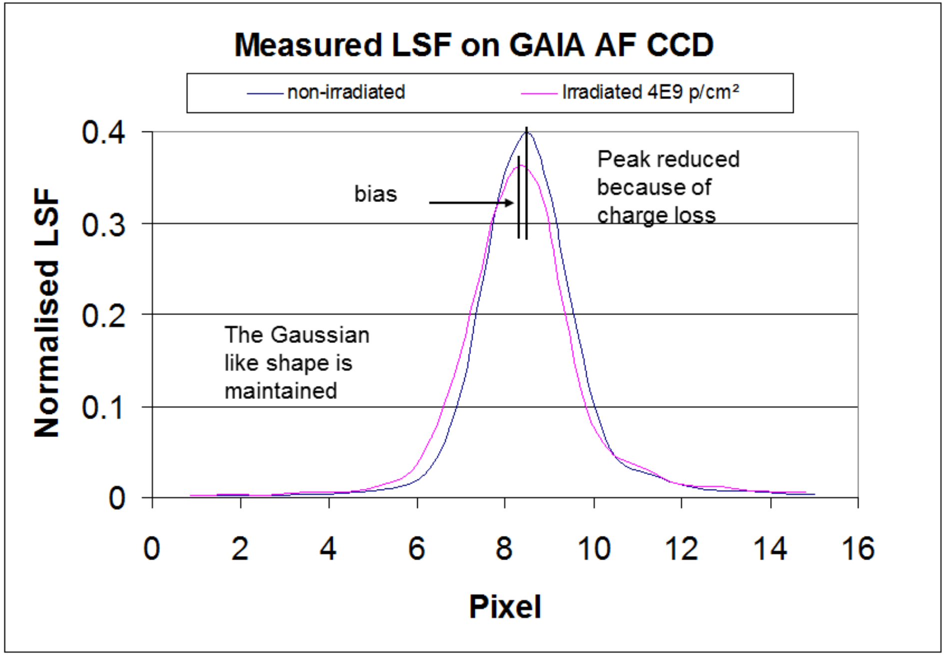
- ❑ Production takes a very long time, one year for the polishing related tasks only.

Critical technologies: radiation effect on CCD's

- CCD performance is progressively degraded due to the radiation accumulated in space, two effects are important:

Charge loss: total S/N is reduced due to electrons being trapped.

Star position bias: trapping and re-emission of electrons bias the star localization measurement.. Position bias is ~10 mas at EOL (0.16 pixel) for magnitude 15 and $4 10^9$ p/cm² irradiation level.

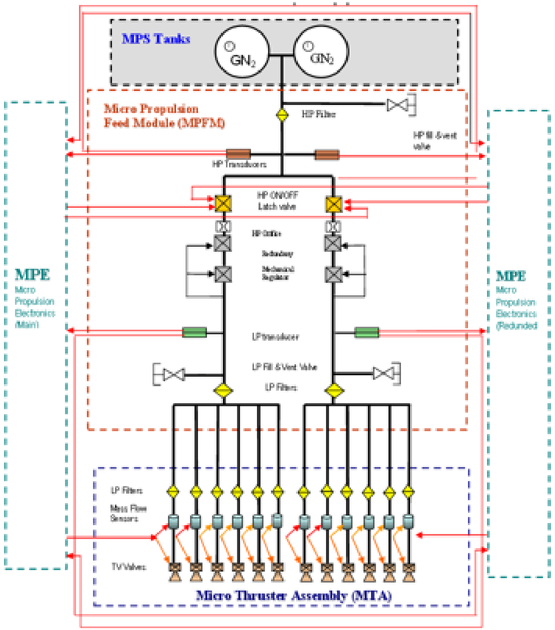


Critical technologies: Cold Gas Propulsion System

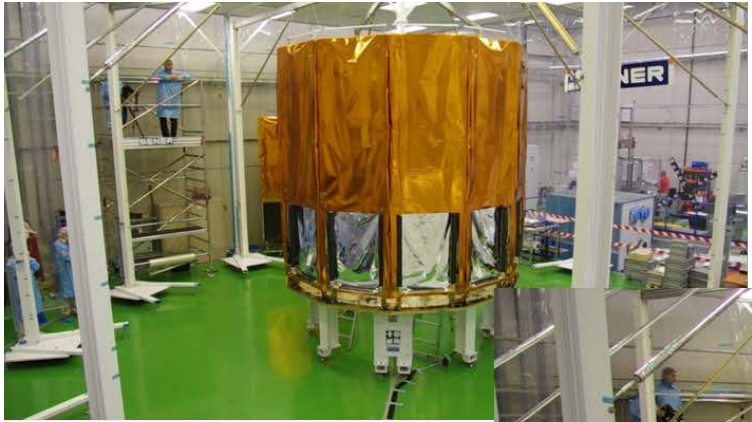
For high accuracy missions with a need for very precise compensation of small disturbances, such as solar radiation pressure, gravity fluctuations, micrometeorite impact, etc., cold gas propulsion systems can be used.

This cold gas propulsion system uses micro-thrusters propelling nitrogen gas to remain perfectly stable and point with the required extreme accuracy: To avoid disturbing the payload measurements, the thrust has to be in the order of one microNewton up to 1 milliNewton.

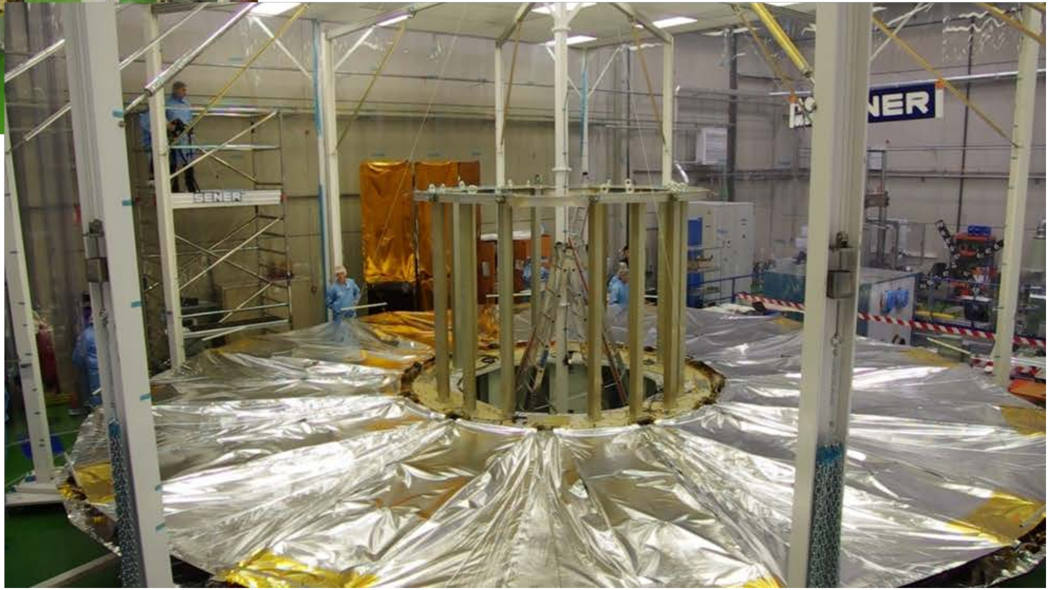
To put this into perspective, 49 thrusters would be required, operated at their maximum thrust, to lift up a single 5g A4 size paper sheet



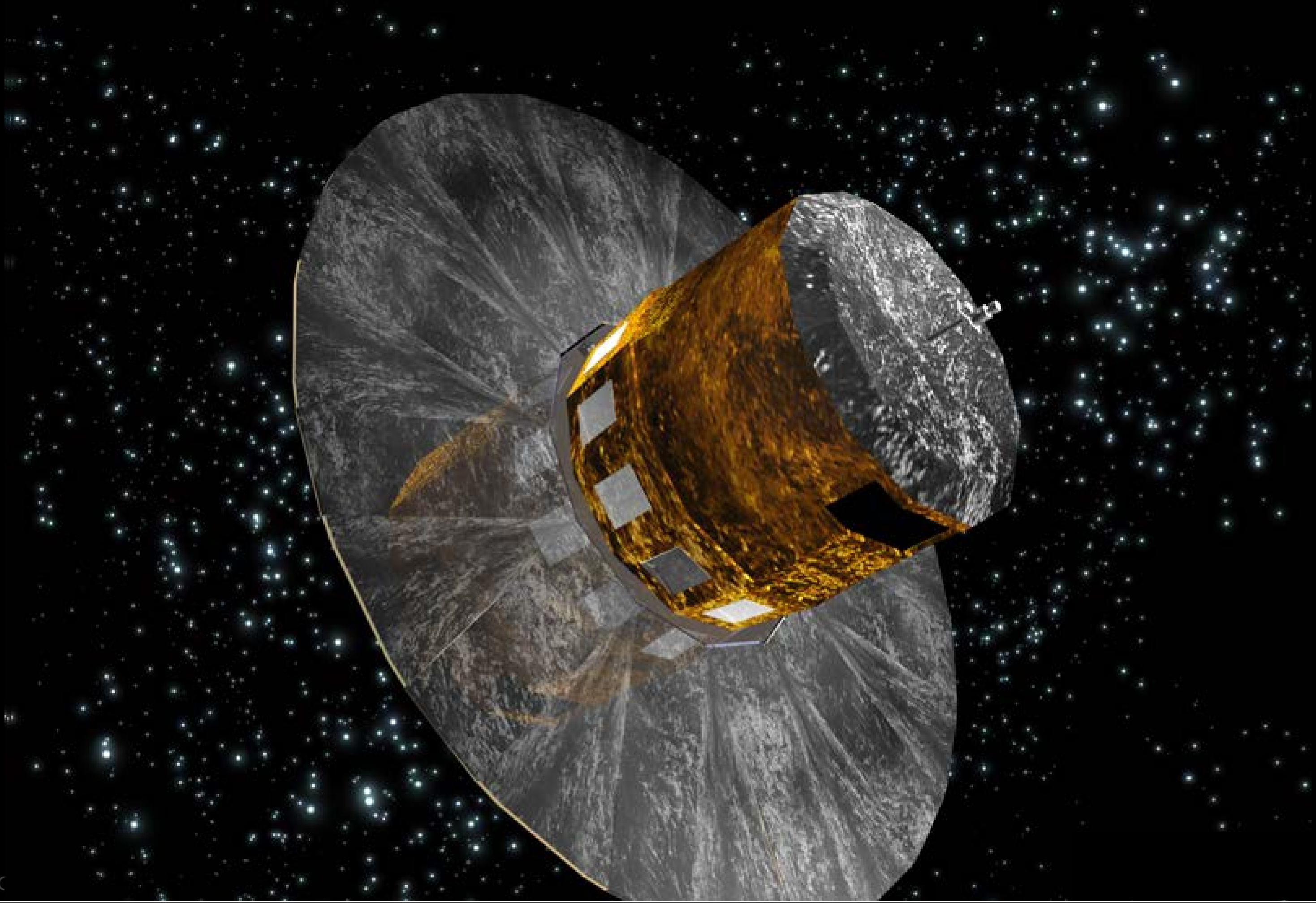
Critical technologies: Deployable Sunshield (DSA)



Stowed



Deployed



Main Lessons Learned (1)

The following are some of the Gaia lessons learned that are good to keep in mind:

Generic:

- Special care at start of definition phase shall be paid to requirement documents: poorly written or unnecessary requirements can result in major cost contributor. Critical review of requirements shall be a priority in study phase, involving project teams that have experience with similar missions
- Do not underestimate the impact of accuracy requirements at the limit of technical capability: verification of these requirements is very difficult and costly or sometimes even impossible (due to limitations of test facilities or environmental disturbances that are greater than the value of parameters to be measured)
- clearly plan how to test requirements that cannot be directly measured on ground. Understand the impact of testing compromises
- For mission critical performance, such as Basic Angle Variation, an independent party shall model and verify the expected parameter's behaviour, to minimise the risk of (modelling) errors
- For critical electronic units (e.g. the transponder) have a qualification model which can be used later for debugging issues of the FM. Keep in mind that an EM is never truly representative as it always is the results of compromises
- Payload integral part of S/C: allowed for efficient AIT sequence rather than PI led payload procurement. This is mainly due to the fact that Gaia is built around the payload: it's not a bolt on instrument that can "easily" be procured by third party

Main Lessons Learned (2)

TT&C

- Early test of transponder EM with Ground Segment very valuable (identified spurious issues and problem with Gaia phase noise/GMSK demodulation in Coherent Mode)
- RF suitcase best to incorporate CDMU Engineering Model or functional breadboard to drive Transponder
- Mission Timeline shall allow for ample margin in number of telecommand capacity, especially for long autonomous operation timeline uploads. Gaia was limited to 2400 TC's, which required cumbersome workarounds in order to upload multi day sequences

Software:

- To improve the fidelity of the software validation facility (SVF) and to maintain tests on the real HW, especially where the SVF lacks of representativeness
- Stress tests to the SW proved a good tool to unveil operational faults or mission inefficiencies
- Data traffic scenario to be agreed early, and kept up to date by project/prime with Operations & Science involvement as it will be used to drive budgets, SW design/sizing and mission tests
- Flexibility is needed to adjust the SW development plan during the development
- Include comprehensive end-to-end tests on the complete SW (after the incremental development) and to increase the number of operational test scenarios

Main Lessons Learned (3)

Thermal Control:

- To be extensively stressed during TVAC and simulations
- TVAC to be performed at S/C level (if possible)
- TCS to be modelled in SVF and Operational Simulator to maximise verification and validation
- Test scenarios shall also focus on identifying wiring errors (swapping of heaters, etc.)

Electrical

- SpW grounding specifics to be optimised and agreed early
- Double insulation to be tackled early in design phase and monitored throughout development of unit and at S/C level
- Strict review at PDR and CDR (absolute latest) for Part Stress Analysis/Worst Case Analysis & Radiation analysis/resulting circuit provisions.

Main Lessons Learned (4)

Mechanical

- If there is a deployment mechanism (DSA in Gaia) carefully verify the torque margin and have enough margin in particular for the non motorized approach. Properly trade off the passive deployment versus the motorized deployment
- The structural verification approach and test results need to be approved by the launcher authority: an early involvement in the definition and information about possible changes is profitable and can limit the repeating of tests (allows timely implementations of constraints from the launcher authorities in analyses, test definition and test results)

AOCS and Propulsion:

- Gaia AOCS innovative as it used the payload star mappers integrated into the AOCS in order to meet the very stringent AOCS requirements. Relevant spacecraft and payload activities need to be harmonised
- CPS is integrated very early on the structure which is then delivered to the prime with hundreds of wires for the propellant lines thermal control. Later, the power S/S responsible is supposed to connect them to the correct PCDU LCLs. If the wires are not well labelled or if the definition of the connections is not coordinated or maintained, the connection becomes complex and time consuming
- MPS: (1) allow for cross strapping of MPE's
  (2) test in operational conditions and perform long duration test to identify issues such as MFS offset drift
  (3) allow for calibration in operational conditions (avoid interrupting science observations)
  (4) Gaia LL implemented on MPS system for Microscope, LPF and Euclid for more robustness

Main Lessons Learned (5)

AIT:

- Test in relevant environment: a lesson learnt from the problem encountered in Kourou: an oscillation on the power lines was found once all the thrusters were operating and could reach their operating temperature. TBTV test scenarios shall cover the full in flight temperature range for a sufficiently long duration, to ensure reaching thermal equilibrium: this will lead to on/off toggling of heaters, which can induce disturbances on the electrical system
- In the MPS case, relevant environment should cover temperature, fluidic supplies (He vs GN), presence of the full MPS system (all thrusters connected to the electronics and operating at the same time) and presence of vacuum (wherever possible)
- Emphasis on operational and system wide end-to-end tests
- During AIT, support from the S/C engineering team is crucial to ensure an efficient transfer of knowledge, treatment of anomalies and test result handling.

Validation & Verification:

- Very useful to put in place a working team on the verification matrix to ensure it is always up to date and ready to support major reviews. This was very useful for Gaia and prevented the usual rush at CDR & FAR and allowed for a proper requirement verification, rather than a formality

gaia is operating successfully

The considerable technical challenges Gaia faced were successfully overcome resulting in the first data release, which is heavily used by the scientific community

Milky Way view and neighbouring galaxies, based on first year of Gaia science data