The Past, Present & Future of INTEGRAL Operations

Thomas Godard,

INTEGRAL Flight Control Team

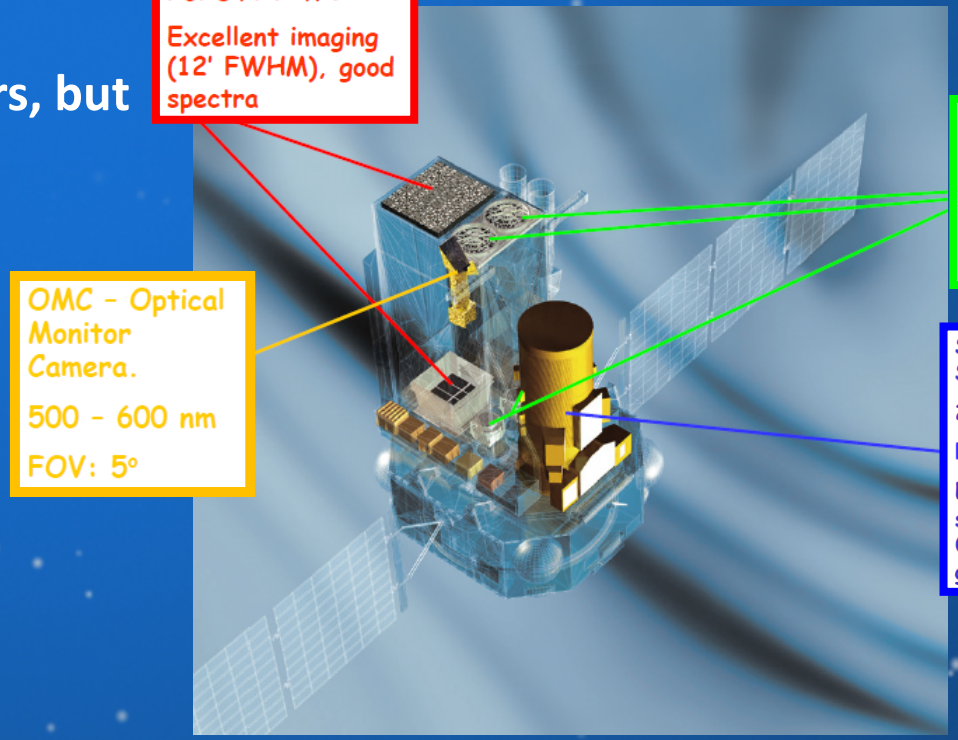
12th INTEGRAL Conference

11th February, Geneva, Switzerland

esa

INTEGRAL Overview

- **INTErnational Gamma Ray Astrophysics Laboratory**
- **ESA Science Mission: study most violent & exotic objects in the universe**
- **Most sensitive & accurate soft gamma ray observatory in space**
- **Launch: October 17th, 2002**
- **Nominal & extended lifetime of 2.5+2.5 years, but expected lifetime now far exceeded**
- **Unique payload: 4 scientific instruments**
  - Multispectral observations
  - Co-aligned with large FoV
  - Simultaneous observations
- **Excellent scientific return**

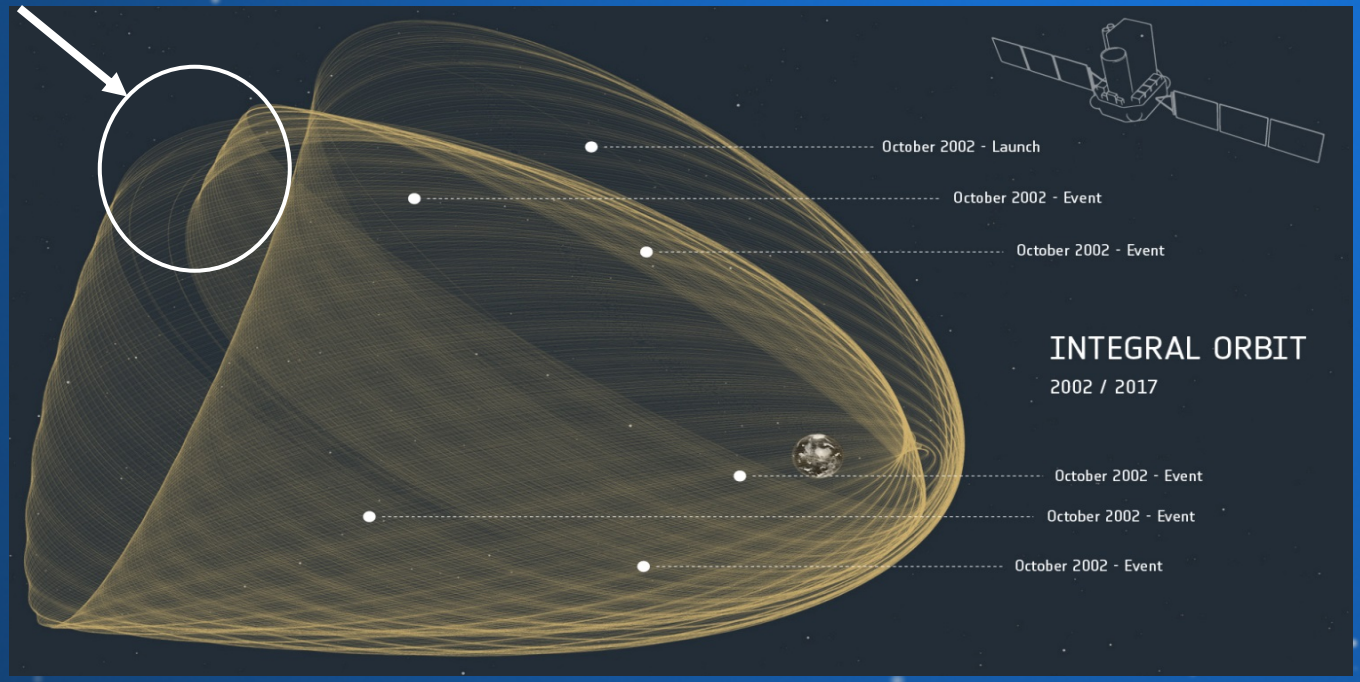


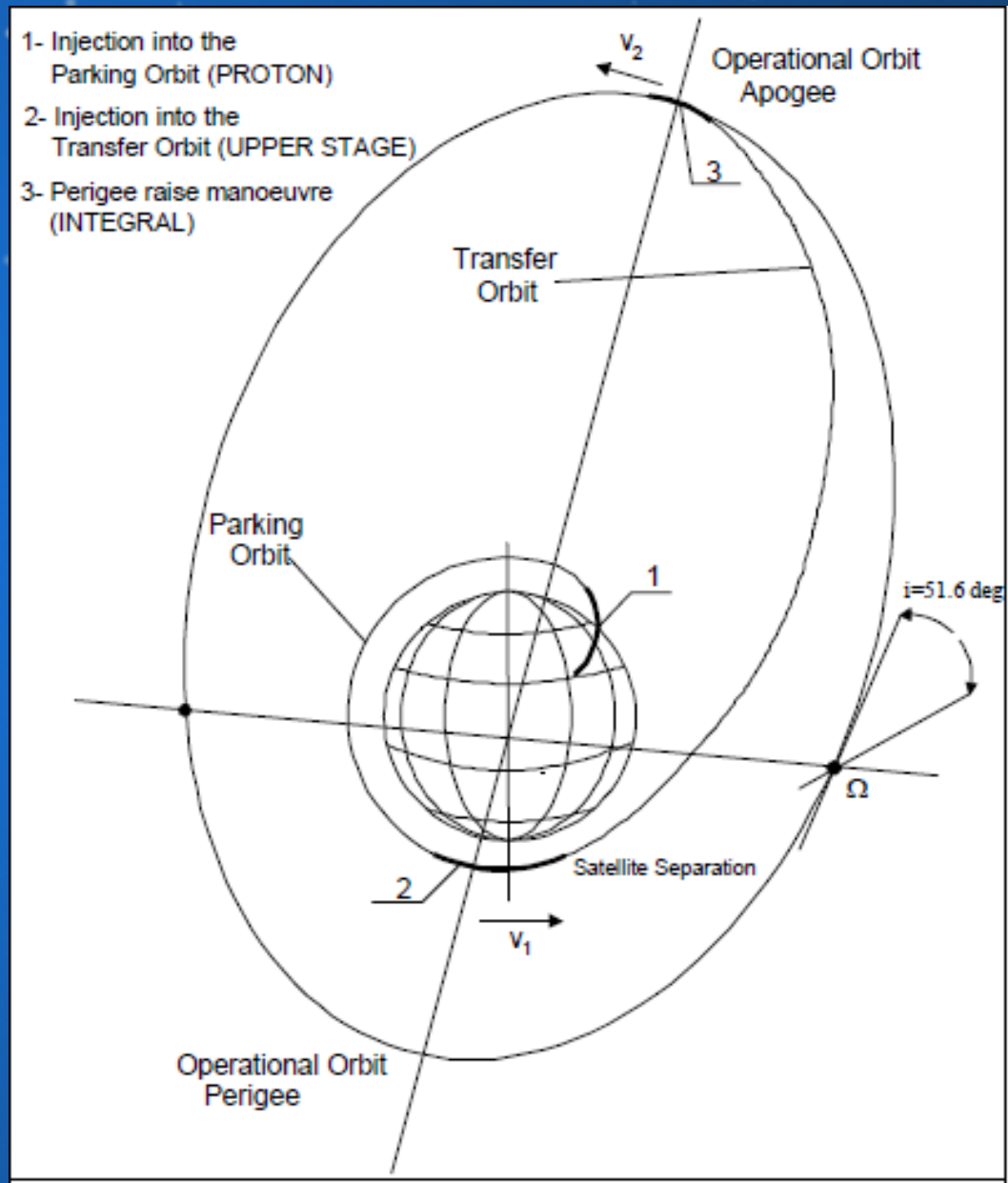
esa

INTEGRAL Operational Orbit & Evolution

- **INTEGRAL has a highly elliptical Earth orbit:**
  - **~140,000 km apogee** *(originally ~150,000km)*
  - **~8,000 km perigee** *(originally ~10,000km)*
  - **~54 deg inclination** *(originally ~51 deg)*
  - **64 hour period** *(originally 72 hours)*
  - ***Majority of orbit is above Van Allen belts to maximise science***
- **Orbit varies over time due to gravitational perturbations from Earth, Moon and Sun:**
  - **'reference orbit' maintained to ensure ground station coverage**

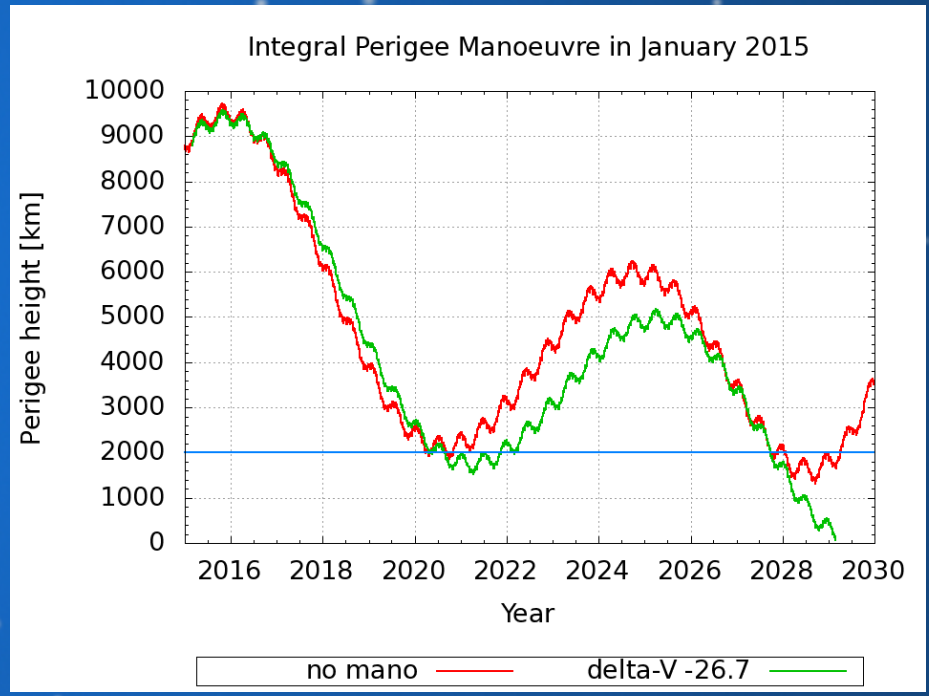
Delta-V in 2015

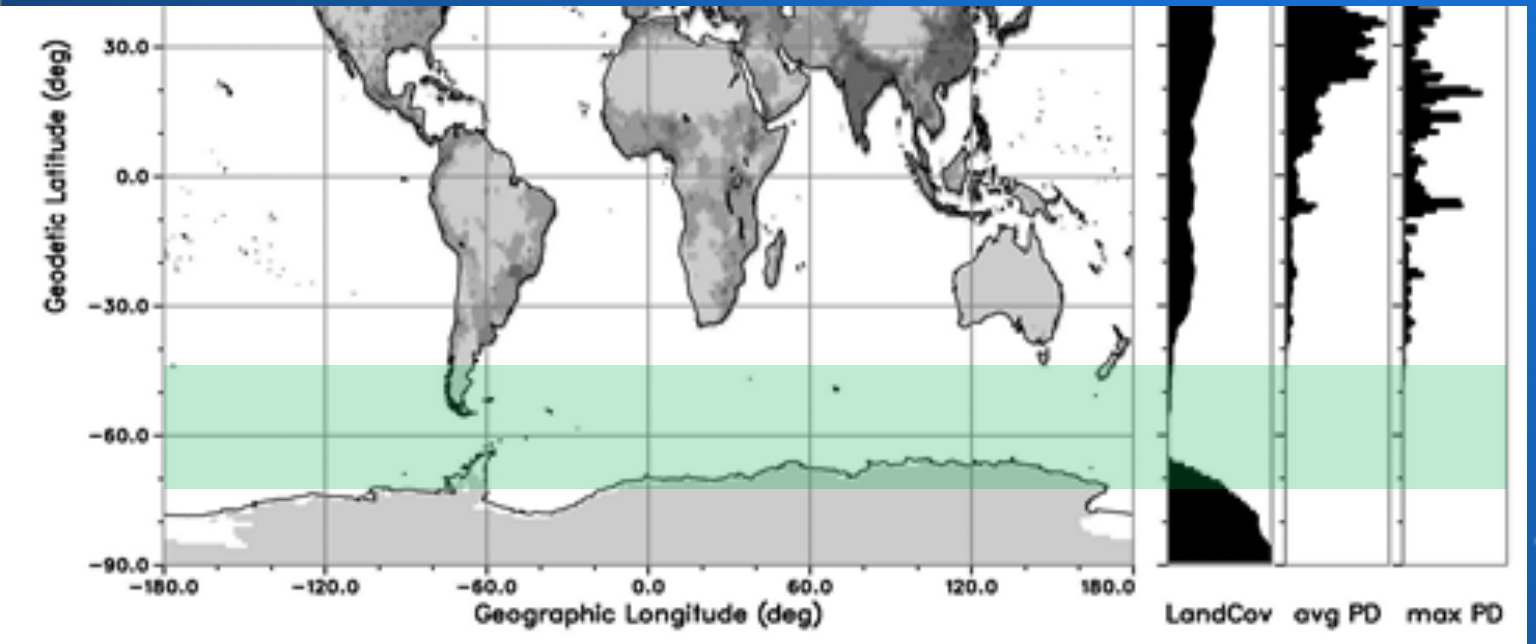




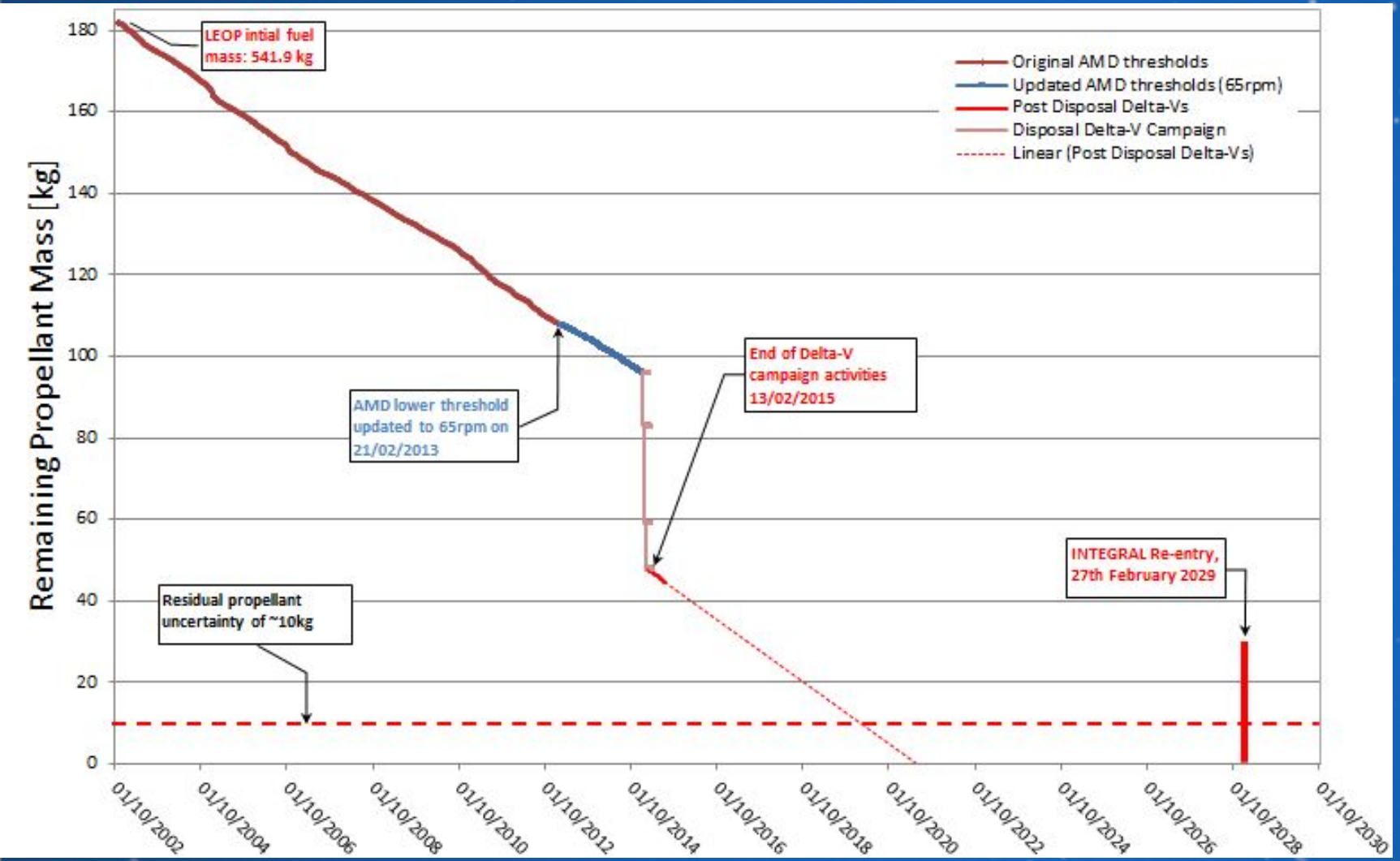
Disposal Activities

- **Propellant consumption & solar array degradation indicated end of science operations <2029**
  - **Orbit predictions indicated no natural re-entry within next 200 years!**
- **To avoid debris hazard after end of mission, disposal manoeuvres were executed in early 2015**
  - **Uncontrolled re-enter in February 2029, below latitude -45deg**
  - ESA Space Debris Policy compliant
  - Longitude is not predictable currently
  - Some elements of INTEGRAL will not demise
    - Mass dependent on final orbits characteristics
    - Simulation cases: up to 1000kg, mostly Tungsten from payload





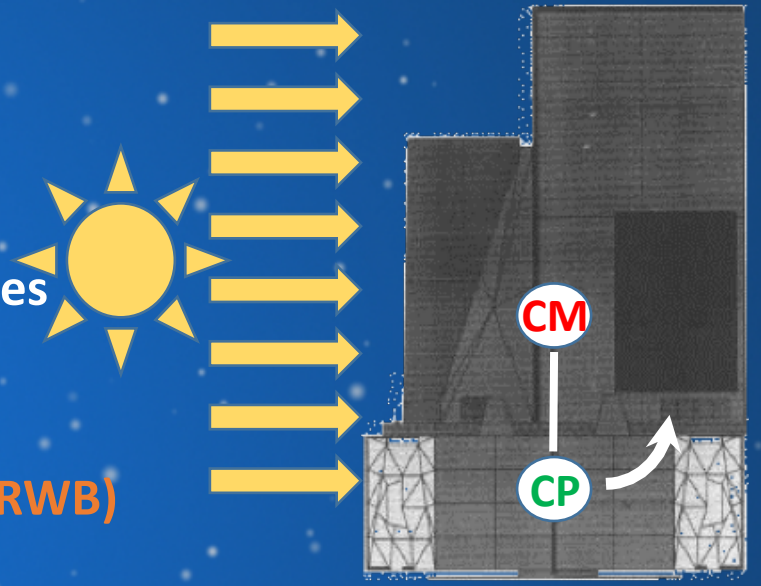
Impact of disposal on propellant

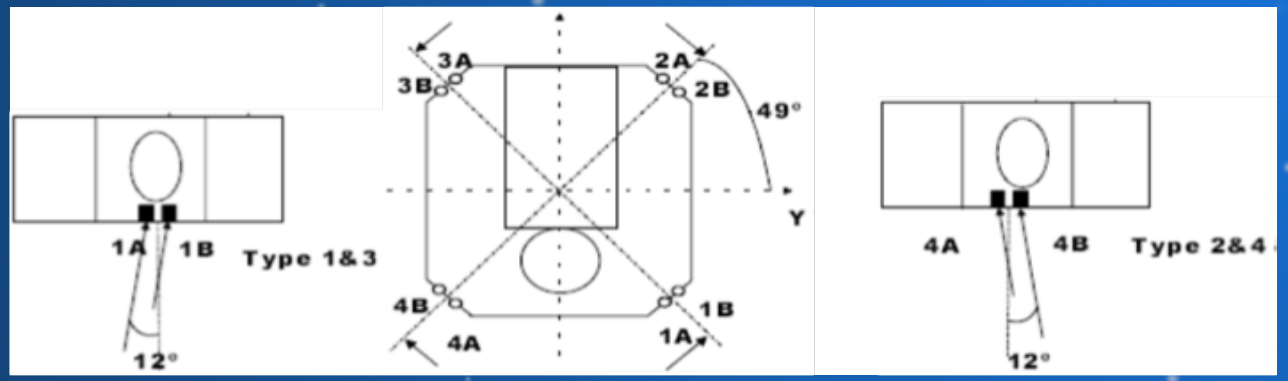


- **Used 50% of the propellant available at that time -> ~50kg**
  - Would be dry in 2021 if historical consumption rate was maintained
  - ***Becomes the satellite's lifetime limiting element***

Reasons for Propellant Consumption

- **Photon pressure from solar flux creates an external force**
  - Centre of pressure (CP) & centre of mass (CM) are not co-located
  - Difference in location produces an external torque
- **Reaction Wheels hold spacecraft attitude by absorbing external torques**
  - BUT *wheels have limited capacity to absorb this angular momentum*
- **Thrusters used to off-load wheels by perform a Reaction Wheel Bias (RWB)**





- **Thruster cannot create *pure torques* due to their fixed locations/directions**
  - RWB always creates a parasitic delta-V
- **Parasitic delta-V can be used to maintain the 'Reference Orbit' by aligning the spacecraft's attitude with respect to the orbit vector**

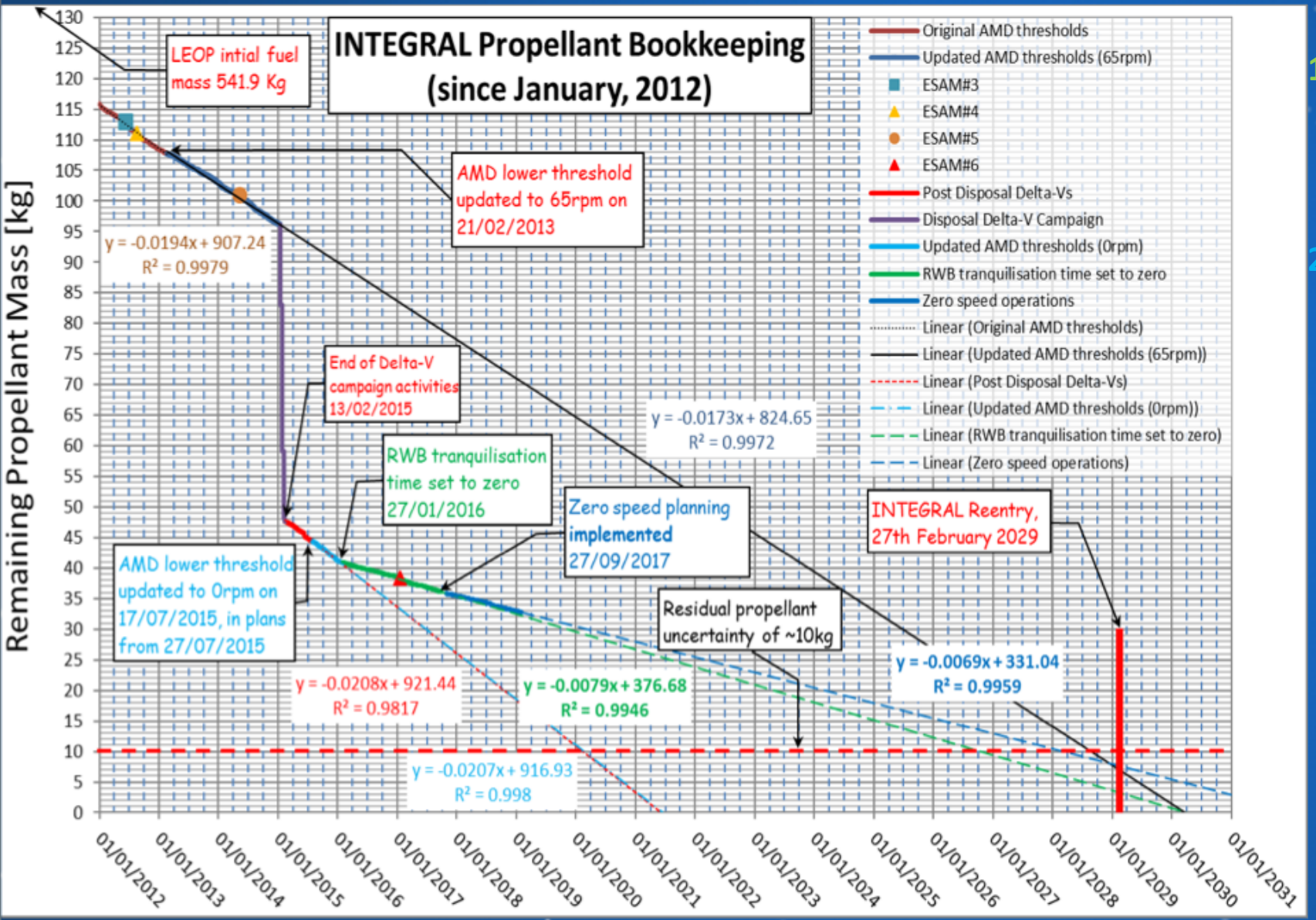
esa

Option for reducing propellant consumption

- **Adaptation of XMM 4-wheel drive for INTEGRAL**
  - ➢ Already implemented & successfully commissioned on XMM-Newton
  - ➢ Estimated fuel saving for INTEGRAL of ~50%
  - ➢ Implementation costs in the order of M€
    - ⇨ ***discarded due to lack of funding***

- **Two alternative options were technically possible and within available budgets:**
  - ***1) Reaction Wheel Bias with Zero Tranquilisation time***
    - ➢ Tranquilisation phase (100 sec) minimises spacecraft rates & pointing errors when transitioning from thruster back to wheel control, firing opposing thrusters simultaneously
    - ➢ Analysis by Industry, XMM in-flight experience and INTEGRAL in-flight testing showed no significant impacts on attitude control and pointing stability (i.e. science)
    - ➢ Removed by simply setting the duration to 'zero' within the TC
  - ***2) Modified angular momentum control strategy***
    - ➢ Increased efficiency & flexibility of reaction wheels' usage by allowing wheels to operate in forbidden 'zero speed' region during stable pointing
    - ➢ 'Zero region' authorised > lower wheel speed > less angular momentum to unload during RWB > Reduced usage of thruster > LESS PROPELLANT USED !!!

Effects of Propellant Saving Initiatives



1) RWB 'zero' tranquilisation time went operational in January, 2016

- Propellant consumption rate reduced >60%
- **Could extend operational lifetime to ~2027**

2) Modified angular momentum control went operational in September, 2017

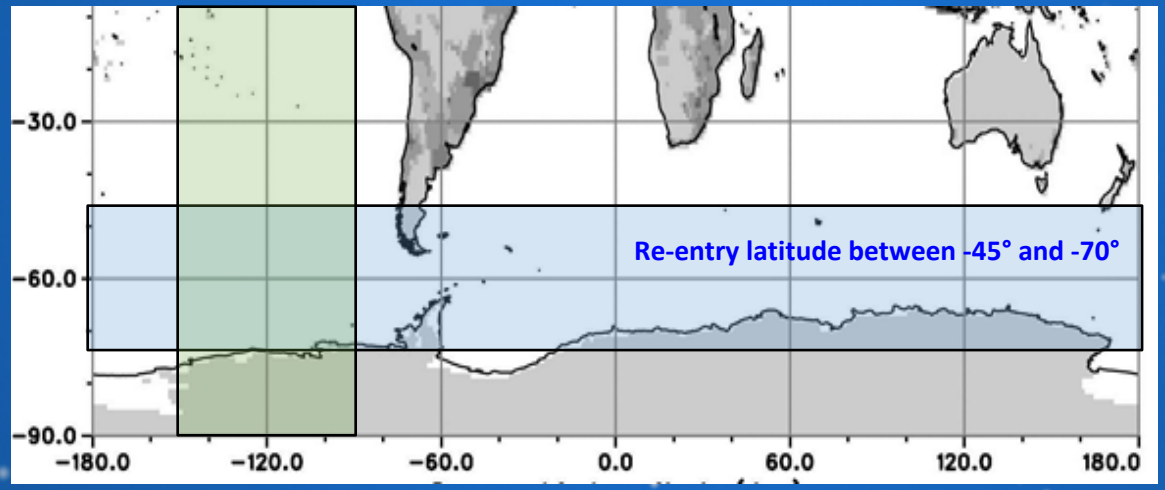
- In-flight testing showed no attitude control issues with all the wheels operating within the low speed region
- Laboratory tests of 'flight spare' reaction wheel at ESTEC since 2015 show no degradation (e.g. increased friction)
- Modified Flight Dynamics planning software verified for operational planning
- Observed consumption rate reduced ~15%
- **Could extend operational lifetime up to the re-entry in February, 2029**

Residual propellant *may* enable some control of *re-entry longitude*

esa

Controlled Re-entry in 2029

- **Major propellant savings in the coming years at very low implementation effort have been achieved, which will:**
  - allow ESA to extend INTEGRAL's science operations phase considerably
  - **possibly allow for a controlled re-entry in 2029 with some residual propellant available for fine-tuning of the re-entry *longitude*, position & profile to ensure a quick demise without returning fragments in a potentially circularised orbit.**



- **This would be the first 'controlled' re-entry ever performed by a ESA mission in such a highly elliptical orbit as well as by an astronomy satellite.**

INTEGRAL Operations Automation

- **Operations are supported 24/7 by the Flight Control Team at ESOC**
  - a SPAcecraft CONtroller (SPACON) is on-console during all 'operational' periods (i.e. whenever the spacecraft is in contact with a ground station)
  - a Spacecraft Operations Engineer (SOE) is always on-call to support the SPACON in contingency situations
- **The main purpose of automation is to reduce the operational errors by reducing SPACON and SOE real-time workload**
  - has also enabled merger of the SPACON team with XMM and Gaia
  - reduced/shared manpower also supports the mission's long term viability
- **Tools to automate the most repetitive and demanding SPACON tasks**
  - ✓ Standard Planned manual activities
  - ✓ Unplanned activities, typically response to unexpected but not anomalous event
  - ✓ Response to on-board anomalies (e.g. activities not covered by on-board autonomy)
  - ✓ Checking actual against expected behavior (e.g. out of limits after eclipse exit)
  - ✓ Check for missed slew updates
  - ✓ Check of wheel speeds against prediction
  - ✓ Check for the correct on-board antenna in use

INTEGRAL Fast Re-Planning

- **Fast re-planning is required for Target of Opportunity (ToO) requests that support Multi-Messenger astrophysics (e.g. Gravity waves)**
- **Large slews to new targets may take up to 8 hours to complete due to spacecraft dynamics and attitude pointing constraints**
  - INTEGRAL maximum slew rates is 200 arcsec/sec
  - to avoid pointing at bright objects (e.g. Sun, Earth, Moon) during the slew, we may need to perform as many as five Open Loop Slews, each taking 10 mins to generate
    - → 1 pitch slew <= 80 degrees (max duration 27 mins)
    - → 4 yaw slews with total slew angle over all four slews <=270 degrees. (av. duration per slew 24 mins)
    - → final Closed Loop Slew (~10 mins) to arrive precisely on-target to enable start of 'science'
  - we must assume a RWB is required between every slew (~25 mins to generate and execute)
  - a change of guide star may be also be required before each wheel bias (~15 mins to generate and execute)
- **Goal is to reach the ToO attitude as fast as possible by performing key activities in parallel**
  - slew products will be planned and executed by ESOC Flight Dynamics *before* the full Mission Planning products are received from ISOC, based upon ToO coordinates
  - procedure being developed jointly by ISOC and ESOC for operational use in 2019

INTEGRAL Operations in the Next Decade

- **Currently – after more than 16 years in orbit**
  - **INTEGRAL's performance**
    - Excellent & still far above design specifications
    - No significant unrecoverable failures & minimal degradation, still using prime unit
    - Effects of aging on-board INTEGRAL are not critical and mainly compensated for by modest operational countermeasures
    - Very good margin on consumables and all limited-lifetime components
  - **Continued significant interest in INTEGRAL's science data**
    - Healthy over-subscription at each announcement of opportunity
    - Undiminished rate of target of opportunity requests
- **Given continued interest by scientific community**
  - **INTEGRAL has the potential to provide excellent scientific data well into the next decade.**
  - **INTEGRAL as calibration baseline & support of International Astronomical Consortium for High Energy Calibration**
    - Standards for high-energy calibration
    - Cross calibration with currently operating space and ground observatory (XMM, Chandra, NuSTAR, Swift, Suzaku , LIGO and VIRGO..)

APPENDIXES

- ***ESA Article about the delta-V manoeuvre and video of the orbit evolution***
  - VIDEO http://sci.esa.int/integral/59688-integral-fifteen-years-in-orbit/
- ***ESA Space debris policy***
  - https://www.iadc-online.org/References/Docu/admin-ipol-2014-002e.pdf
  - https://www.iadc-online.org/References/Docu/admin-ipol-2014-002e.pdf