Gaia Flight Operations Experience

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D. Milligan / Gaia Spacecraft Operations Manager

gaia

Presentation Plan

esa

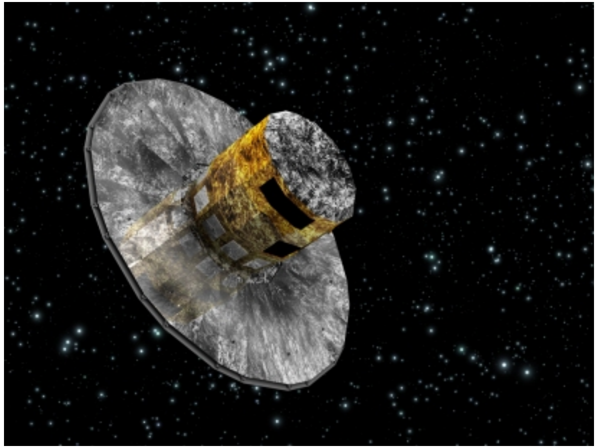
- **Gaia Mission, Spacecraft and Ground Segment**
- Mission Phases
    - Launch, LEOP and Transfer
    - Commissioning
- Some challenges and what we learned
- Gaia's ultra stable performance
- Precision time
- Rate stability & clanks
- Thermal stability
- Conclusions

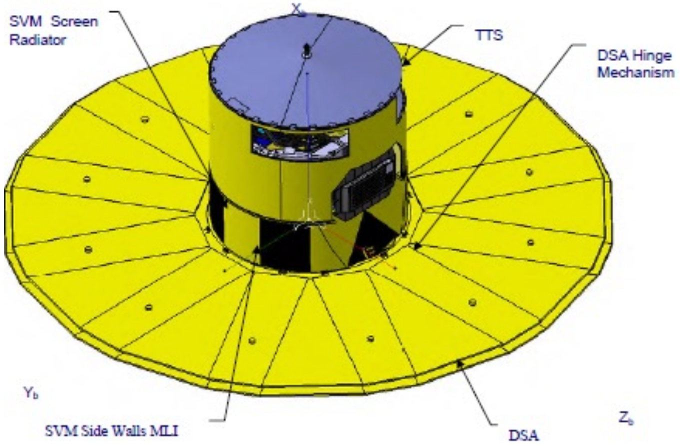
The Gaia Scientific Mission

- Produce a map of 1 billion stars (Vmag<=20)
- High Accuracy (based on Hipparcos principles):
  - Astrometry (position typically 10’sμas, a (euro) coin on the moon)
  - Photometry (luminosity, chemical composition etc)
  - Spectrometry (Radial velocity).
- Each star 70 times in 5 years (The Hipparcos Star Catalogue in 3 minutes)
- 3D map of our galaxy – gives structure, history (dark matter), but includes asteroids to Quasars.
- 100,000’s Object Discoveries expected including exoplanets, brown dwarfs.
- Test of general relativity

The Gaia Spacecraft

- Launch mass ~ 2 tonnes
- Designed around the Payload Module (top of Conic Structure ø3.2m)
- Optical Telescope with two FoVs, Torus structure of SiC
- Service Module (lower Conic Structure)
- Deployable Sunshield Assembly (~10m diameter deployed)



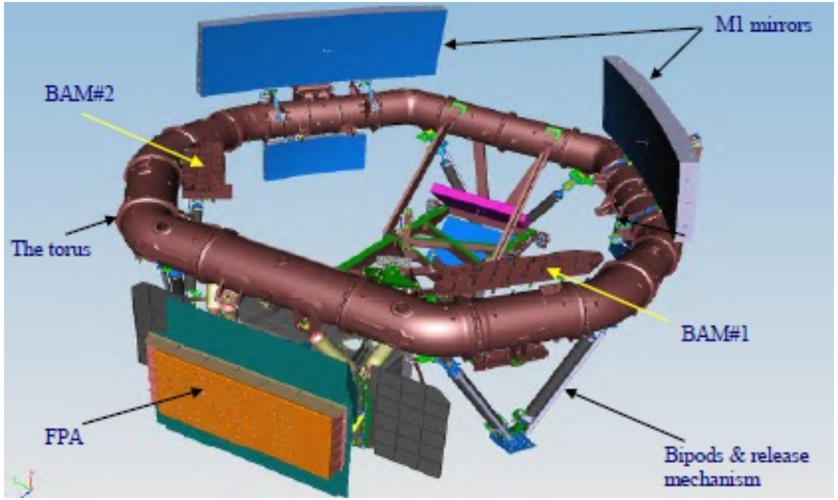


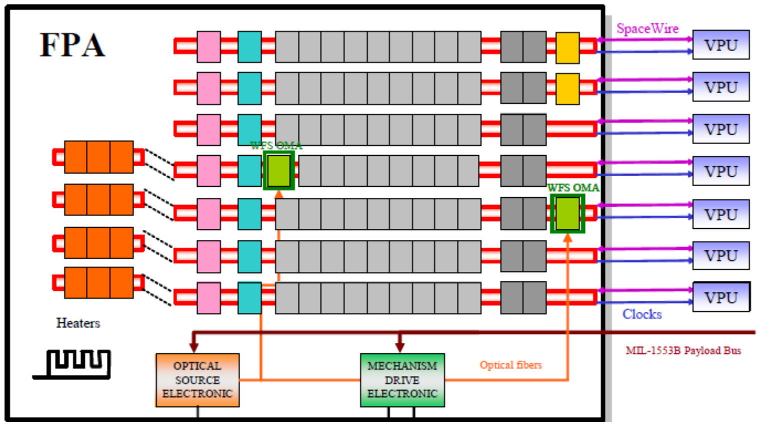
The Gaia Spacecraft – bespoke units

- Two Propulsion Subsystems:
  - Chemical – MMH MON, 2x8 10N thrusters for orbit maintenance
  - **Micro Propulsion – Cold Gas (N_2) 2x6 (1μN to 1mN) for attitude control**
- AOCS sensors
  - Fibre Optic Gyros, Sun Sensors, Automatic Star Trackers
  - **Payload in the loop (rates) in science mode**
- Communications
  - X-band U/L (low 125bps, med 4kbits), D/L (low 62.5bps-16kbps, med 250kbps, high 4.3-8.7Mbps – 6 rates selectable)
  - **Phased Array Antenna** with GMSK with Concatenated Convolutional Punctured Coding

The Gaia Spacecraft - PLM

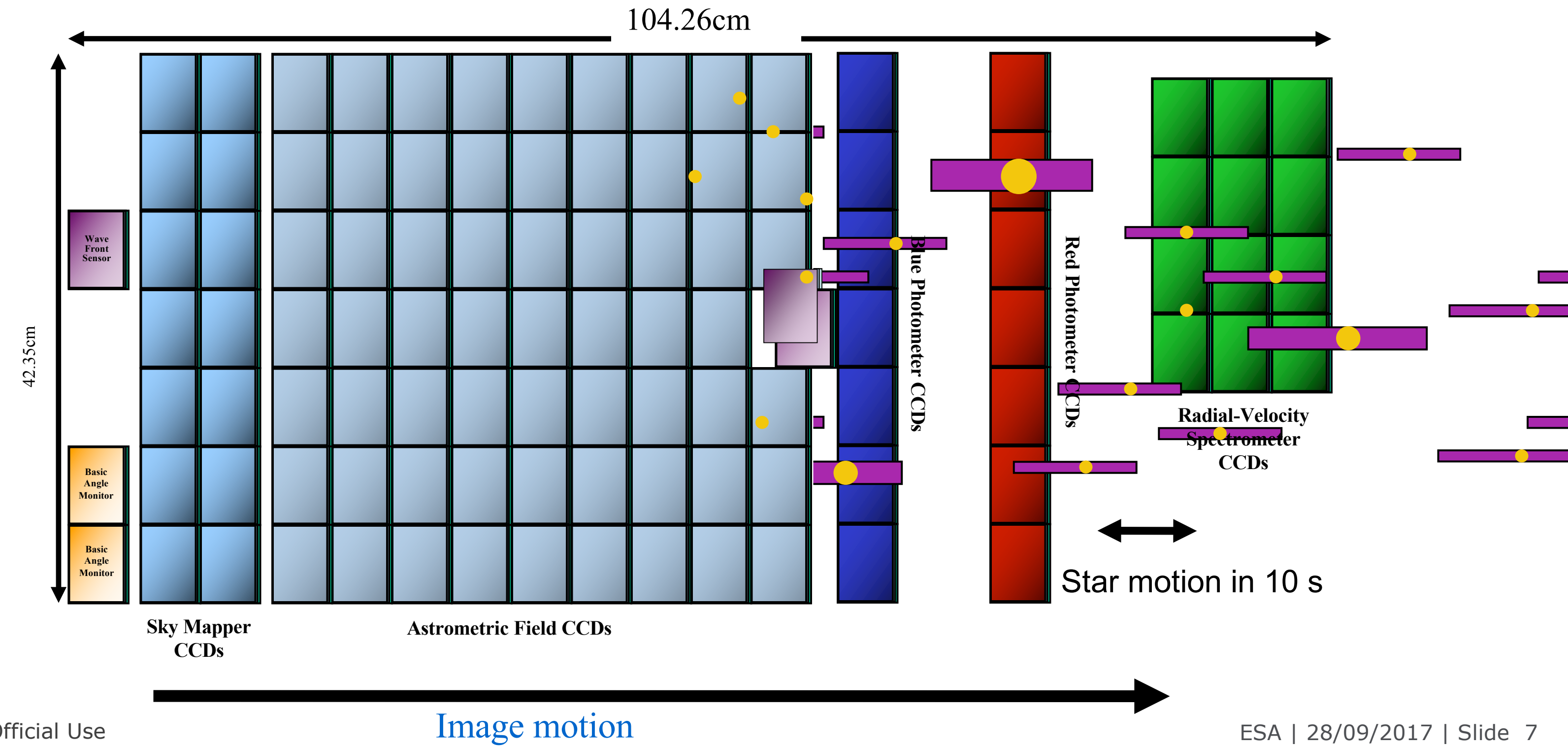
- Light from **FoVs focussed by a series of mirrors** onto **Focal Plane Assembly** (**106 CCDs** in an array of ~ 1 billion pixels)
- CCDs read in TDI mode – binning matches star transit rate
- **Rubidium Atomic clock** used for onboard time (1.6uS end-to-end TCo requirement)





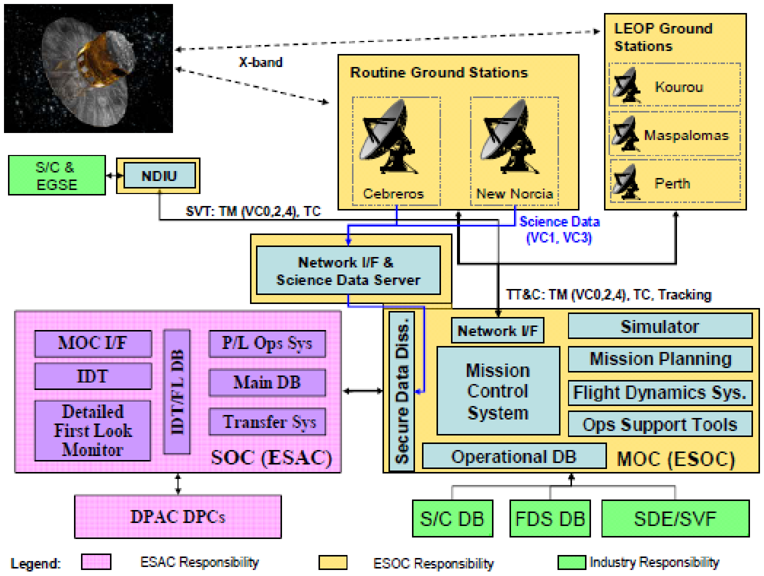
The Gaia Spacecraft - PLM

106 CCDs , 938 million pixels, 2800 cm²



Gaia Ground Segment

- MOC (ESOC): Mission Control System (MCS), first ‘science kernel’ mission based on S2K V5
- Mission Planning System (including D/L modelling and data driven scheduling)
- Flight Dynamics System, including ground based optical observations for orbit determination (150m, 2.5mm/s). Use of DDOR.
- Ground Stations, 35m deep space network:
  - New Norcia, Cebreros, Malargüe
- Science Operations Centre (SOC) ESAC
- Data Processing and Analysis Consortium 9 units (DPAC)
  - Largest Computing Project in Astronomy to date



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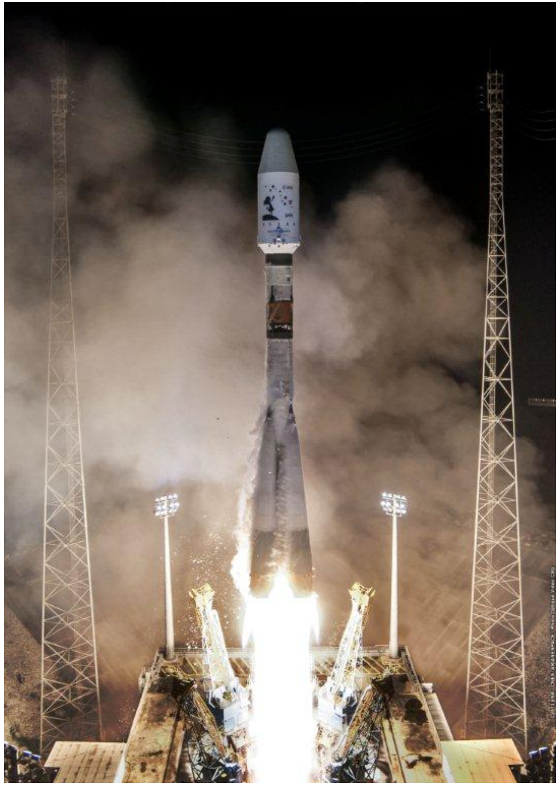
Launch & Manoeuvres

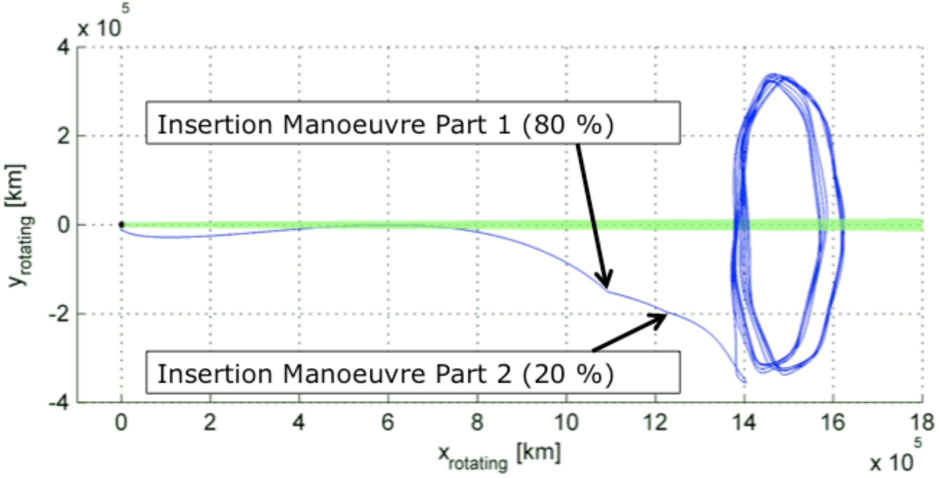
- **Launch** 19-Dec-2013, 09:12:19z
- **4 day LEOP**
  - First signal acquisition auto sequence monitoring
  - Attitude acquisition and sun shield deployment
  - Prepare and execute day#2 manoeuvre (23.5 m/s)
  - Start commissioning (power allowing)
- **L2 insertion** part 1 after 19 days, 7 days later second part (166 m/s total). Excellent performance (thrust vectoring)



Lift-off on Soyuz from Kourou, CSG – courtesy of Arianespace

Transfer Commissioning

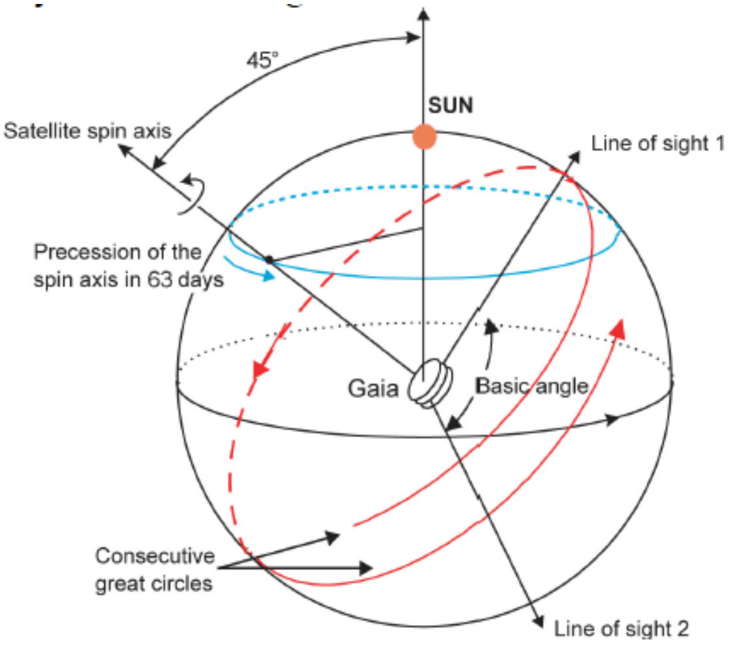
- During the transfer (19 days to first insertion manoeuvre) the more complex spacecraft units and modes gradually exercised.
- Systematic check-out of redundant units not done
  - Backup units checked when prior knowledge of failure would lead to changed FDIR
  - Critical redundant units tested out of the loop (e.g. CPS)
- During transfer various units commissioned (CDU, PDHU. MPS etc).
- Power reduced to decontamination – other more power demanding units brought online
  - Phased Array Antenna
  - Telescope Focal Plane Assembly



Iterative Telescope Commissioning

- Focal Plane Video Processing Units have thousands of configuration parameters

- The telescope is part of the AOCS control loop
  - The atomic clock pulses are used to time the CCD data extraction
  - The spin rate must be precisely aligned for this 'TDI' to work
- The telescope must be finely focussed – ground command to mirror motors
  - but changes focal length – changes star rate
- Iteratively
  - Change focus, adapt parameters, change S/C rate
- Performed with a dedicated attitude scan law – Ecliptic Pole Scanning (multiple scans of well known parts of the sky)
- Commissioning completed by June 2014



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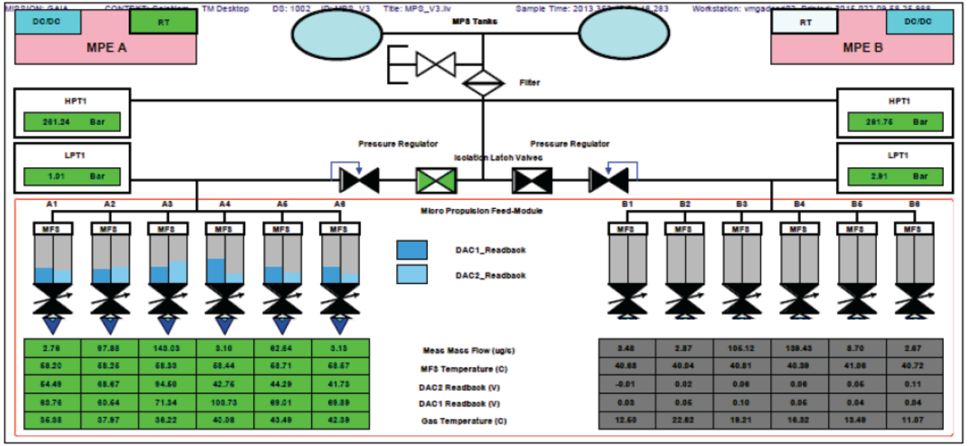
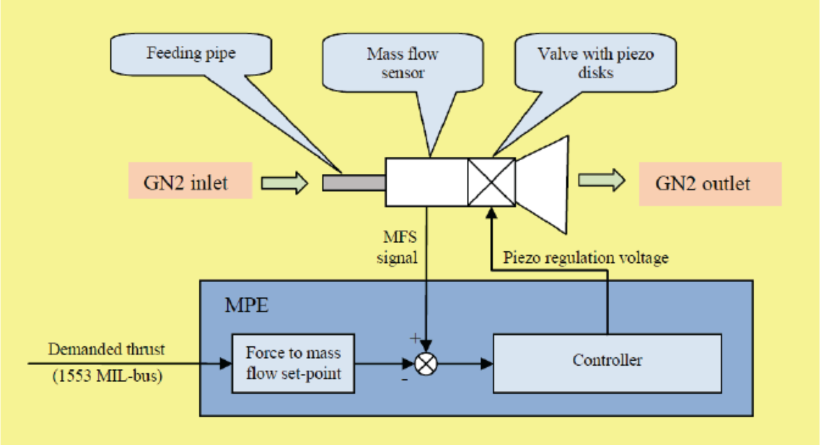
Some Challenges (MPS examples)

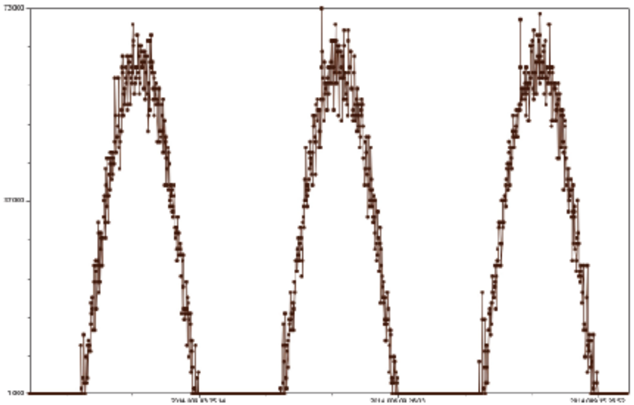
- Occasional LCL tripping in flight (x2 in 4 years)
- Partial unpowering of thruster circuits (SEU/ESD) - Erratic thruster performance → S/C safe mode
- **Fixed by new autonomy** (On Board Control Procedure – resets LCL before the S/C over-reacts!)

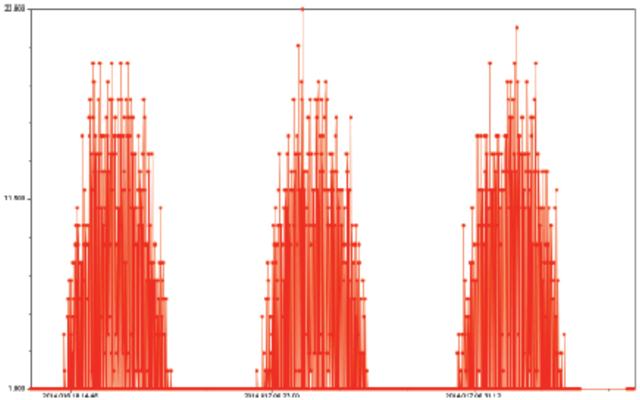




Some Challenges (MPS examples)

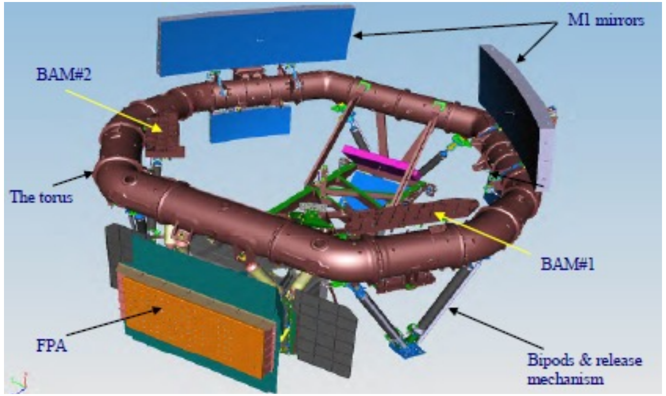
- After L2 insertion – thruster 3 showed anomalous thrust (cx7)
- Control stabilised but not good enough for fine performance
- A non functioning heater in a mass flow sensor – but with the scale factor and bias change in the main SW full functionality recovered
- Main SW had **configurable parameter** to work around the problem (no SW patch needed)

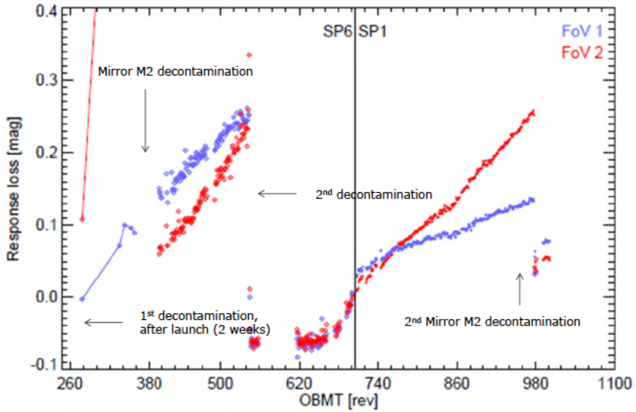




Some Challenges (PLM example)

- After telescope first light – **dimming seen** seen first on the Basic Angle Monitor laser interference pattern – then confirmed on the stars themselves.
- Contamination by water ice.
- Periodic re-activation by ground of the decontamination heaters removes the problem, period between operations increasing (possibly last operation now performed)
- Mirror re-focus operations also performed





Some Challenges (ground example)

More science data!

For several reasons (telescope ice mitigation, **better telescope performance**), more data generated **(+ c45%).**

More ground station time possible – but operations concept needed changing (controller team not large enough)

Solution – move rapidly to more automated operations: implemented with onboard link protection (Nov 2014)

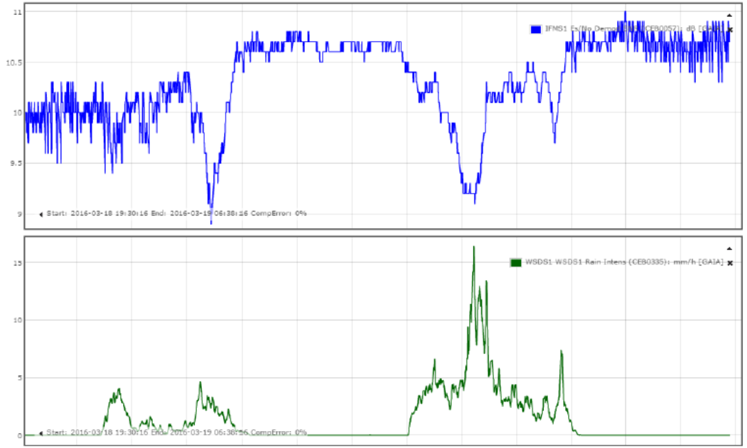


Fig. 7. Rain effects on the signal to noise ratio as measured at the ground station. Rain intensity on the bottom view (mm/h), Signal to noise ratio on the top view (dB)

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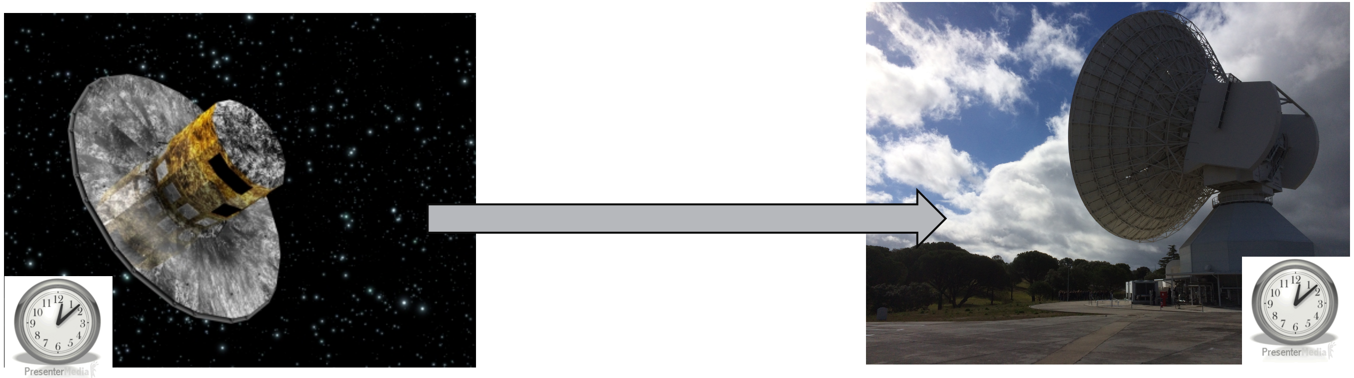
Timing (1/4)

- End-to-end <u>scientific</u> time correlation accuracy req: 1.6uS
- Gaia has an on-board atomic clock
- The Ground Stations have MASERS, checked against GPS time
- End-to-end <u>operational</u> time correlation accuracy req: 1ms



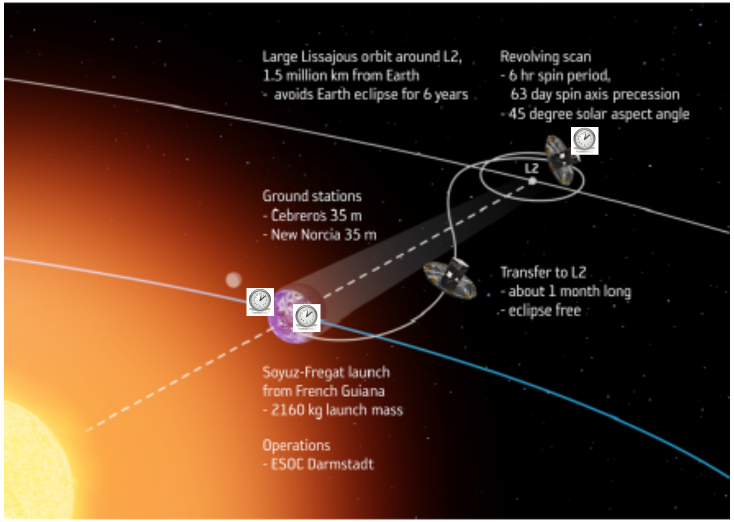
Timing (2/4)

- Basic Principles of Time Dilation
    - Kinematic Time Dilation - Diurnal
    - General Relativity – includes acceleration and gravity (gravitational potential) – Long term ’drift’ Gaia’s clock c 0.1s ahead after 5 years
- Perfect clocks at the ground station and at Gaia run at different rates

$$T = \frac{\tau_G}{\sqrt{1 - v_G^2 c^{-2}}}$$

$$T = \frac{\tau_G}{\sqrt{1 - 2U_G c^{-2}}}$$

$$\text{where } U_G = \frac{G\,M}{r}$$



Timing (3/4)

- Time correlation (uncorrected relativistically)
  - Short term diurnal effect clearly visible
  - Not possible to monitor onboard clock health
  - Not possible to identify timing problems on the ground

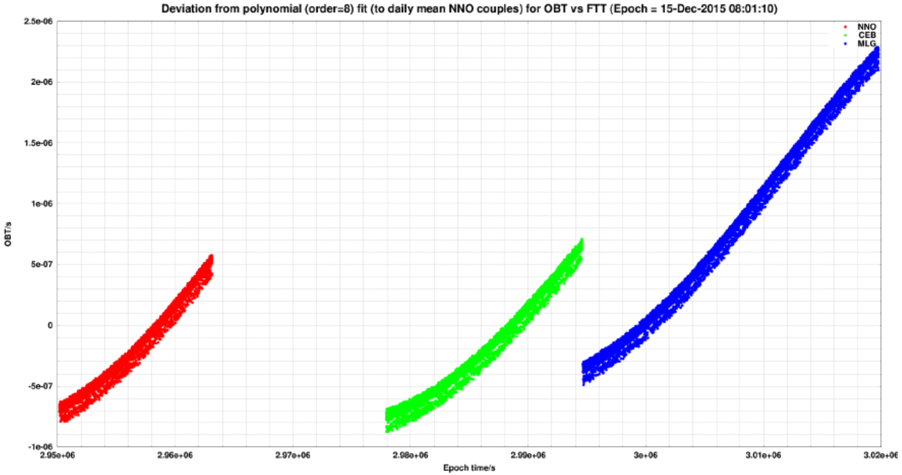
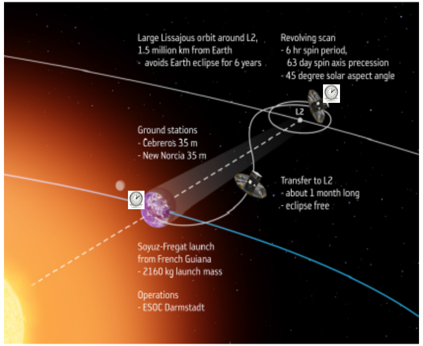
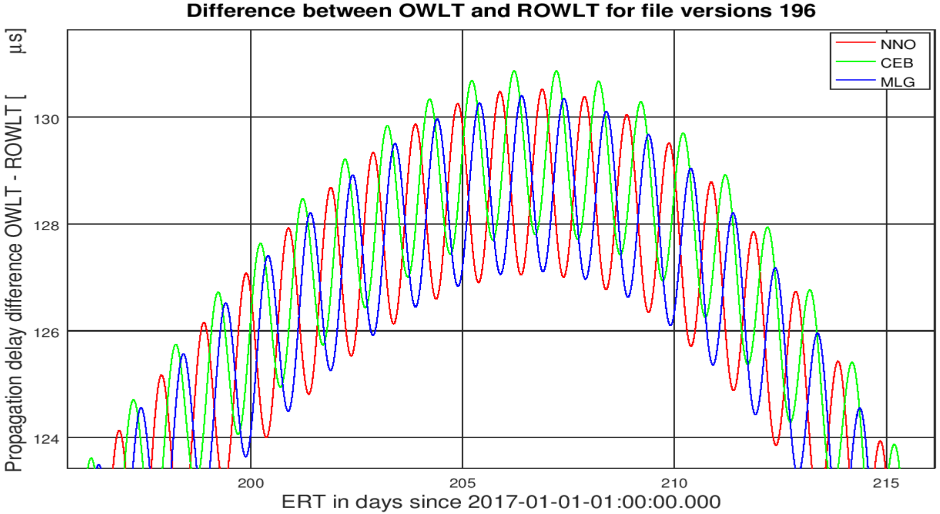


Figure 6: Relativistically uncorrected time couple deviation from long term fit.



Timing (4/4)

- Offline analysis removes diurnal relativistic effect
  - Jumps at ground station transitions gone – offsets of ground station clocks visible
- MCS integration: quicker response – S/C proper time vs S/C dynamic time



e 7: Relativistic (diurnally) corrected time couple deviation from long term fit, using equation 4.

Dynamic Stability (1/4)

- Micro Propulsion Subsystem - attitude control (acquiring science) – Telescope – rate measurement
  - Primarily opposing Solar Radiation Pressure (photon momentum)
  - Seasonal variation (sun- distance) seen (torque difference 10uNm)
  - Need account for MLI ageing when predicting mission lifetime

Attitude control when acquiring science

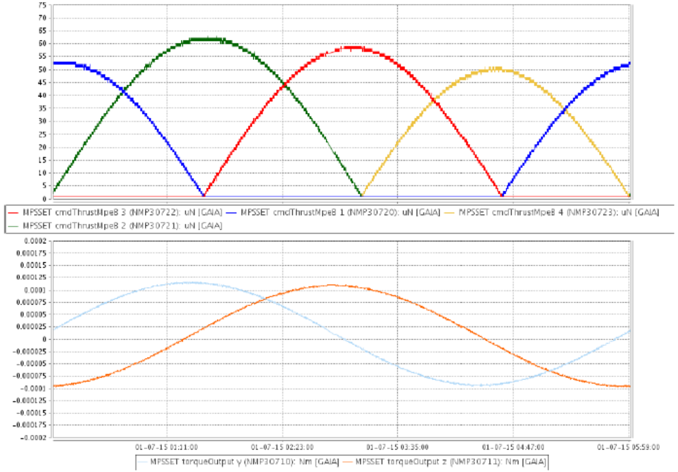
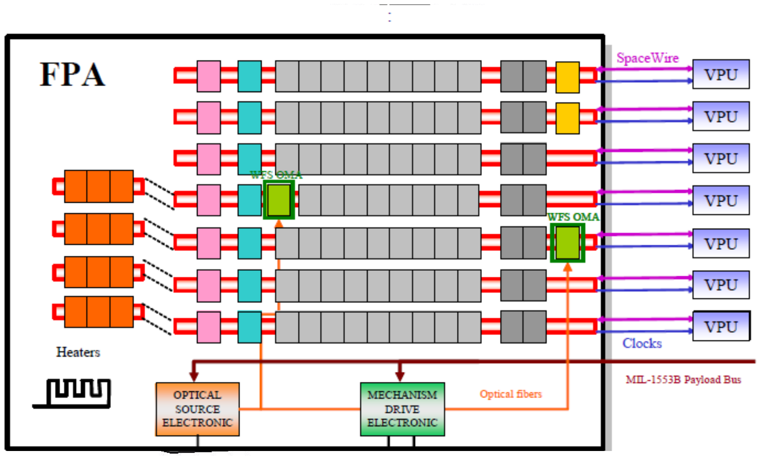


Figure 12: MPS commanded thrust and torque output July 2015



Dynamic Stability (2/4)

- Achieved rate stability circa 0.1 mas/s
    - Rate error equivalent to one rotation in 420 years!
- Several effects can be seen : micro-meteorites

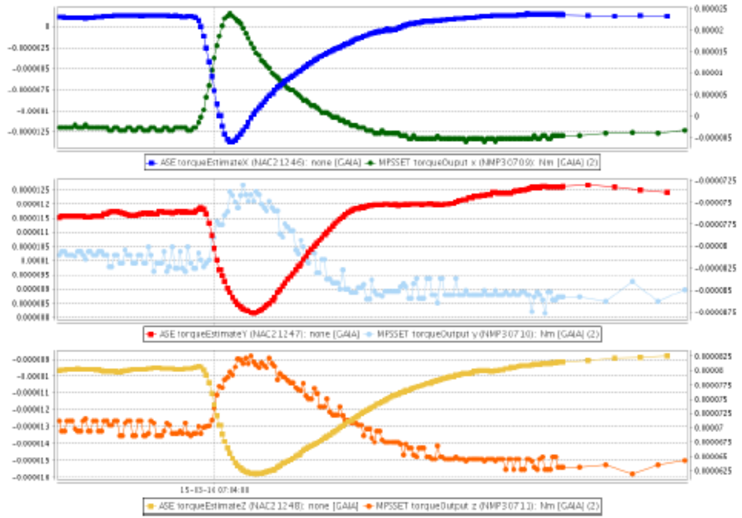


Figure 14: Suspected micrometeoroid impact 15th March 2016

Dynamic Stability (3/4)

- Achieved rate stability circa 0.1 mas/s
  - Rate error equivalent to one rotation in 420 years!
- Several effects can be seen : CPS Tank Bubble (correlated with temperature)

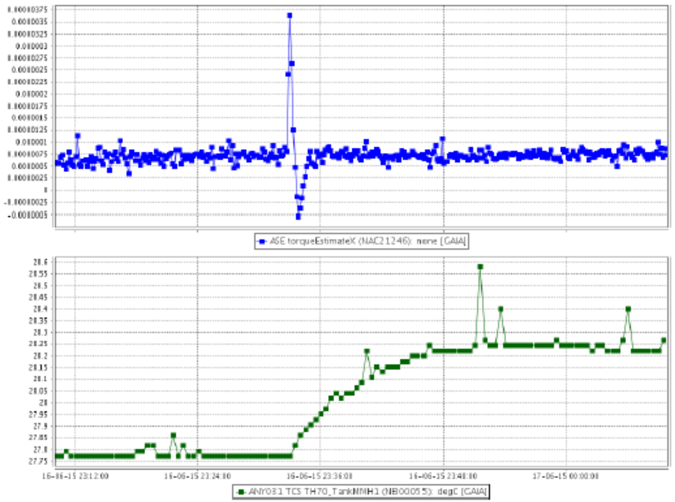


Figure 16: Disturbance Torque against Spin direction due to propellant movement

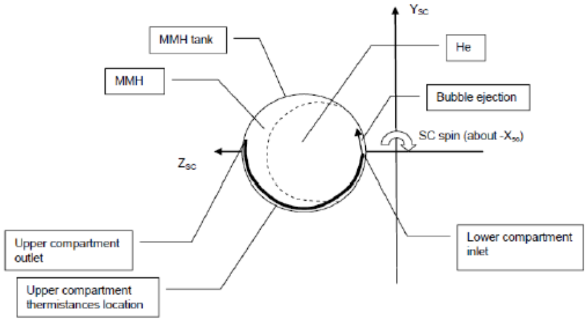


Figure 15: Propellant bubble movement inside Gaia MMH tank

Dynamic Stability (4/4)

- Achieved rate stability circa 0.1 mas/s
    - Rate error equivalent to one rotation in 420 years!
- Several effects can be seen : Star Tracker Map
    - Astro Stellar Estimator (telescope → rates, STR → attitude) – due to nearby companion stars not in the STR map

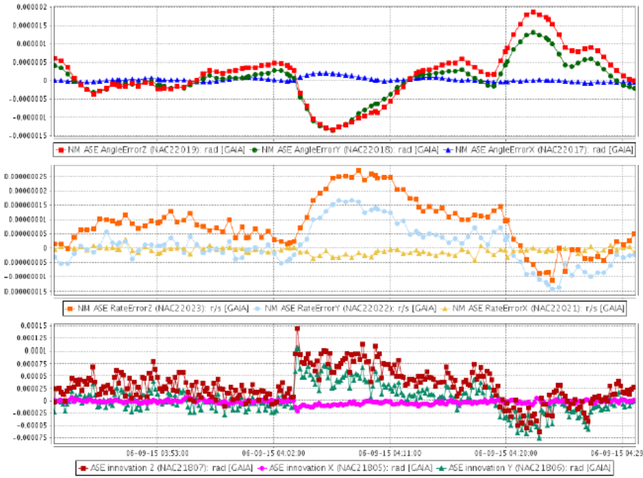


Figure 19: Typical signature for attitude/rate disturbance due to a 'bad' star in STR FOV

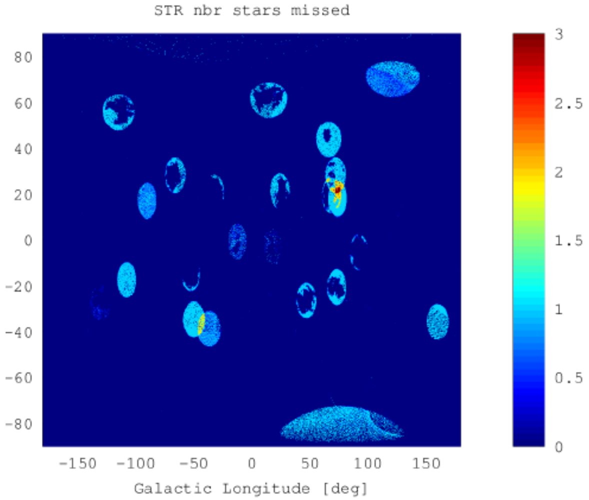
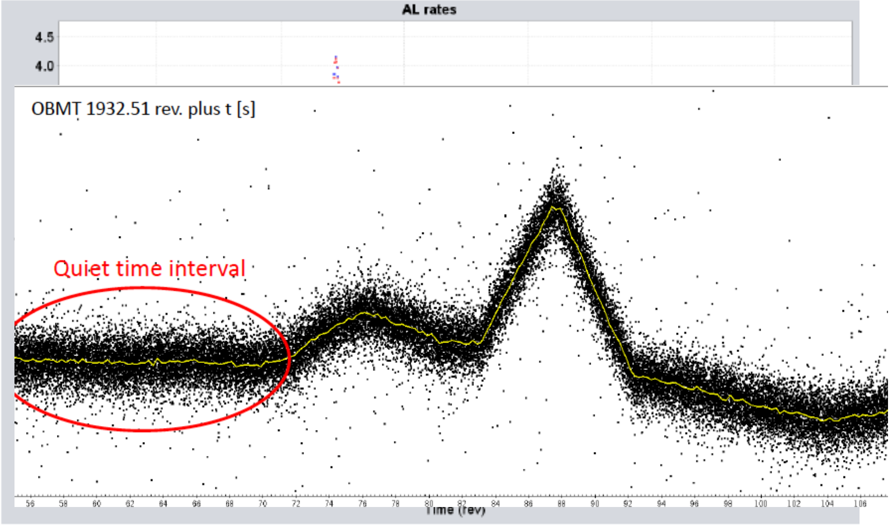
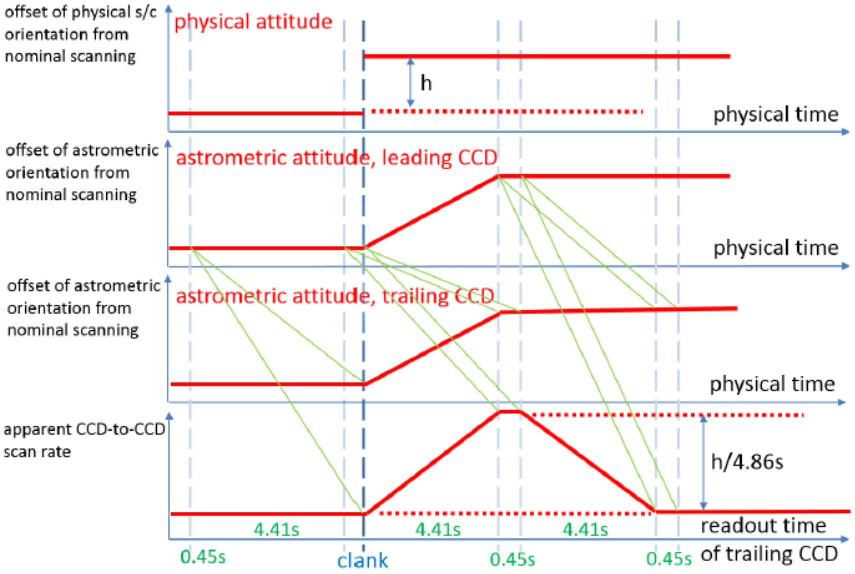


Figure 18: Gaia STR average number of "missed" stars

Dynamic Stability & Clanks

- Another signature is in the rate data (in particular in science ground processing)
- Many small '(micro-)clanks'
- Repeatable triangular shape – related to CCD transit time with no net rate change
- Effect removed in ground processing

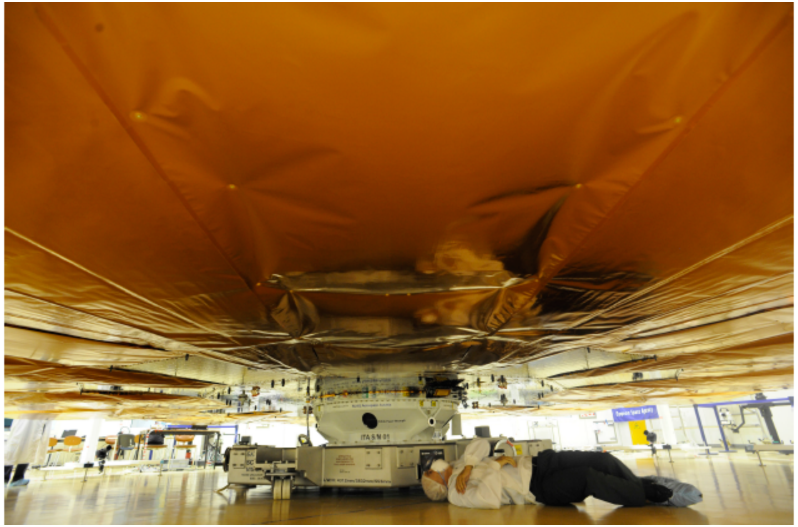




Thermal Stability (1/5)

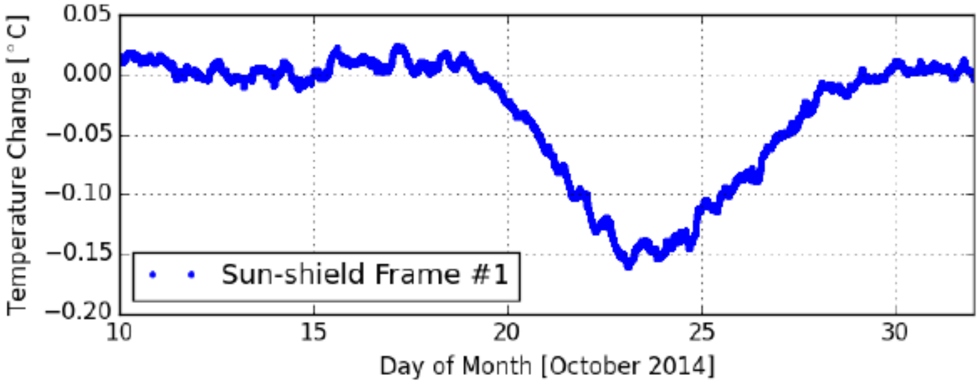
- Extremely stable thermally – telescope passively cooled and protected by the sun shield
- This thermal stability is needed (telescope thermo-elastic effects)
  - No heater switching on the spacecraft
  - Most HKTM temperatures must be low pass filtered & have an unusual event so see anything in the short term
- Need to monitor flat or highly repeatable trend lines:
  - Accuracy / range
  - Filtering

Sunshield shown in AIT →



Thermal Stability (2/5)

- Interesting temperature event on the sun shield:



- What caused it?

Thermal Stability (3/5)

- Sunspot transit (Solar Const. -3W/m2 or -0.2%)

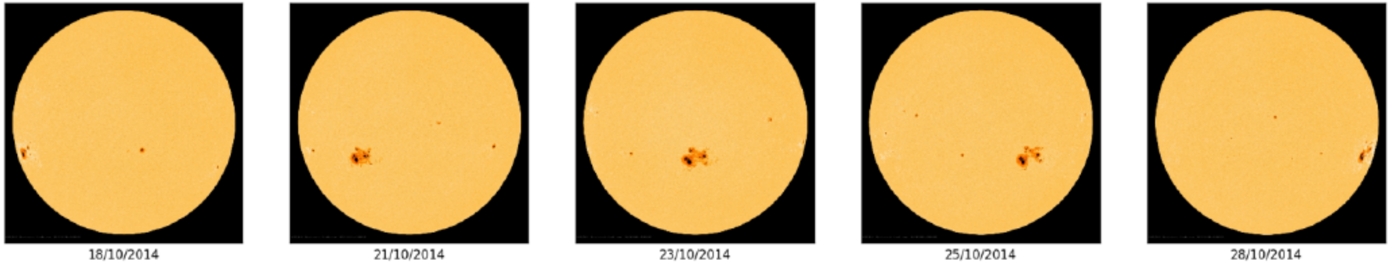
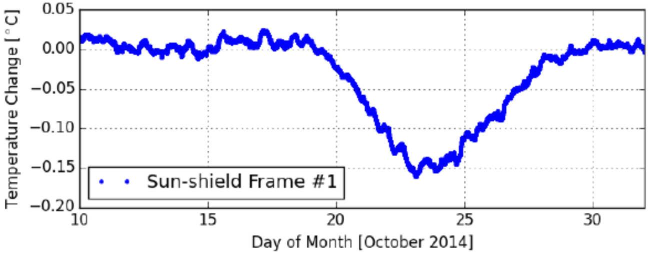
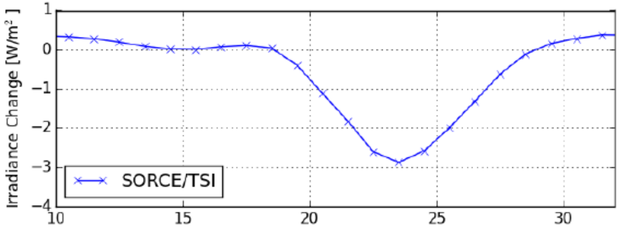


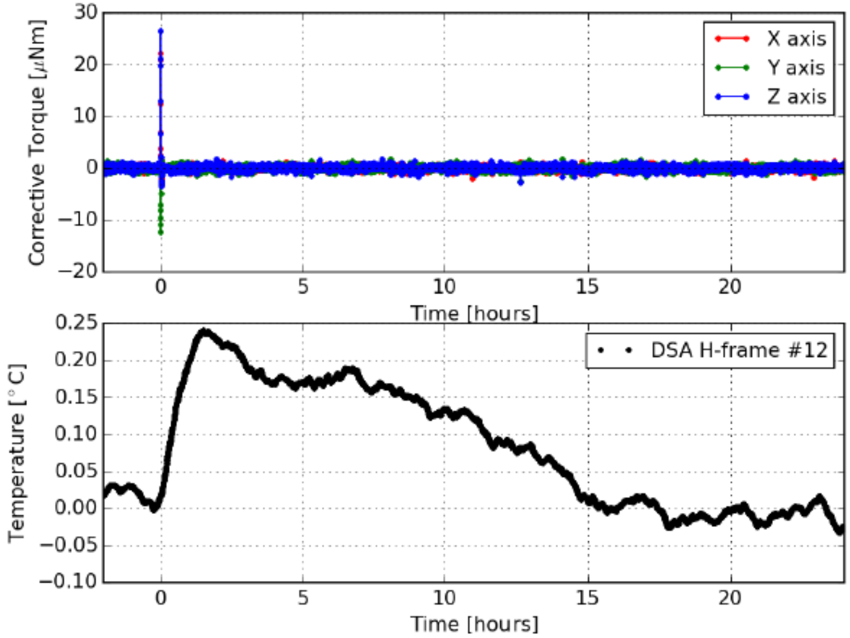
Figure 21. Full Sun disk images showing sunspot AR12192 as it passed across the face of the Sun in 2014. (Images courtesy NASA/SDO and the AIA, EVE and HMI science teams.)

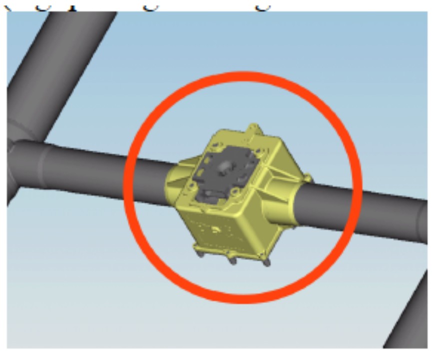




Thermal Stability (4/5)

Another sunshield (H-frame) thermal event

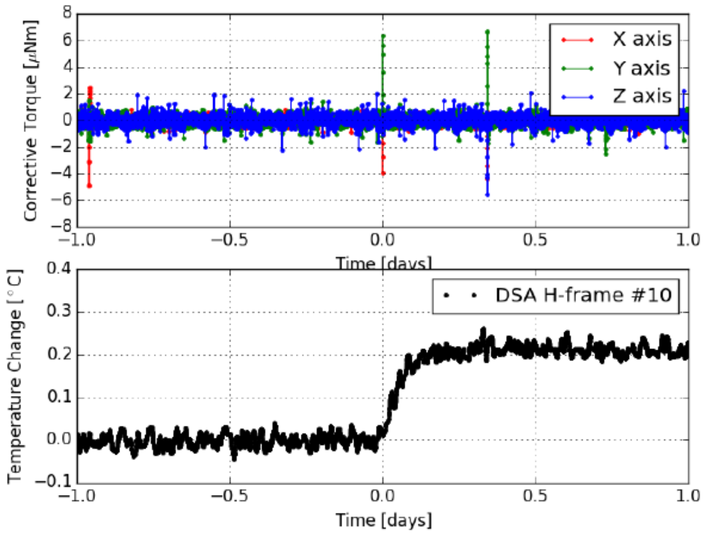


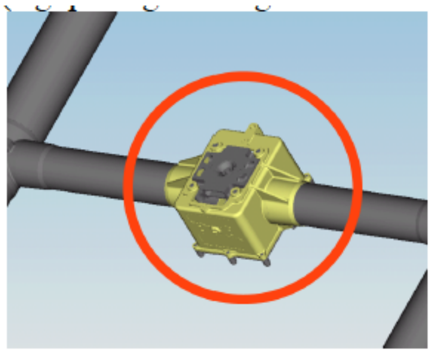


- Micro-meteorite hit – detected thermally!

Thermal Stability (5/5)

Another example – this time permanent change – MLI damage?





- Micro-meteorite hit – detected thermally!
  - Combining this data should allow directional information

Conclusions

The Gaia mission → breakthrough Astrometry Mission

Technological firsts and bespoke system design has delivered extraordinary performance.

Flexibility of the space and ground segments and the dedication of the teams involved, key to delivering mission performance when challenges come. (Operations Services, Automation)

The **extraordinary precision** make **subtle effects** visible across subsystems not visible on other missions. Think about how you'll do this (thermal sensors etc)

Timing (relativistic effects)

Fine detail – in periodic highly repeatable trends

Dynamic / Thermal HKTM monitoring of new set of phenomena

See also papers: D. Milligan et al. / Acta Astronautica 127 (2016) 394–403

D. Milligan et al. / Flying ESA's Ultra-Precise Gaia Mission, SpaceOps Korea 2016