Integral Users Group 10/7/2020, Propulsion System Anomaly

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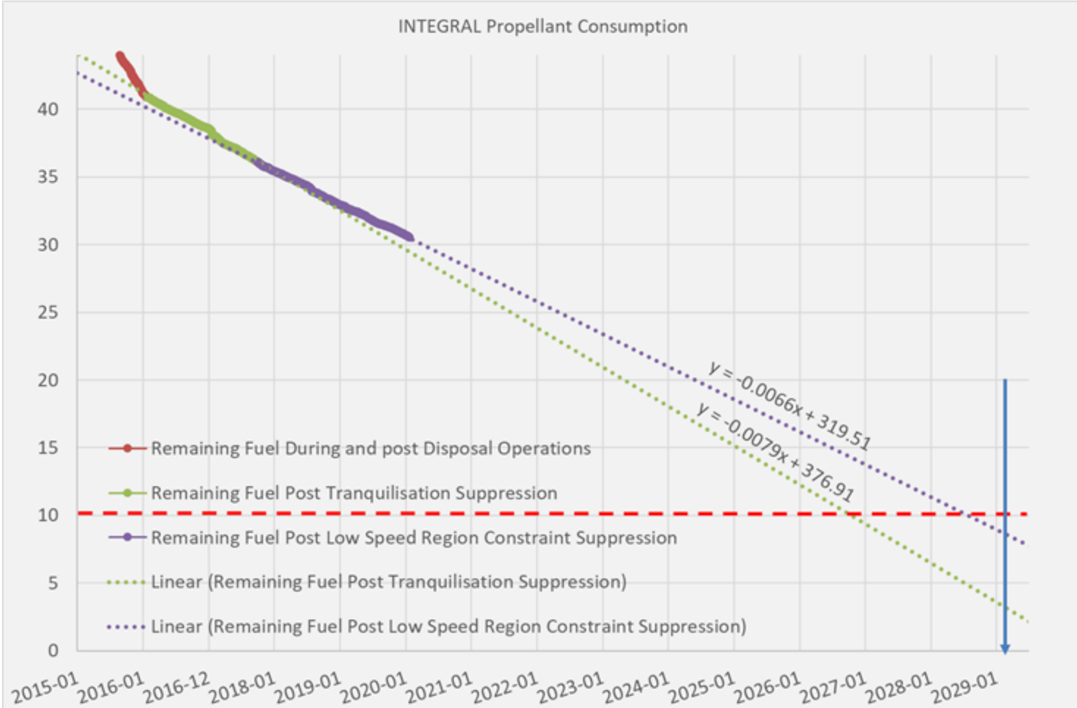
Recap of MEOR Status 27/2/2020

Positive status of Spacecraft given after 17years in orbit.

Concentrated on 3 issues:

- SA degradation possibly implying some seasonal pointing constraints
- CDMU Anomaly in summer 2019
- Remaining Propellant

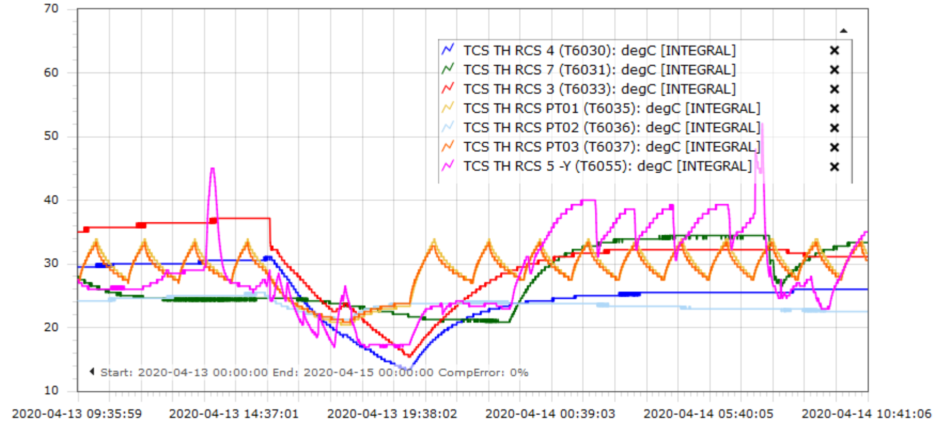
PVT and FD Bookkeeping indicated propellant reserves until late 2020s at current rates of usage



Events since MEOR – 13/4/2020

SVM PDU Initialisation and Subsequent safe mode (ESAM)– SEU?

- AOCS Control Computer and Reaction Wheels OFF => ESAM Entry
- SPI Cryo Compressor OFF
- IREM OFF
- Pressure Transducers OFF
- Propellant System heater A OFF



2nd SEU? isolates Propellant System Heater B, about 2 hours later

- On-board monitoring intervened to switch on Heater B without effect

Leading to general cool down of propulsion system

- Propellant cool down was not critical – coldest point on RCS 13.3DEG
- Trigger of anomaly????

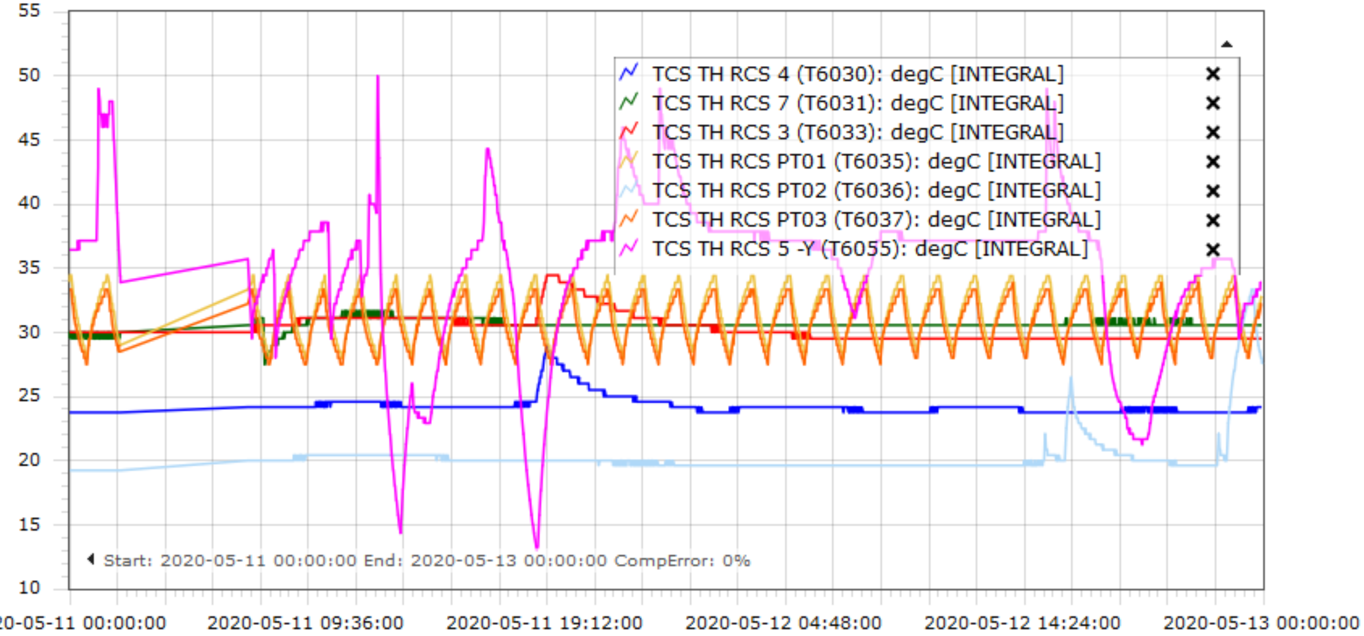
Events since MEOR – 11/5/2020

Low propellant temperature detection, On-board reconfiguration triggered

- Low temperature (13.67DEG) on RCS Line 5 detected
- Propellant heater B commanded ON
- Low temperature limited to line 5 only

Possibly 1st symptom of RCS Anomaly??

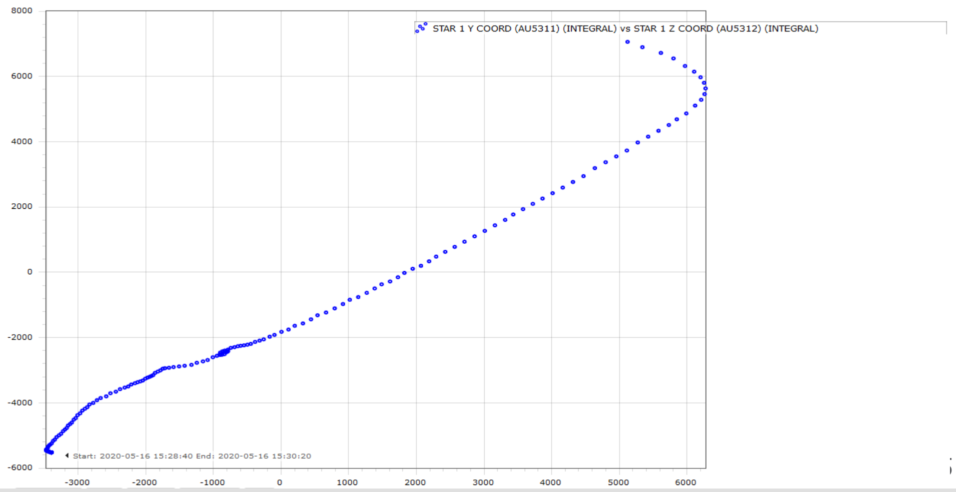
Part of heater circuit enclosed in N2 bubble??



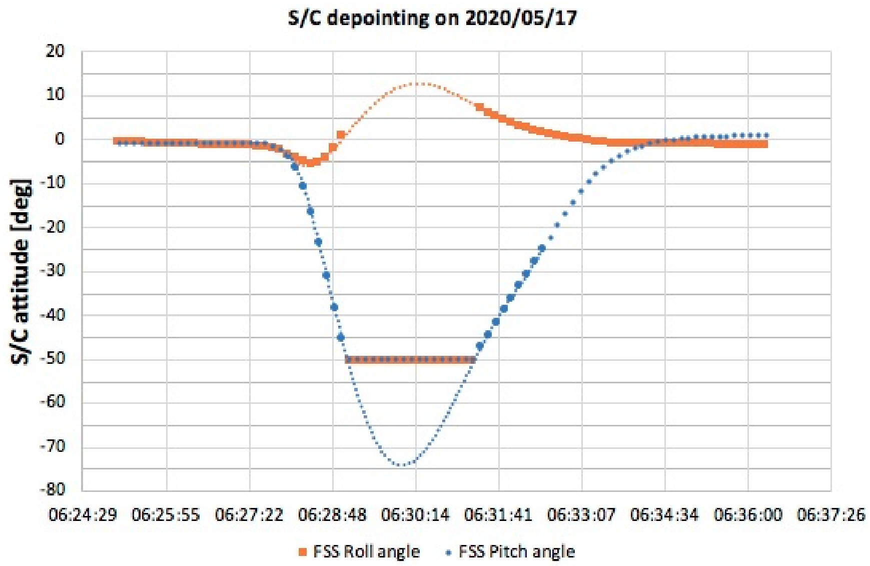
Events since MEOR - 16 + 17/5/2020

ESAM#8 and de-pointing/rotation under thruster control in ESAM

- Excess on-time demand on thruster 2 at end of a reaction wheel momentum offload operation causes ESAM (thruster under-performance?)
    - De-pointing also observed (Guide Star)
- ESAM stable, maintaining pitch and roll angles within expected range
- Suspicion of RCS-A or thruster 2A anomaly => recover on RCS-B next morning



Events since MEOR – 17/5/2020



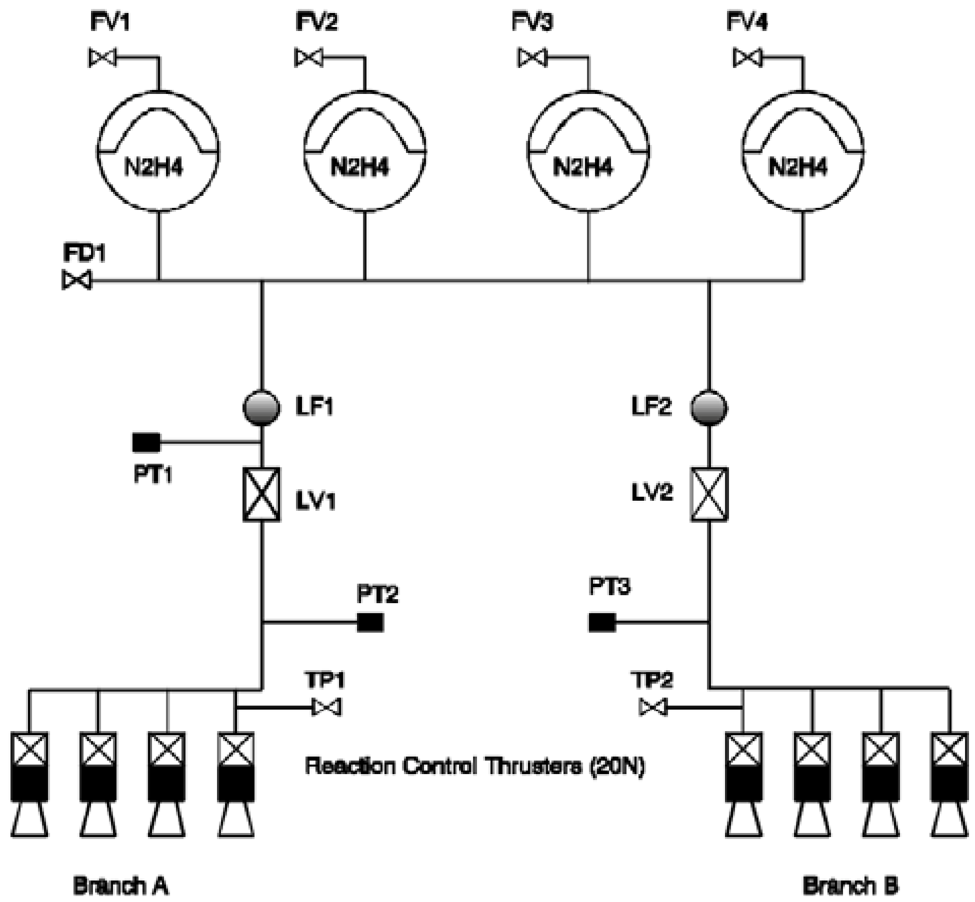
Depointing under ESAM Control

- Pitch 75DEG, Roll 13DEG (estimated)
    - Instruments enter eclipse mode
- Controller recovers attitude within 7minutes
- Simulations show that the ESAM controller could cause such a depointing in case of significant thruster under performance (particularly 3B)
- At the same time a drop in propellant pressure of about 0.2bar was observed
    - Consistent with release of N2?
- Fast recovery to wheel control executed
- Thruster Torque Calibration indicated reduced (55%) and intermittent thruster performance on both RCS branches.

Anomaly Signature and Investigations

Integral Propulsion System

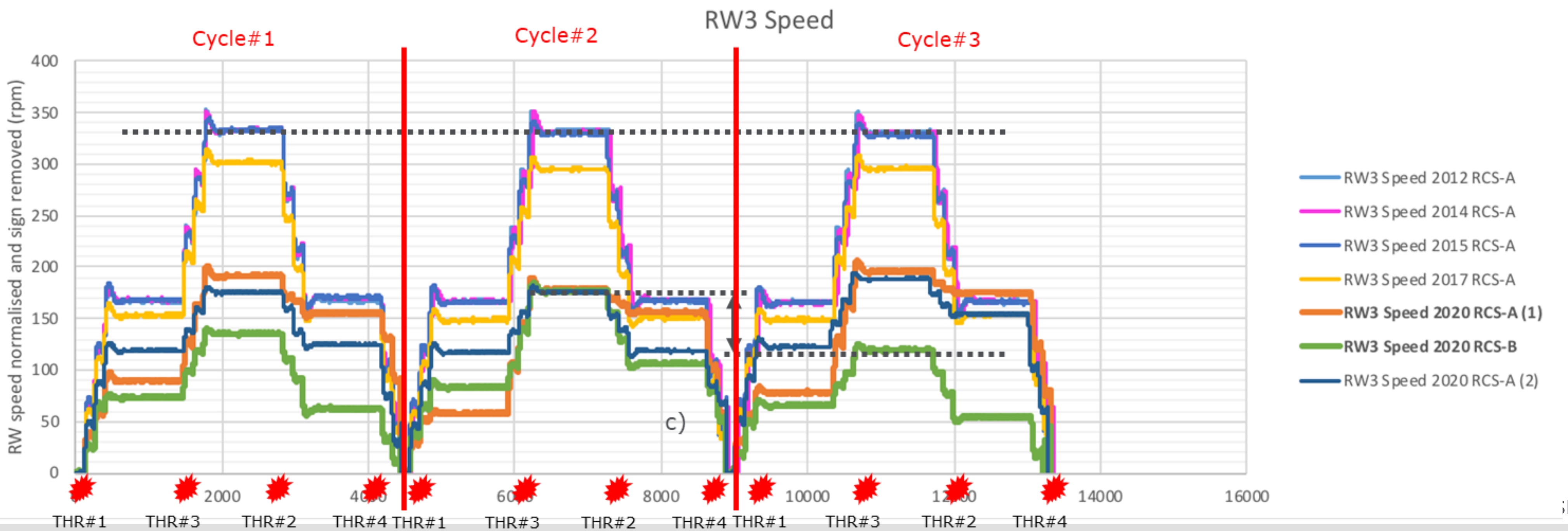
- 540kg at start of mission
- Estimated 25 – 30kg currently



Thruster Torque calibration (RCS-A / B)

Repeated series of thruster firings, measure change in reaction wheel speed to determine impulse / performance.

- Thruster performance is much reduced: ~4N, rather than the expected 8N
- Thruster performance is variable

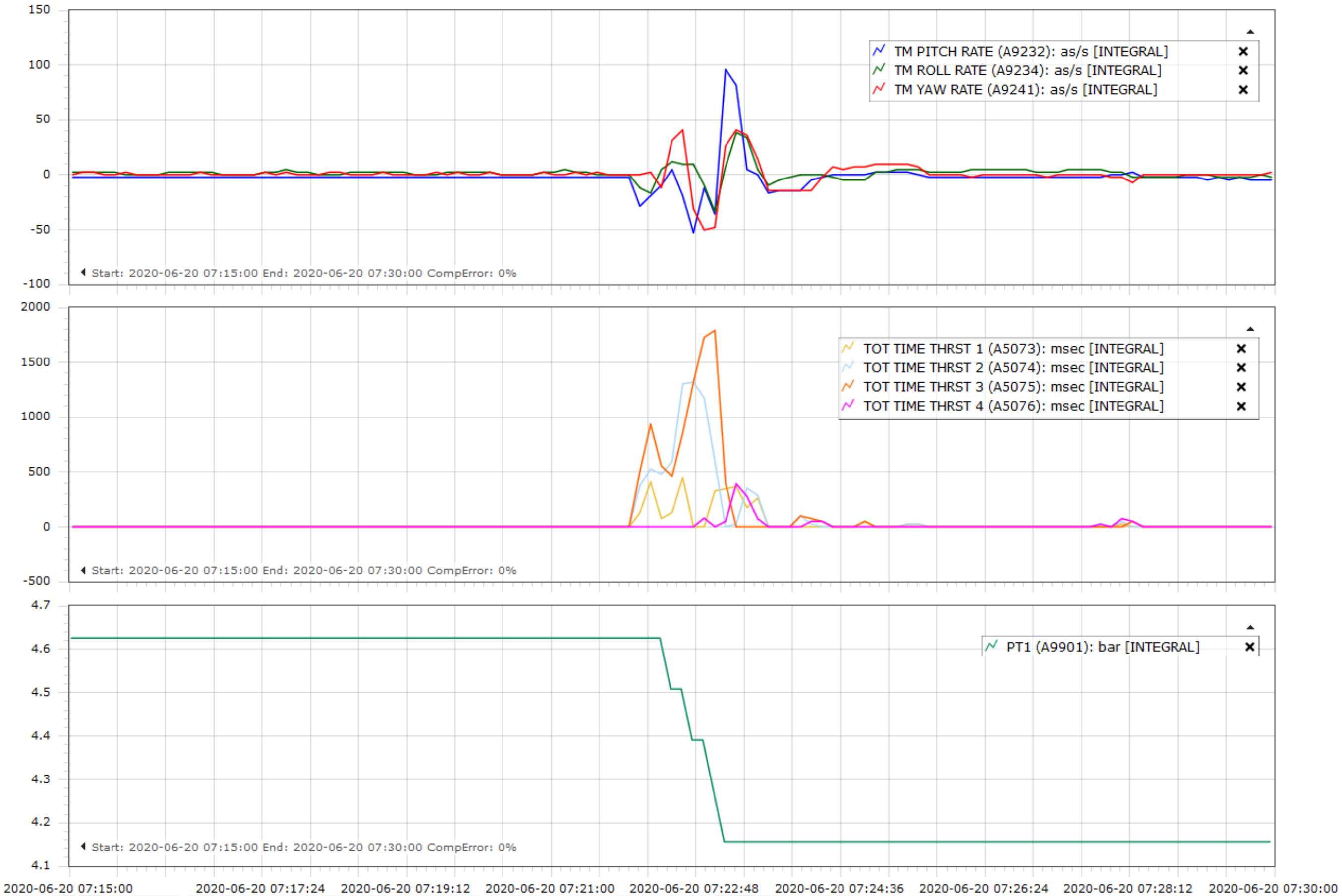


Reaction wheel Biasing

Observed body rates are high.

Thruster On-times demand high and unbalanced

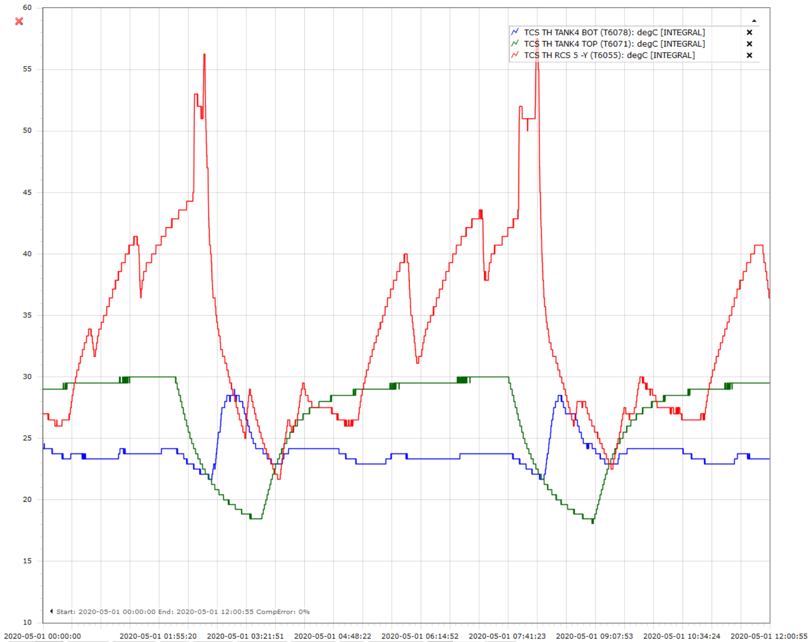
Loss of Tank Pressure

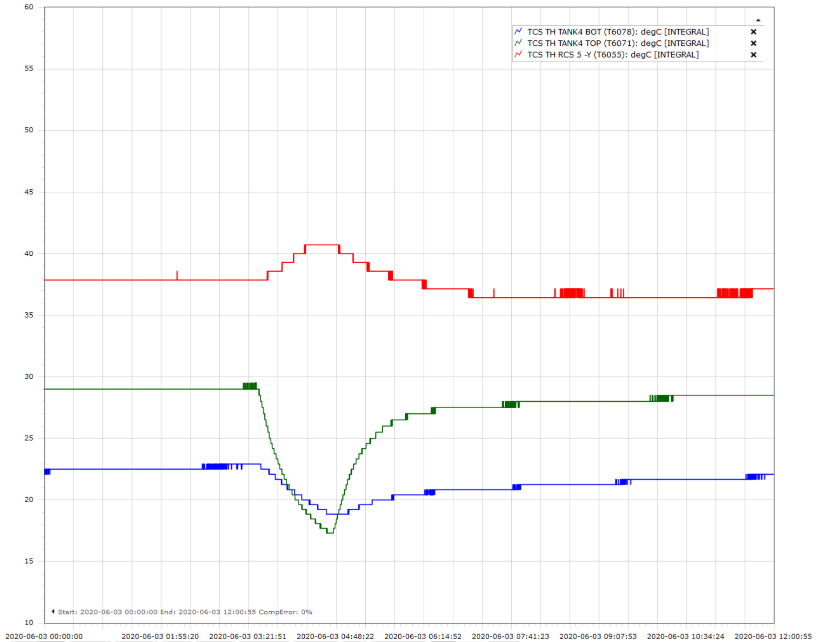


Changes in RCS Thermal Behaviour

Ex. Hot Plug Behaviour Tank 4

- Possibly caused by inflow of warm hydrazine after Tank Heater switch-off and N2 contraction / pressure drop - This behaviour has ceased since ESAM #8



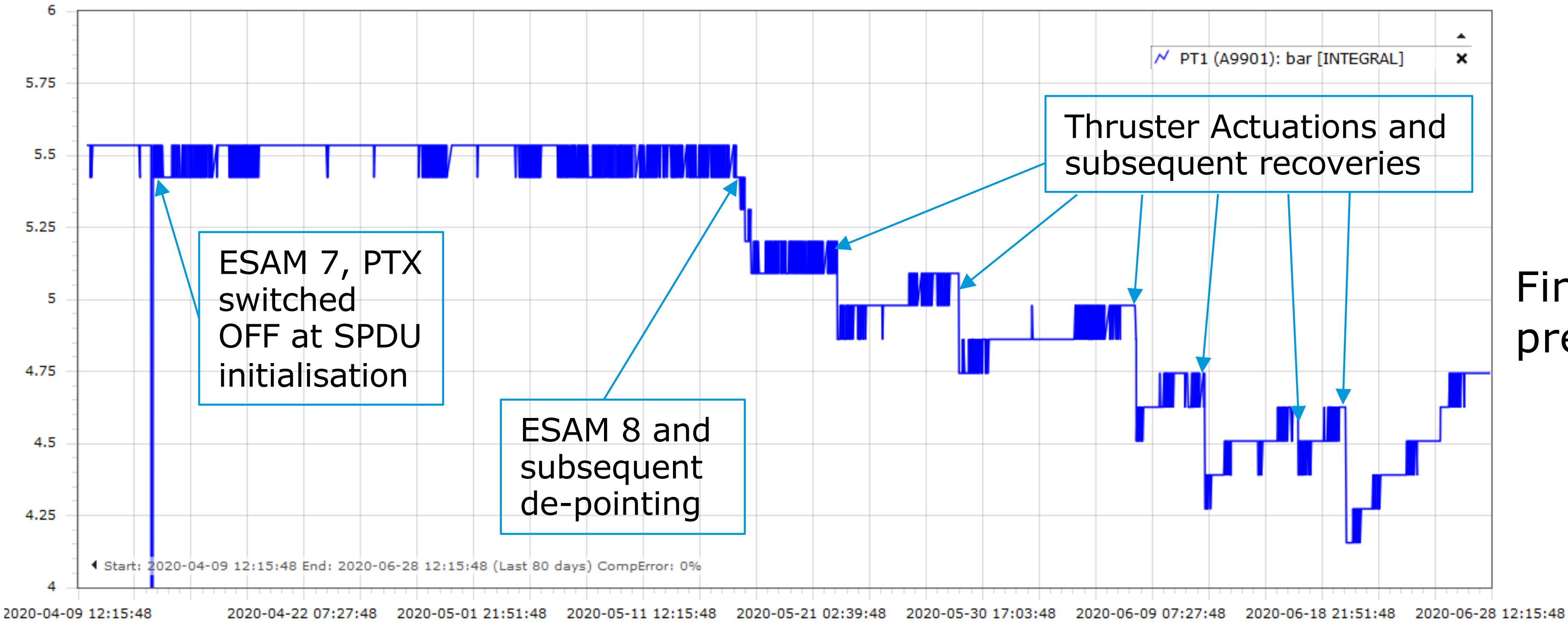


T6055 (RCS Pipes –Y) thermal excursions

Analysis of all observed changes in TN “INTEGRAL ESAM #8 Anomaly Investigation”

RCS Pressure Drops

RCS Pressure drops significantly at each thruster actuation (Post ESAM 8) and then recovers over a period of days



Final stable pressure?

Residual propellant assessment methods

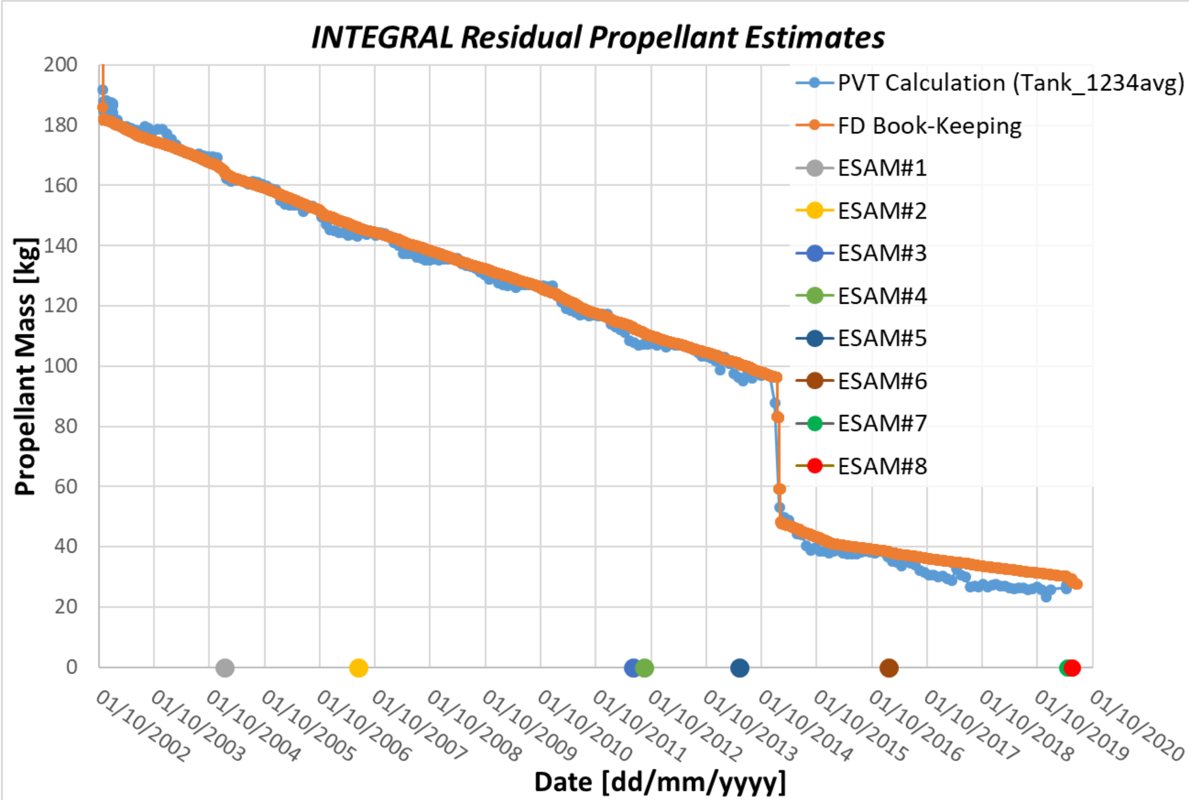
- Two methods used to assess the residual propellant

  1) **Book-Keeping**: based upon counting the number and duration of discrete thruster pulses and then calculating the propellant consumed by each, using thruster performance characteristics derived from ground-based calibration tests

  2) **PVT**: using 'Ideal gas law' equations to determine the tank 'ullage' volume (i.e. gaseous Nitrogen), based upon the RCS pressure and temperature measurements, to estimate the volume/mass of the residual propellant.

- Book-Keeping is calculated by Flight Dynamics and gives a reasonably stable estimate

- PVT is calculated by FCT off-line monitoring software but gives a more erratic estimate
- ESOC calculations, confirmed by ESTEC
- +/-10kg uncertainty



MEOR estimate can still be considered as reasonable.

Nitrogen

N_2 Absorption/Desorption

- N_2 absorbed into Hydrazine at BOL: **70 g**
- N_2 released back as gas into propellant side (tank and lines): **48 g (7.6 l @ p=5.5 bar)**
- The pressure decrease from 5.5 to 5.2 bar experienced on 2020-05-17 from branch B firings would mean ~**38 kg** propellant consumption in nominal conditions. This is clearly not possible and seems to indicate gas in the propellant lines and possibly empty or nearly empty tanks.

Pressure drop during manoeuvres

Possible cause of the anomaly: Expulsion of N_2 gas from the thrusters

- But the total estimated amount of trapped gas (48 g) would only be responsible for a pressure drop of **0.06 bar** in nominal conditions
- Observed pressure drop: 0.3-0.4 bar drop during the anomaly, and additional drops in later manoeuvres

→ Other phenomena must be contributing to the pressure drop

Expelled N_2 during wheel bias manoeuvres (2)

Results

Wheel_Bias	ON-time [ms]	N_2 [g]	N_2H_4 [g]	dp [bar]	N_2 (4 tanks) [g]	N_2 (1 tank) [g]
	Flight data	Sonic flow	BK	Flight data*	PVT	PVT
22/05/2020	44212	34.7	71.8	0.350	264.9	66.2
29/05/2020	34453	27.0	56.0	0.298	225.0	56.2
08/06/2020	35640	27.9	57.9	0.357	268.8	67.2

* A pressure recovery was seen after each manoeuvre, not taken into account here.

- Each wheel bias manoeuvre could have expelled 27-35 g N_2 gas bubbles (from ON-times)
- The associated pressure drop (excluding recovery) is compatible with an expulsion of 56-67 g N_2 gas bubbles **if 3 out of 4 tanks are empty and their membranes are intact**

Possible root causes

a) More N_2 may have passed through the membranes than the 70 g absorbed into the propellant at BOL. This would could have happened for 2 possible reasons

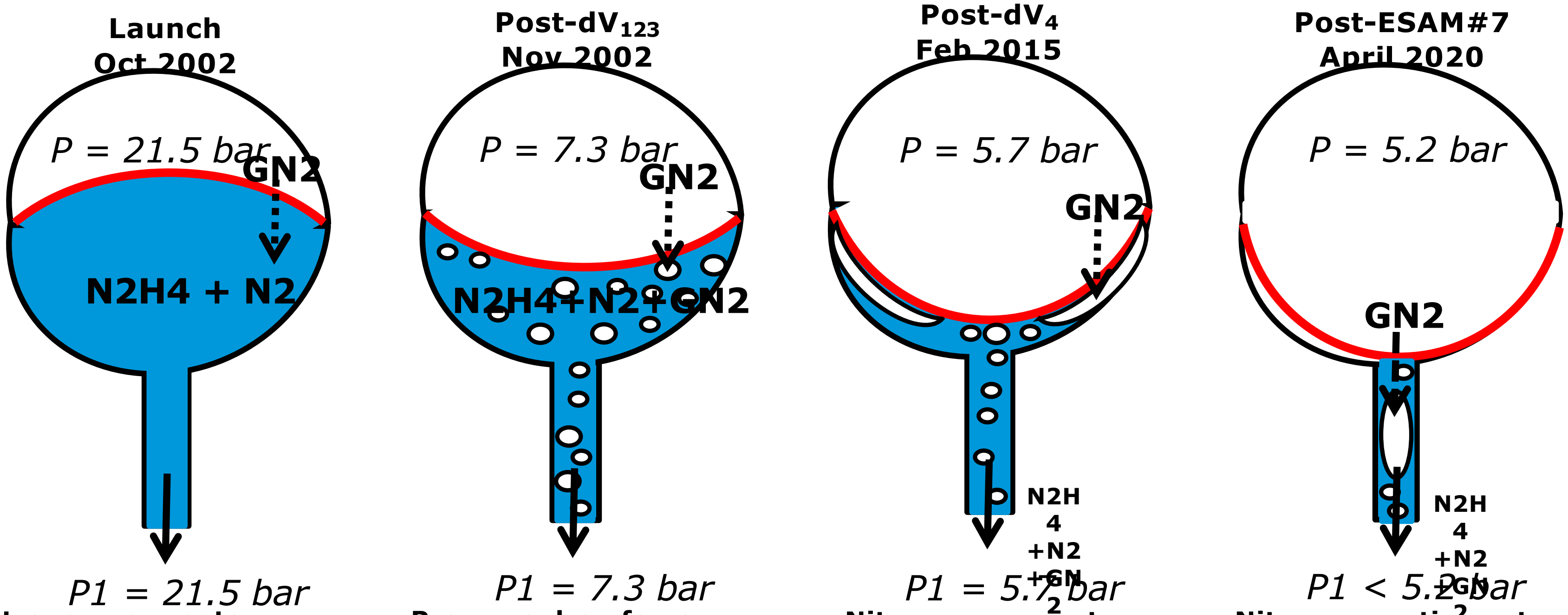
   i. rupture of a bladder membrane **(unlikely)**

   ii. diffusion of nitrogen through the membranes due to a positive delta pressure between pressurant side and propellant side (e.g. in case of empty tanks)

b) One or more of the tanks are empty. Therefore, their ullage can't further increase with decreasing system pressure, and a loss of pressurant in the propellant side would yield bigger pressure drops.

c) All tanks are empty. In this case, the only propellant left would be in the lines and as non expellable residuals in the tanks, for a maximum of about 2.4 kg of propellant **(unlikely)**

Nitrogen permeation through tank membrane



Nitrogen permeates membrane, gets absorbed into solution within N2H4 and then expelled through thrusters

Pressure drop forces some N2 out of solution, due to super-saturation, to form GN2 bubbles

Nitrogen permeates membrane to form gas bubbles as N2H4 is already fully saturated

Nitrogen continues to permeates membrane to form gas bubbles as N2H4 is already fully saturated

Thruster Tests proposed to determine cold gas (N2) performance at low pressures

- Worst case intermittent thrust

Proposed additional investigaton

In order to find the most probable root cause, a few additional activities are proposed:

1. **Re-assess the accuracies of both PVT and book keeping methods**, taking into account pressure transducer accuracy and drift, thermistor accuracy, thruster model (Isp) accuracy, and other possible error sources. This would limit the probable range in terms of remaining propellant
2. **Assess which tanks are empty by simplified thermal modelling** of the tanks with heaters and comparison with the thermistors reading. This could help explaining the pressure drops during wheel bias manoeuvres and point to either b) or c) as root cause.
3. **Perform cold flow tests on a spare thruster** with N_2. This would on one hand confirm the estimations of expelled N_2, and could also be used to estimate the "cold gas thrust" of the thruster.

Current Status

It is likely that between 25 and 30kg propellant are still on board

- Thruster firings are less efficient at low pressure
- Possibly one or more tanks are empty

Thrusters are firing Nitrogen in addition to hydrazine

- Why there is so much N2 in the system is not fully understood
- Why this behaviour suddenly started now is not fully understood
- Recovery of system pressure after thruster activity is not fully understood

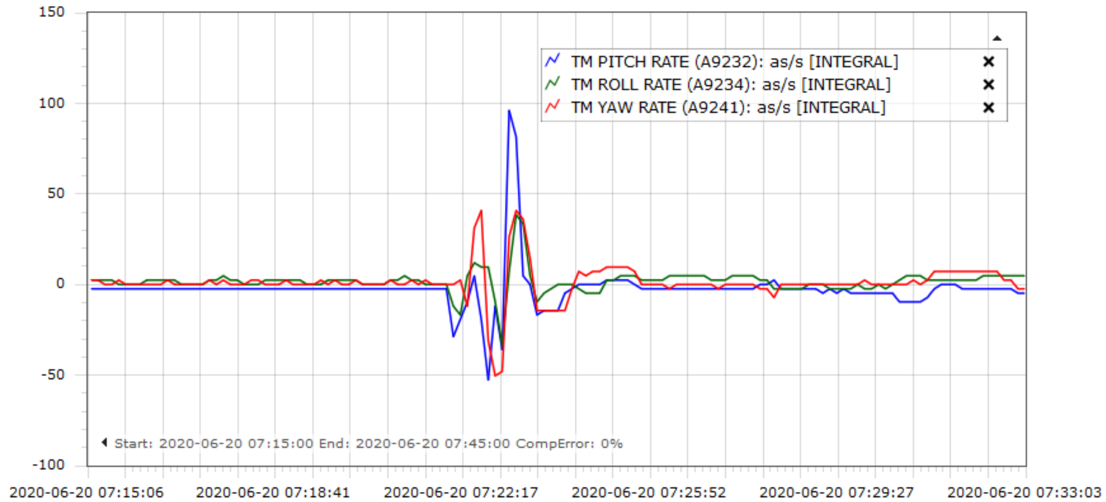
The spacecraft is under control and we can continue to operate under the current conditions

Way Forward

The Problems we face

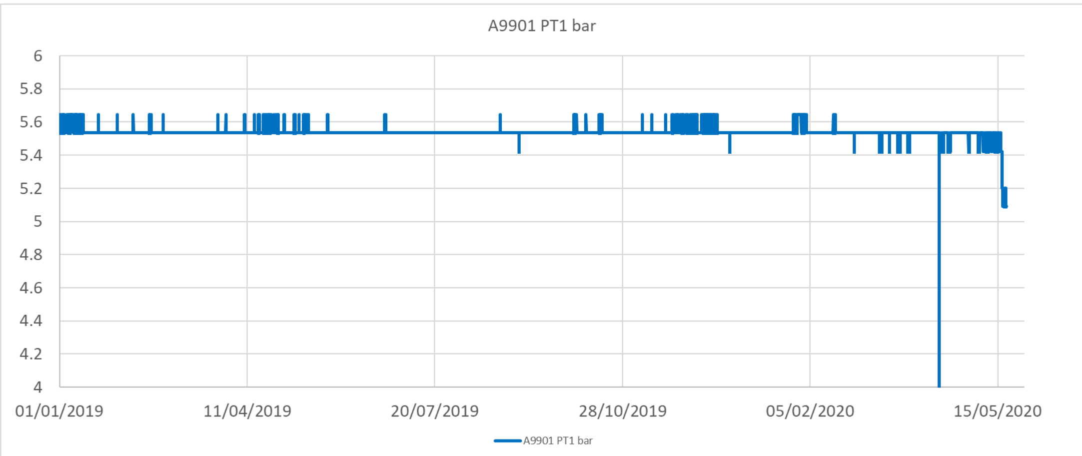
Thruster performance is unpredictable

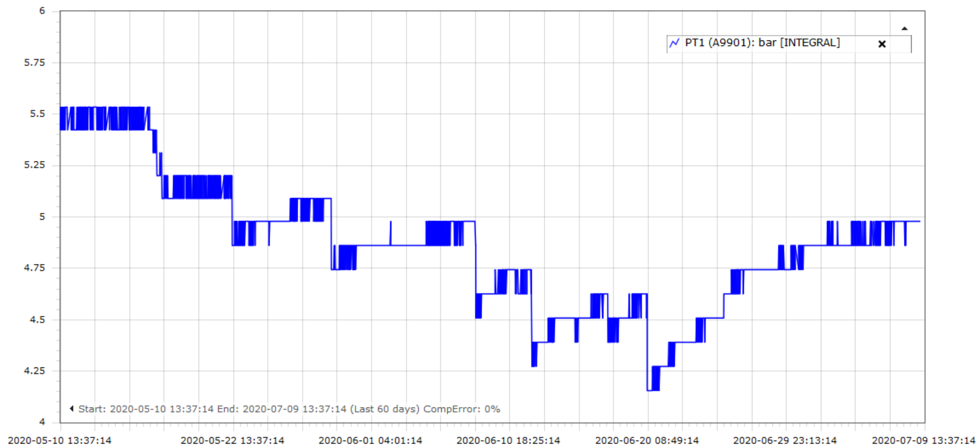
- Leading to safe mode entry
  - Waste of time + unreliable



Use of thrusters causes significant loss in RCS pressure at each actuation

- There is a slow recovery afterwards over several days



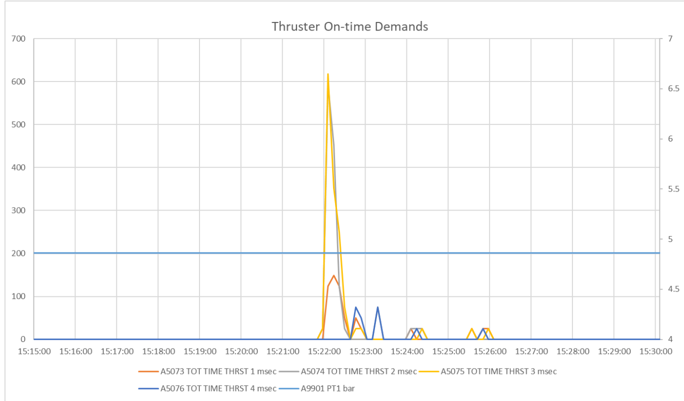


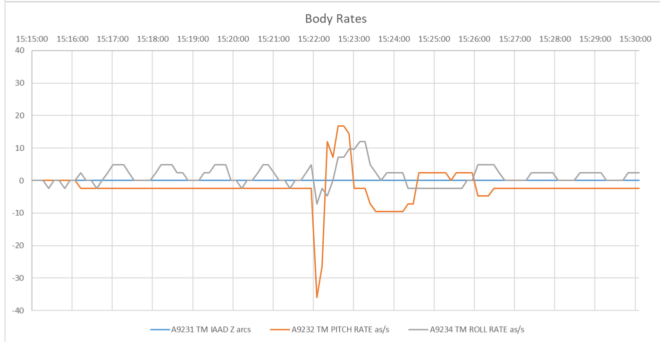
The Solutions

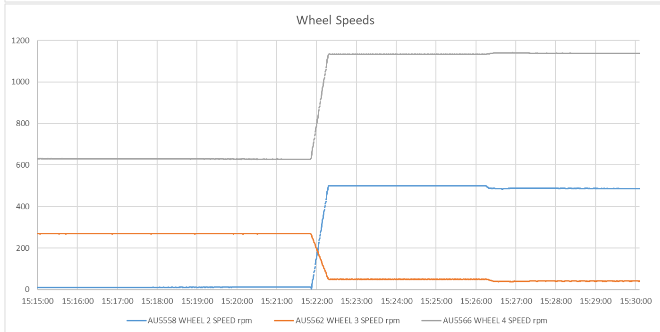
A two pronged approach is being followed

- Design of a new bias procedure to ensure safe, reliable biasing without ESAM entry in the case of manageable under performance

- Wheel Speed adjustment by selection of suitable yaw slew pattern (Z-flip)
  - Allows us to minimise the number of biases (thruster usage)
  - Implies multiple revolution planning (SOC and MOC FDS affected)







Future Wheel Bias Strategy

Bias related operations split into three parts:

- Automated Pre bias configuration: Some safety criteria disabled + Gyroscope switch on to allow ground to monitor rates
- Wheel bias using classical procedure + Bias execution monitored by MOIS
    - MOIS intervenes before possible ESAM entry
- Automated Post bias reconfig: set standard safety criteria Requires _Gyroscope off
- WHEEL_BIAS window of duration 1 hour, Bias ED at WHEEL_BIAS open + 20m.
- automated Procedures for pre and post bias
- automated safety monitoring during bias
- On-board monitoring entry

Future Wheel Bias Strategy

Monitoring

- Safety Level 1a
    - if body rates > 72 as/s abort the manoeuvre (Safe mode at 720as/s)
- Safety Level 1b: On board monitoring for Thruster on times >2000ms
    - On-board command to abort the bias
- Safety Level 2
    - if > body rates > 120 as/s perform an RCS swap to B branch
- Safety Level 3: safe mode will trigger if one of the new active FDE criteria during TCM will be violated (TTIM=992 sec, RADX,Y,Z=720 as/s, FSPAAD)

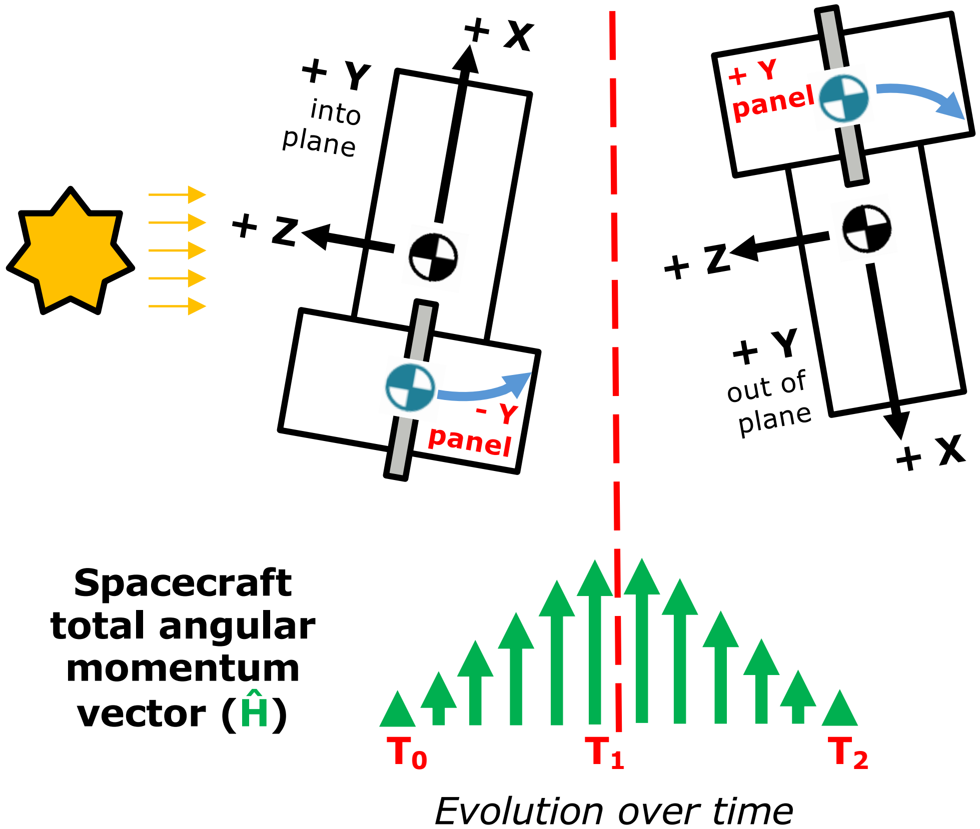
Will prevent any unnecessary safe mode entry

Future Wheel Bias Strategy

Fully implemented, tested and deployed

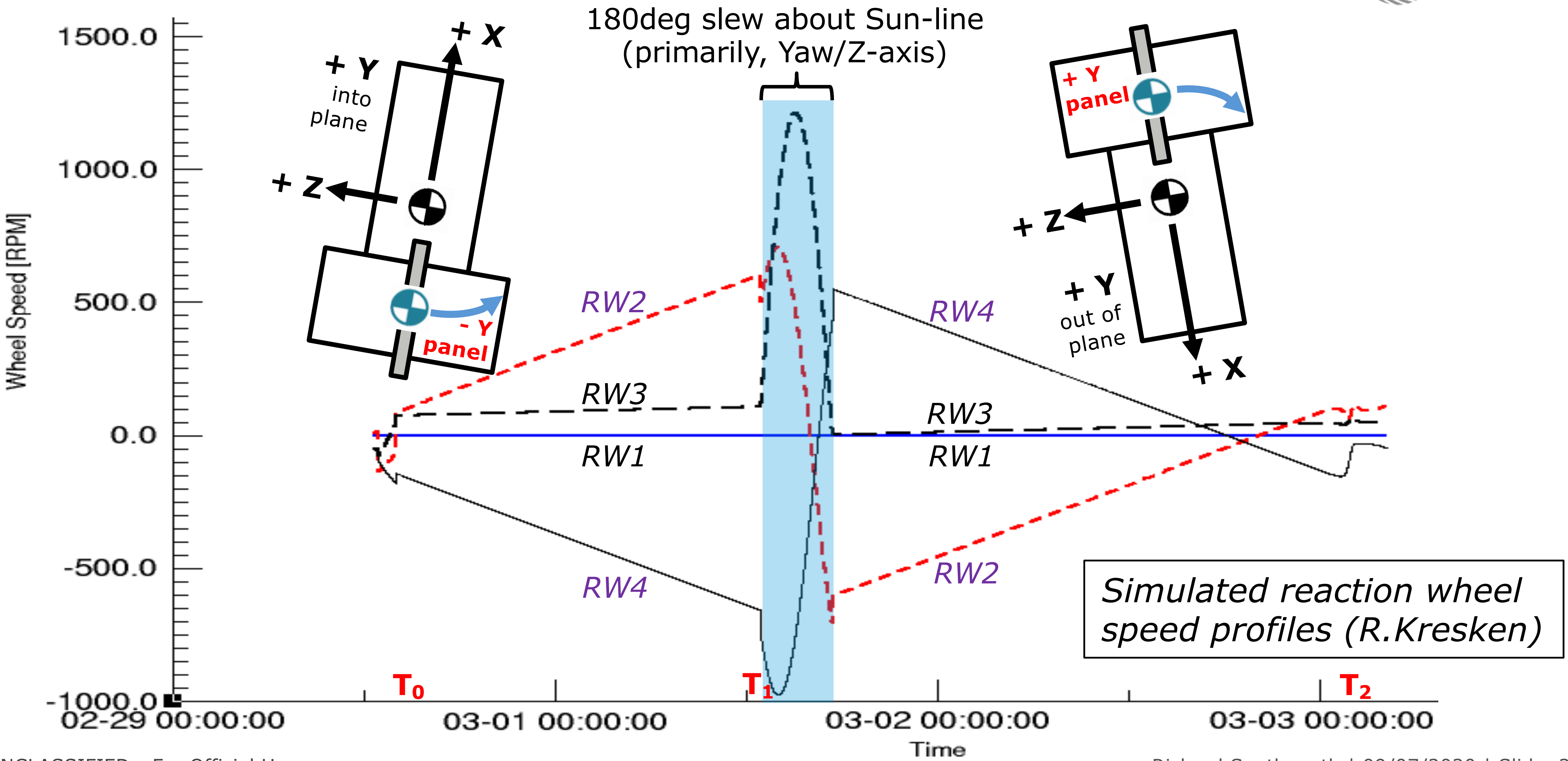
First autonomous bias was on 3/7/2020

Wheel speed Control by Yaw Slew



1) Reaction Wheel Bias at T_0 establishes the spacecraft's total angular momentum vector (Ĥ) at a low value (e.g. all speeds to 0 rpm)
2) Solar photon pressure imposes an external torque on the spacecraft
   - '<u>anti-clockwise</u>' in the inertial frame, increasing Ĥ
3) <u>180deg slew on reaction wheels</u> about the Sun-line (primarily, Yaw/Z-axis) performed at T_1 when Ĥ reaches upper threshold
   - Ĥ is <u>conserved</u> throughout the slew, transferring angular momentum between the reaction wheels
4) Solar photon pressure imposes an external torque on the spacecraft
   - '<u>clockwise</u>' in the inertial frame, decreasing Ĥ
5) <u>180deg slew on reaction wheels</u> about the Sun-line (primarily, Yaw/Z-axis) performed at T_2 when Ĥ again reaches a low value
   - Step 2) to 5) can now repeat indefinitely

Resulting reaction wheel speed profiles



In Flight Test - Wheel Speeds

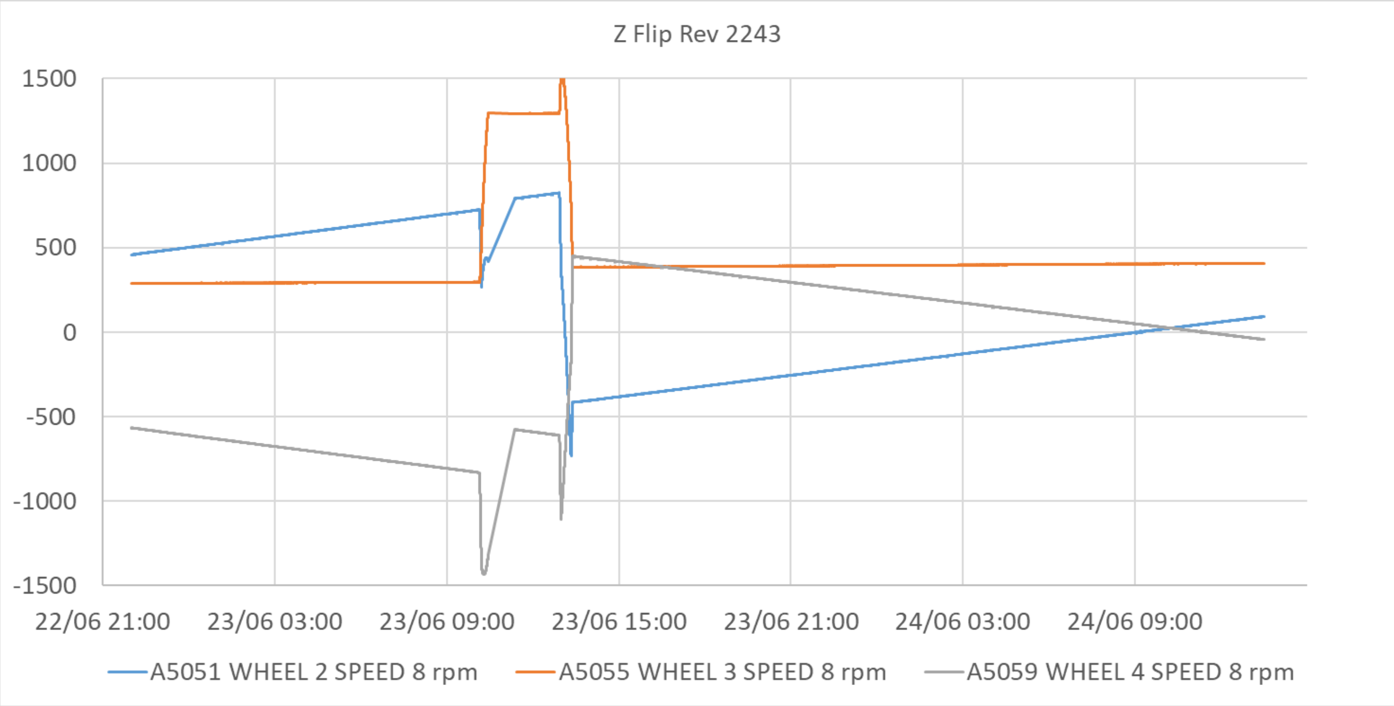
The manoeuvre consisted of 2 slews (to respect the slew stability constraint) separated by about 2 hours the total magnitude was about 155DEG.

At a drift rate of 20RPM/hour we compensated for about

- 55hours drift on wheel 2
- 64hours drift on Wheel 4

Wheel 3 drifts only slowly – no SRP compensation

Integral has no low speed constraint



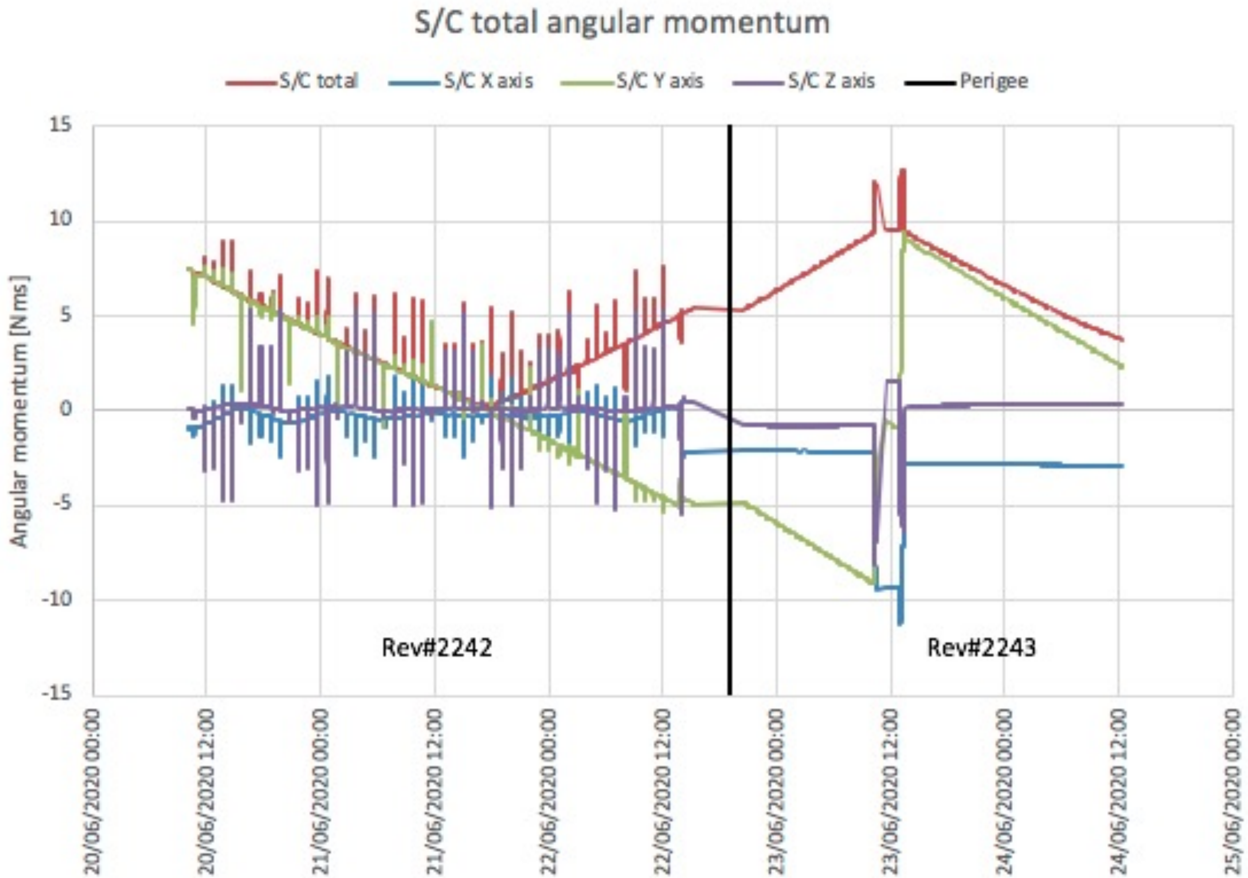
In Flight Test – Angular Momentum

Angular Momentum Evolution

In flight data demonstrates management of S/C angular momentum is as expected

⇒ Angular momentum can be controlled without biasing reaction wheels

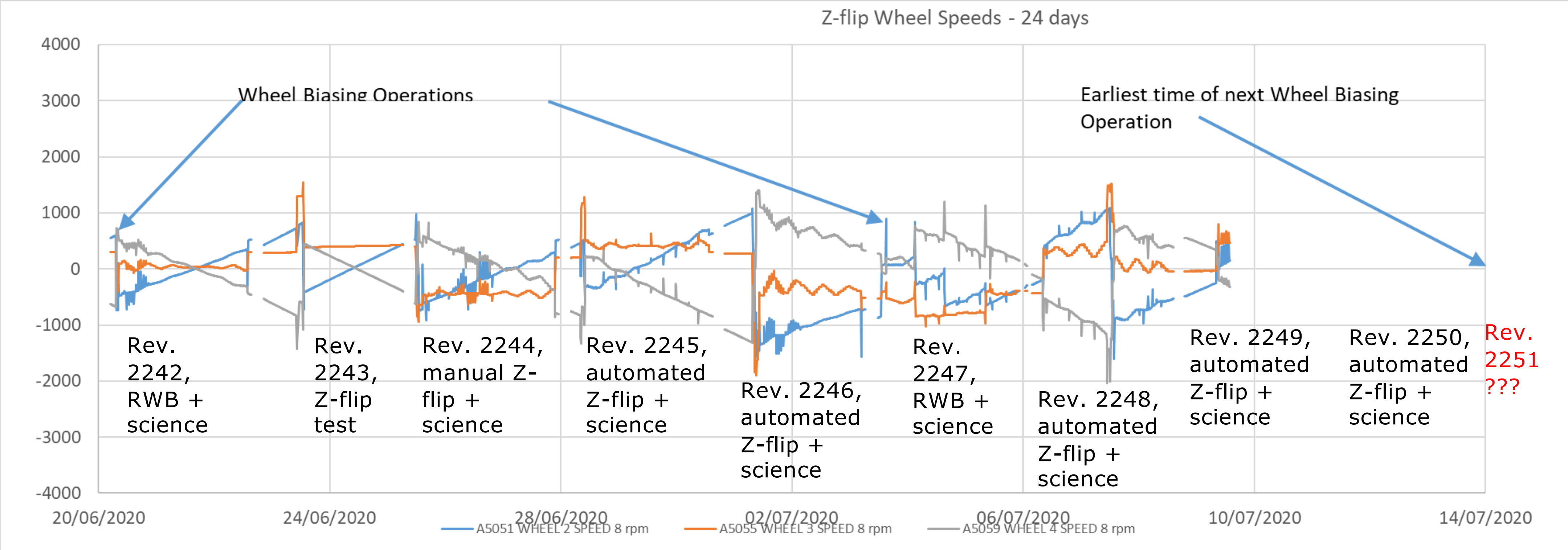
We were so impressed we started using it immediately!!



Resulting Wheel Speed Management

Wheel speeds since last RWB

- 20 days with just 2 biases, and counting…



Science Activities Since ESAM 8

Routine Science based on manual wheel bias in working hours, Monday to Sunday

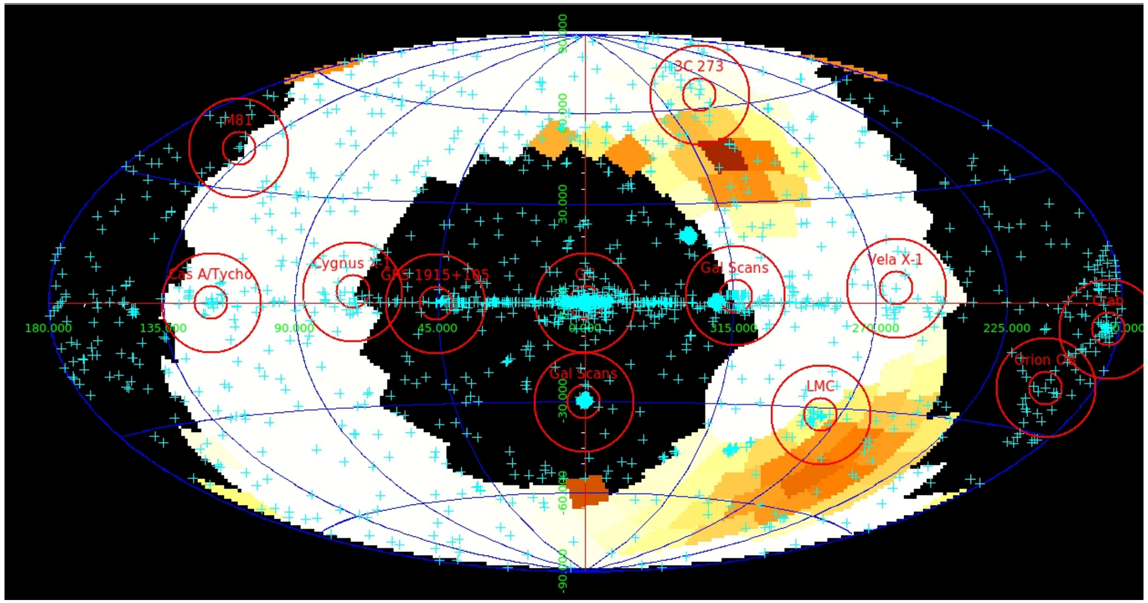
- Revolution 2239 (12/6/2020) to
- Revolution 2242 (20/6/2020)

Z-flip test revolution – no science

- Revolution 2243 (22/6/2020)

Routine science based on Z-flip

- Revolution 2244 (25/6/2020)
- Revolution 2245 (28/6/2020)
- Revolution 2246 (30/6/2020)
- Revolution 2247 (3/7/2020)
- Revolution 2248 (6/7/2020)
- Revolution 2249 (9/7/2020) – currently executing
- Revolution 2250 12/7/2020) - OK to execute



Coordinated Planning effort MOC-SOC
Manpower intensive
Trial and Error

Interim Planning Approach

SOC will select targets for several revolutions

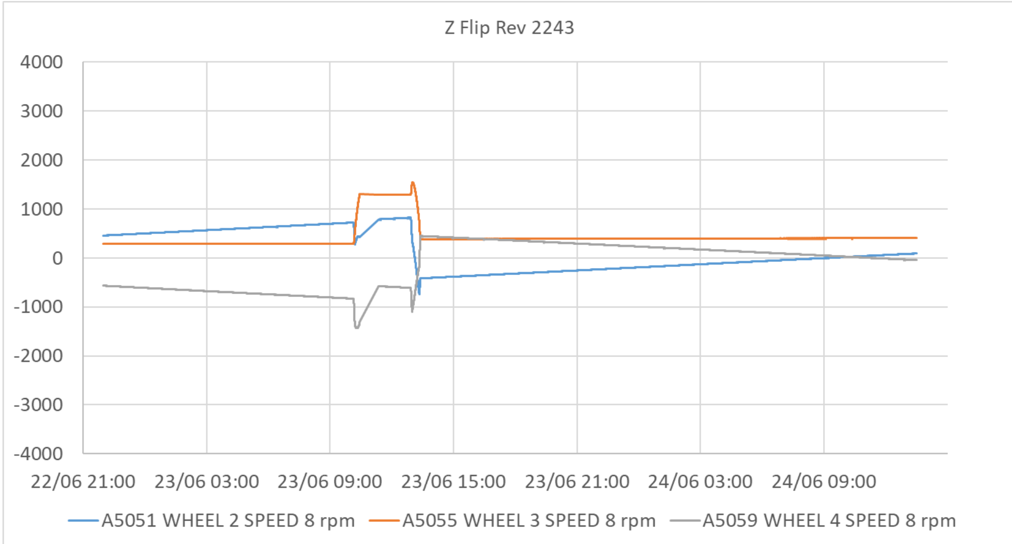
- SOC will try to allocate targets based on Z-flip needs – minimise biasing
  - As SOC / FD gain experience this should become easier and more flexible
- Targets / Slew pattern to be assessed by FD before planning
  - Currently FD can reliably propagate wheel speeds over 2 revolutions
  - Target is 3+
- The results of this will also provide valuable test data for design of an angular momentum management tool to enhance the current planning progress

If we need to bias we will do so – we have a reliable procedure

Long Term Planning Approach

Multiple revolution planning approach

- Angular momentum management to minimise / avoid biases



Up to now

- Bias to accommodate SOC slew pattern

Future

- SOC slew pattern to accommodate Ops without bias where possible and respect all S/C constraints – secondary objective after fulfilling science objectives

To be Done

Deployment of new wheel bias strategy – end July

Z-flip Planning Software Updates at MOC and SOC

- Formulate requirements and Trade-offs, assess effort
    - 1st 'workshop', 7th July
- Wheel profile prediction and planning improvements
    - Give SOC the capability to assess the results of their planning on wheel speeds and angular momentum management