XMM fuel estimates

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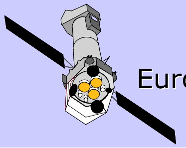
- Fuel estimation
  - Book-keeping
  - PVT (Pressure-Volume-Temperature: applying the Ideal Gas Law)
  - Thermal Propellant Gauging Technique (TPGT) (thermal knocking)
- Review and Way Ahead

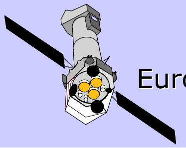
- Reference Documents



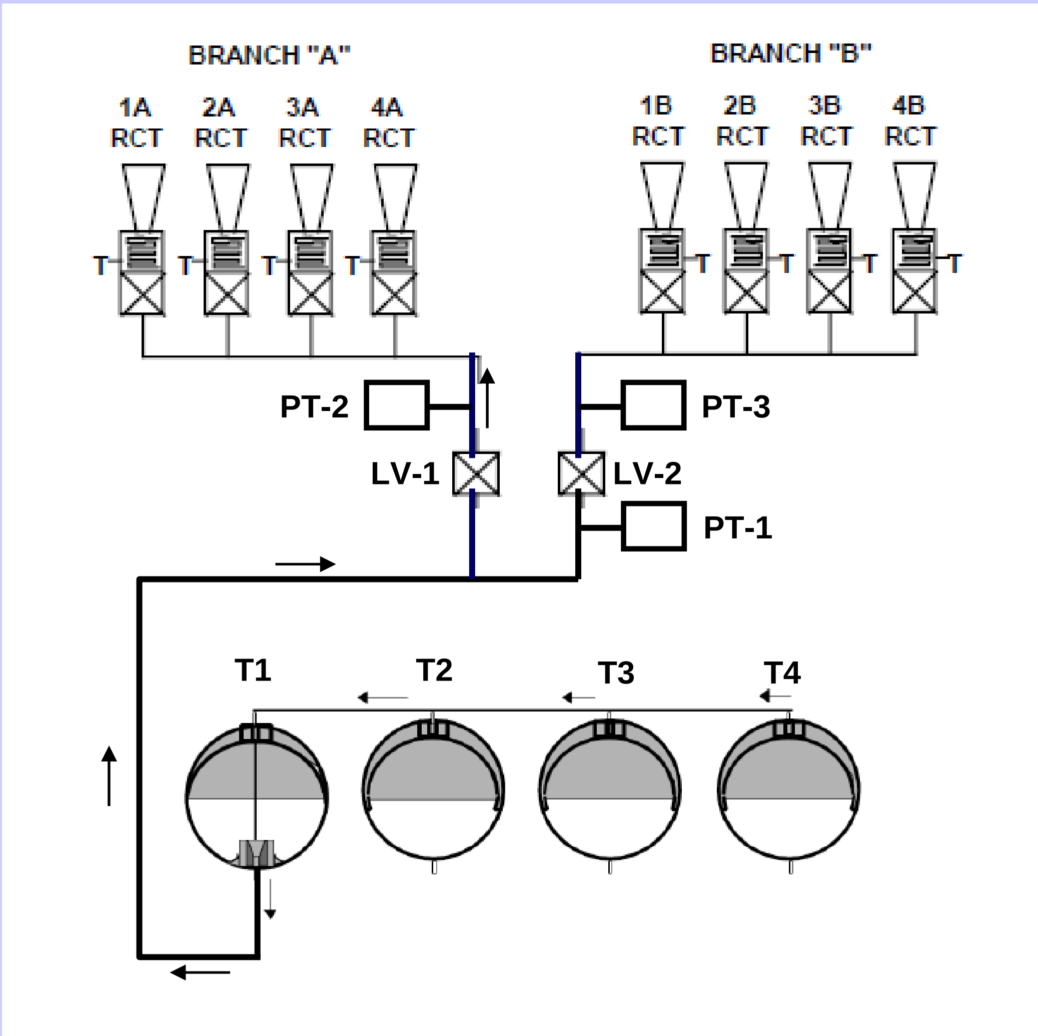
Background

- On July 15, 2009, DP TM TD057 (tank temps. range) went OOL HH with a value of 10.41 degC. Spacecraft Anomaly XMM_SC-60 raised
- Tank1 Thermostat failed
- OOL triggered because Tank1 temperature was more than 10 degC lower than Tanks 2, 3 and 4

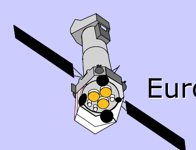
- Conclusion from Industry (Astrium) was that this excursion had no impact on Reaction Control System
  - No possibility of pressurant gas entering pipes downstream of Tank1 unless Tank1 nearing empty (< ~6Kg)
  - Total fuel then ~80Kg (or 20Kg per tank)
  - Lower temp encourages more fuel into Tank 1
- Recommendation
  - Maintain Tank1 temperature control using time-tagged commands keeping temperature range between tanks <5degC
  - Try to gauge fuel distribution between tanks to better determine when a tank is near empty



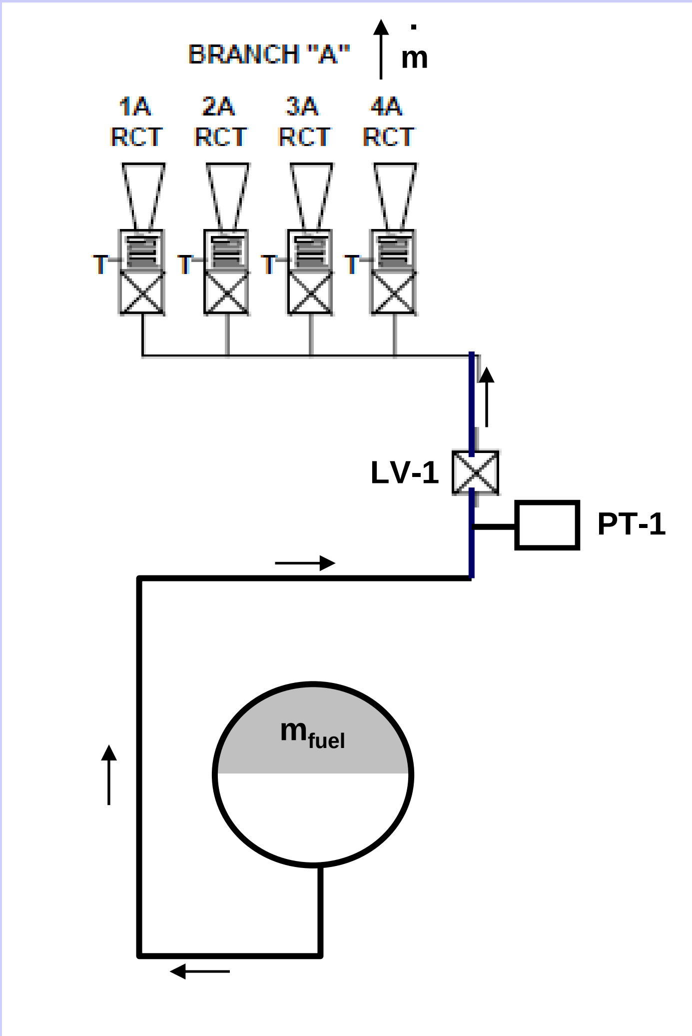
XMM Reaction Control System



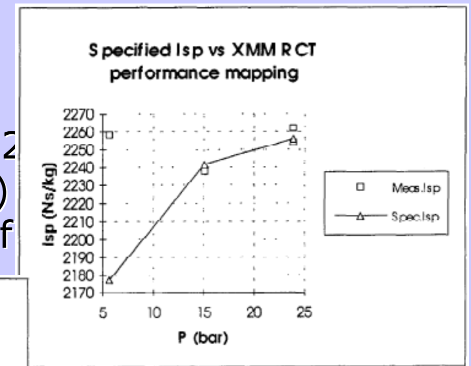
- 4 Tanks
  - Hydrazine Fuel
  - Helium Pressurant
  - T1 Main Tank
  - T2,T3,T4 Aux
- Latch Valves
  - LV-1 feeds Branch A
  - LV-2 feeds Branch B
- Pressure Transducers
  - PT-1 System Pressure
  - PT-2 Branch A Press.
  - PT-3 Branch B Press.
- Reaction Control Thrusters
  - 4x Branch A
  - 4x Branch B



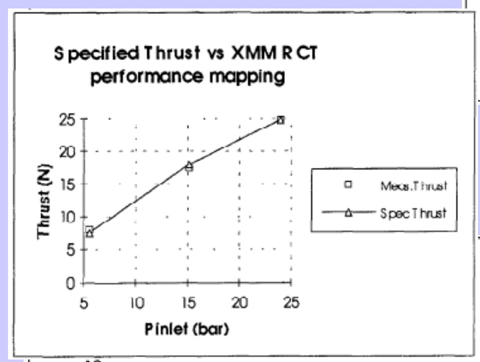
Book-keeping: Principles



- Specific Impulse (Isp) of thrusters known
  Isp ~ 2250Ns/kg but varies with inlet pressure



- Thrust known
  - Nominally 25N (at 2
  - Now <10N (<7bar)
  - Can measure with f



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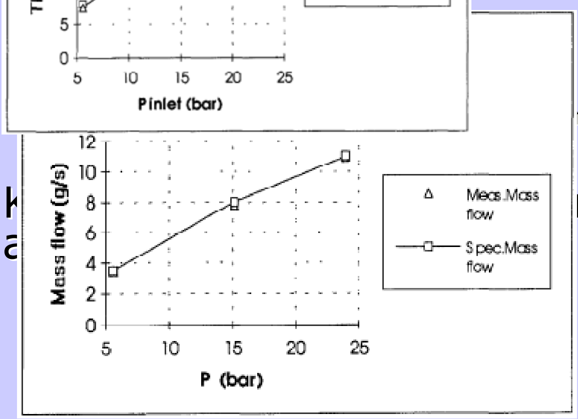
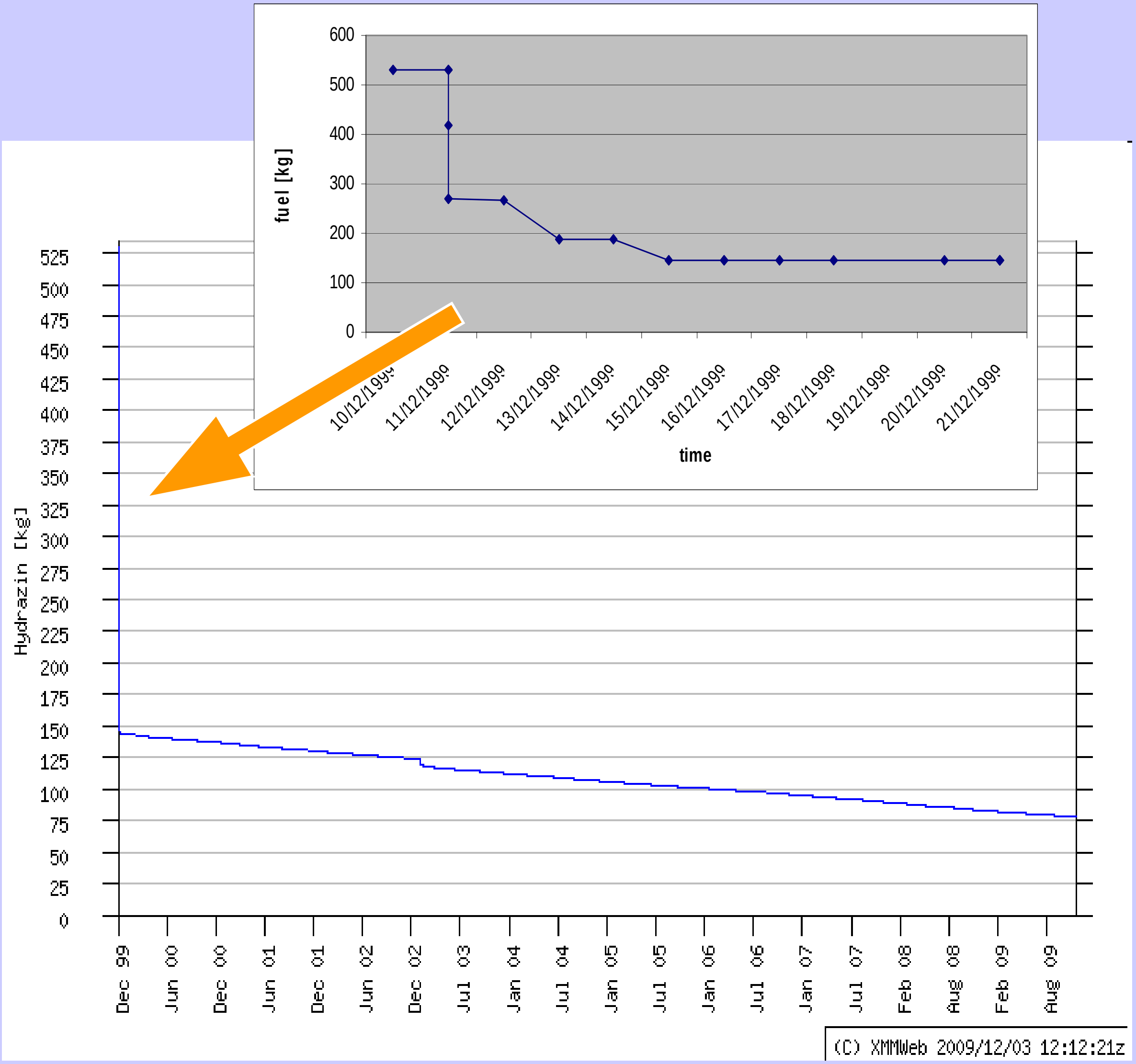
n / Isp

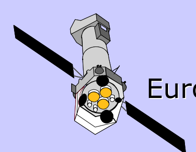


- K uster
  a

Book-keeping: Running figures

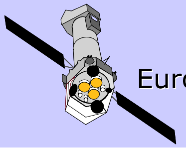


Remaining fuel (March 2010)	76.3 [kg]
Consumption last 12 month	5.29 [kg]
average fuel consumption (since 2003-03-01)	0.48 [kg]
residual lifetime in month	116 [-]
extrapolated milage	Sep 2019

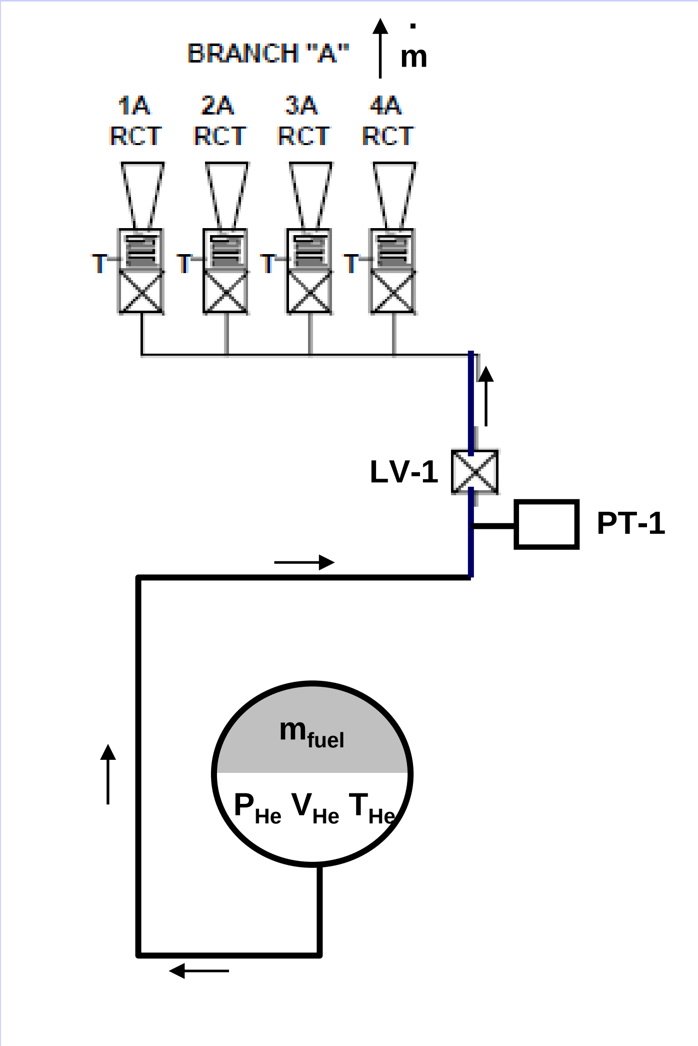


Book-keeping: Errors

- BOL =5 % (<11Kg), EOL =20% (18Kg) [RD-2]
- Actually EOL is when Inlet Pressure = 8 bar. PT-01 < 7bar So we are already past EOL!!
- No calibration for Thrust and Isp below this pressure. Also calibration data is based on constant thrust. Momentum dumping is via short pulse firings.
- PT-01 reading need to be corrected for Temperature variations and also converted to correct inlet pressure to use these calibrations.



PVT: Principles



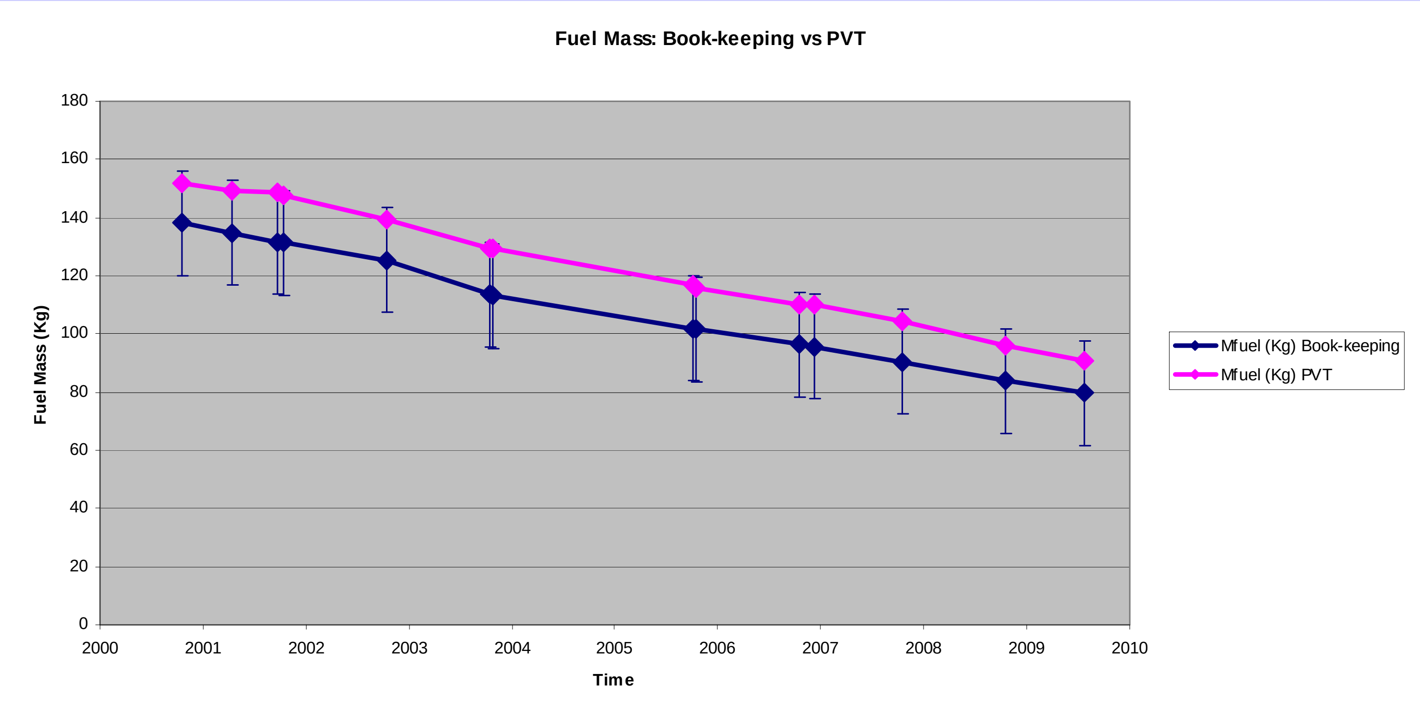
$$P_{He}V_{He} = n_{He}RT_{He}$$

where

- P_{He} ~ PT-01
- n_{He} number of moles of He is constant. Assume 165moles loaded (~660g)
- R gas constant
- T_{He} = average temp of He from tank thermistors
- $V_{He} = V_{tank} - m_{fuel}/\rho_{fuel}$

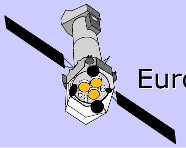
$$m_{fuel} = \rho_{fuel} * (V_{tank} - n_{He}RT_{He}/P_{He})$$

PVT: Spot Checks



- PVT figures (first est. from FCT) follow the book-keeping (Flight Dynamics figures)
- No evidence of leakage

- Error bars for Book-keeping set at +/- 18Kg
- PVT errors estimated to be 12Kg [RD-2]



Thermal Gauging: Principle

- The thermal response of the propellant tank when heated is related to the propellant load.

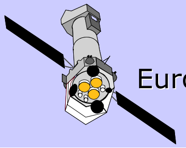
- Apply the Energy equation

$$Q.\Delta t = m.Cp.\Delta T$$

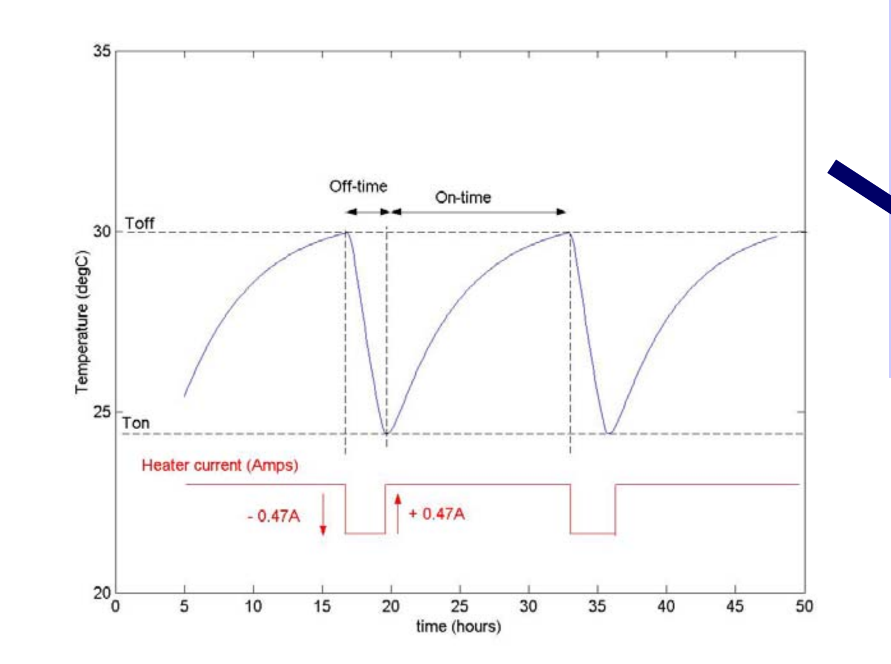
  - Where:

  Q is applied heat rate minus heat loss to the environment (J/s)
  Δt is the change in time (s)
  m is the mass of the tank system (kg)
  Cp is the specific heat of the tank system (J/kg.K)
  ΔT is the change in temperature (K)

- Ie. A full tank should have greater heat capacity, therefore requires longer heating time to reach a given ΔT than an empty tank.

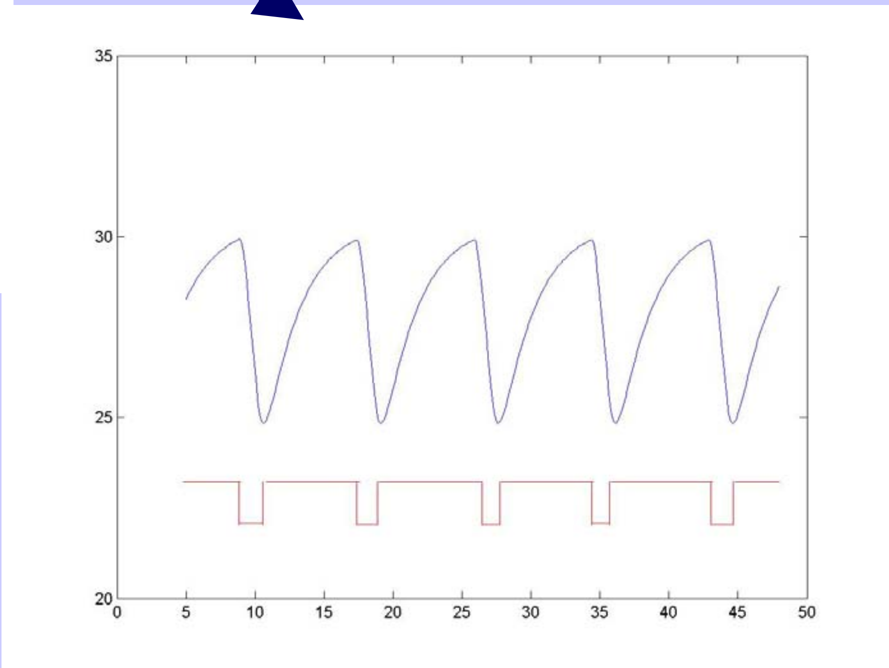


Tank Duty Cycle



Over lifetime

- Temperature gradient increases
- Temperture cycle time (peak-to-peak) reduces
- Heater Off-time (or On-time) reduces



Fuel ratios for each tank

- For any tank

$$m.Cp = [m.Cp]_{tank} + m_{fuel}.Cp_{fuel} + m_{He}.Cp_{He}$$

If $[m.Cp]_{tank}$ and $m_{He}.Cp_{He}$ neglected

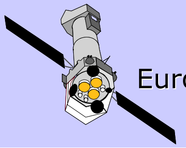
If Q considered constant (ca. 14W steady heat input)

Then

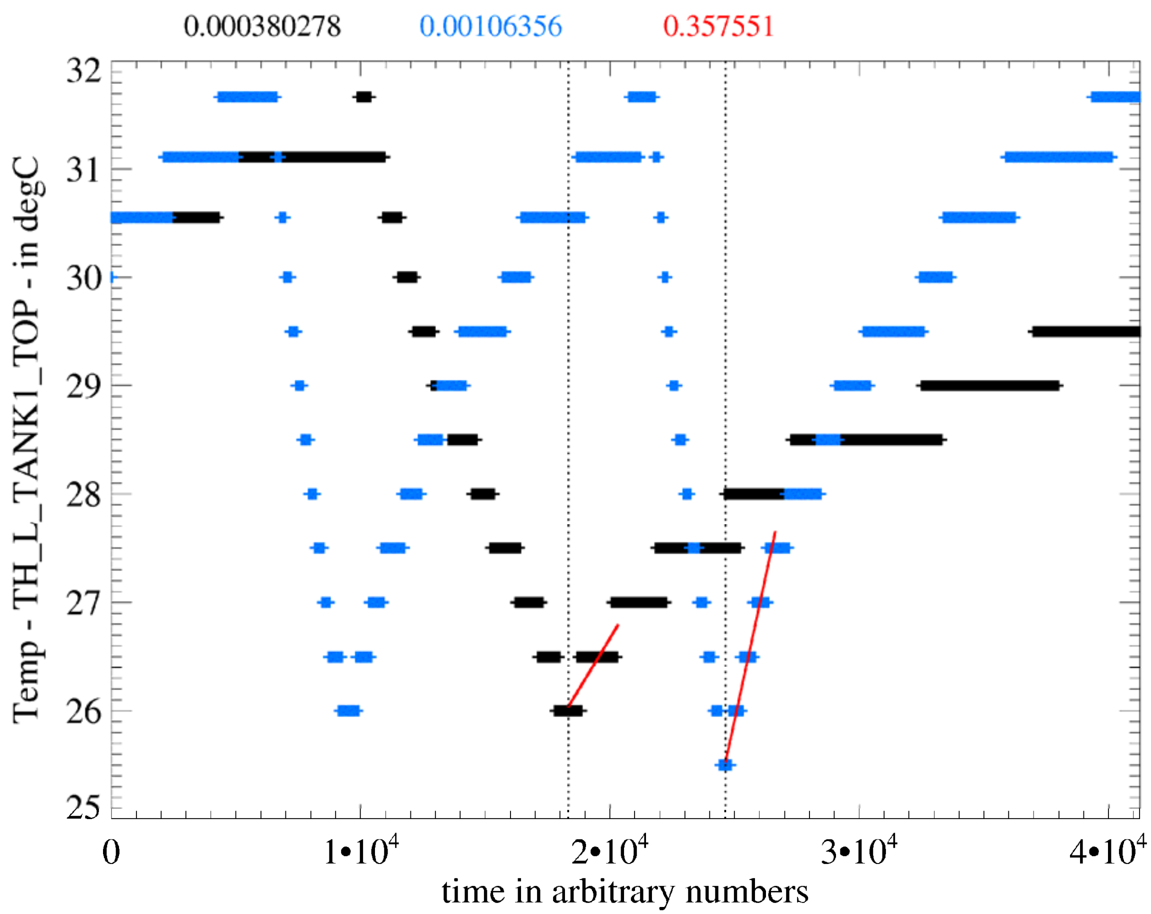
$$[m_{fuel}]_{rev\text{-}1} / [m_{fuel}]_{rev\text{-}n} = [\Delta t/\Delta T]_{rev\text{-}1} / [\Delta t/\Delta T]_{rev\text{-}n}$$

Or if ΔT is constant (thermostat set-points fixed)

$$[m_{fuel}]_{rev\text{-}1} / [m_{fuel}]_{rev\text{-}n} = [\Delta t]_{rev\text{-}1} / [\Delta t]_{rev\text{-}n}$$



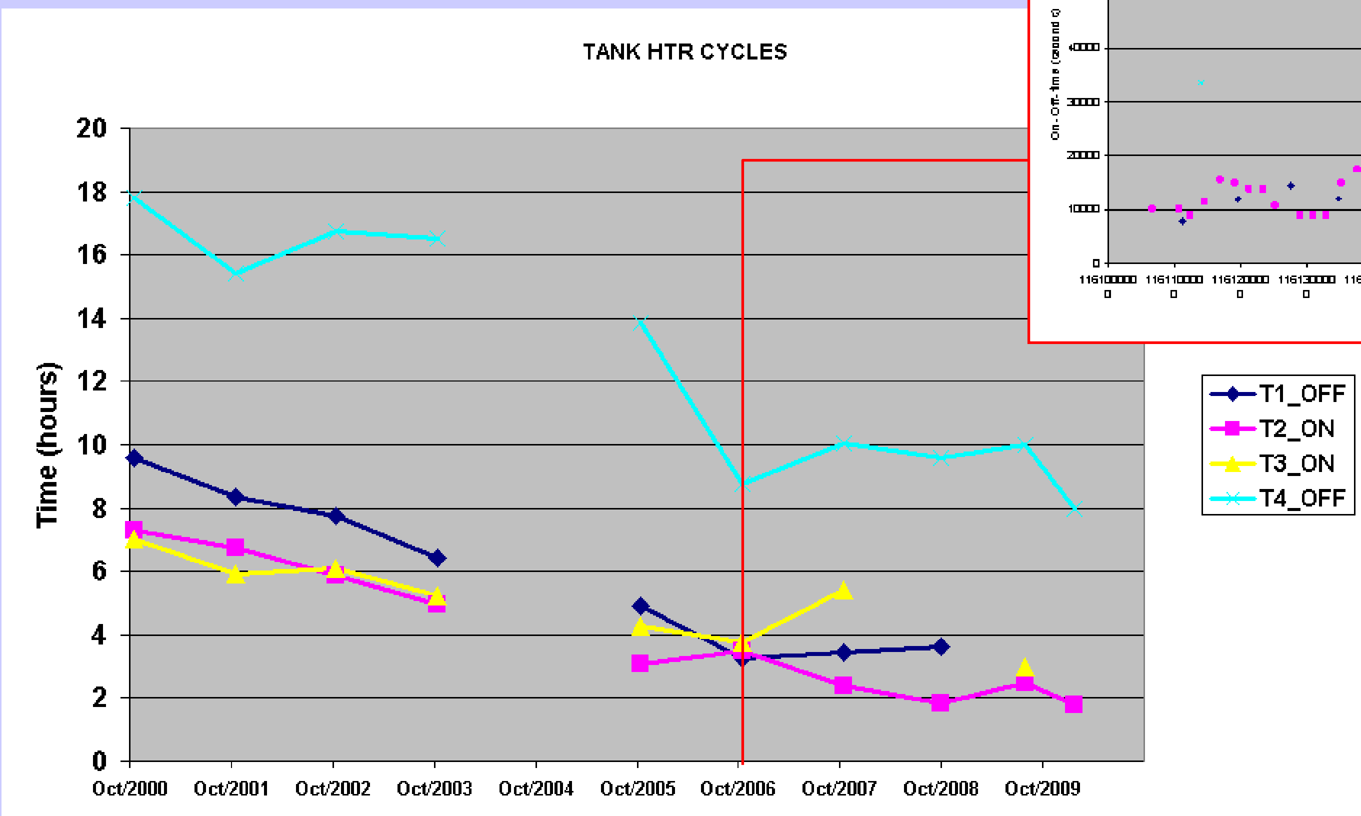
Try Tank 1
$[\Delta t/\Delta T]_{rev-100} / [\Delta t/\Delta T]_{rev-1000}$

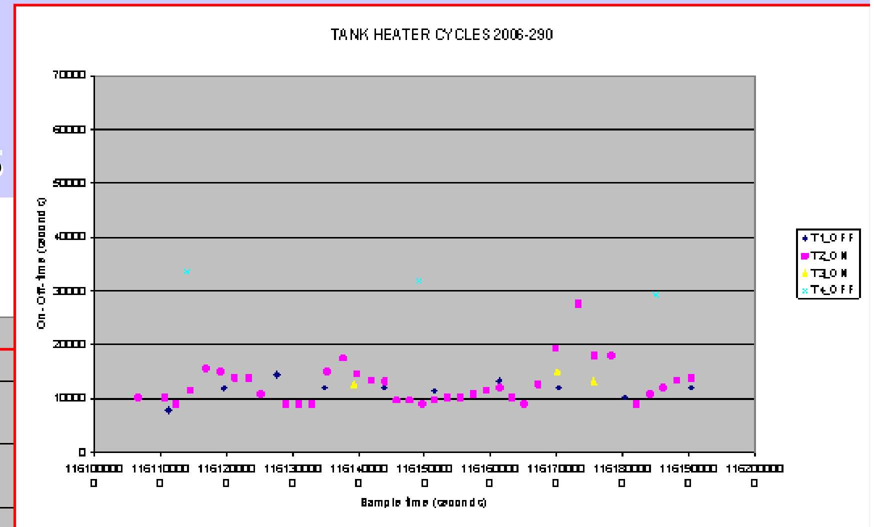


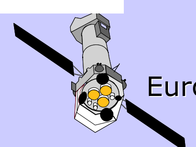
- prove of concept: data from rev 100 compared to rev 1000
- In reality due to the quantization of HK data the method is highly dependent on the data selection for the determination of the slope

Fuel Ratios: Cycle Time Measurement

- Method 1
  - Spot checks of Tank cycles over 10 days at 1 year intervals

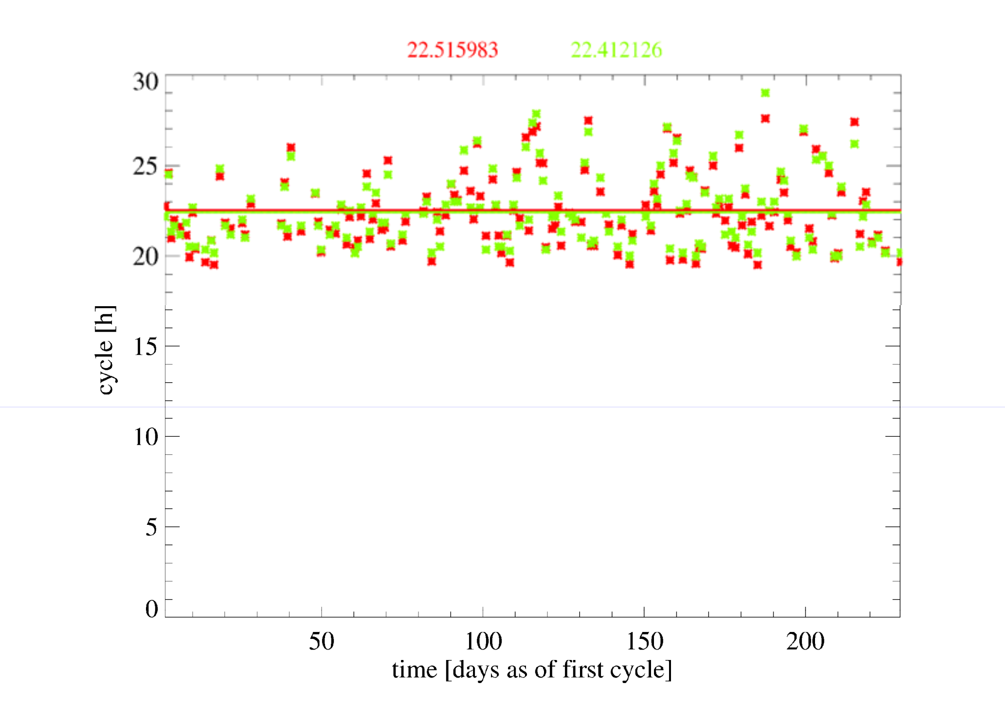






Fuel Ratios: Cycle Time Measurement

- Method 2
  - –Statistical analysis of all temperature data over 230 days in 2000 and in 2008

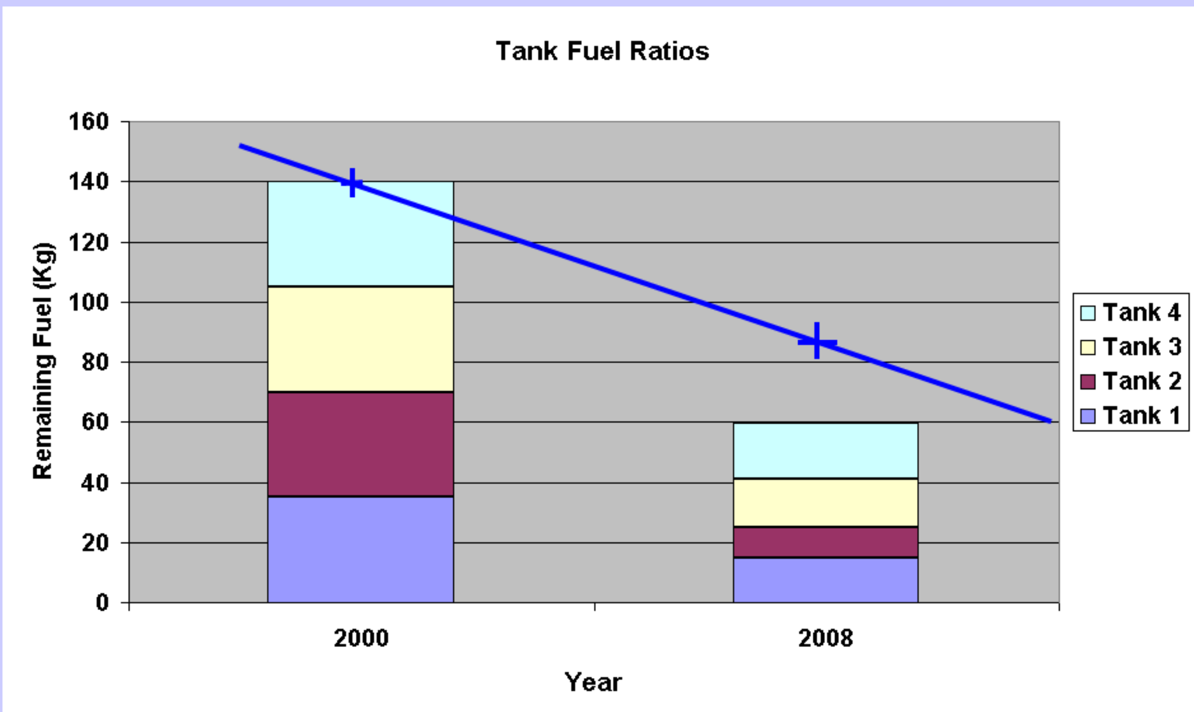


- Example of Cycle times
  - –Green -with angle correction
  - –Red - without angle correction

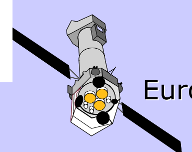
Compare to Book-keeping

	Fuel content in 2008 with respect to 2000			
	Tank1	**Tank 2**	**Tank 3**	**Tank 4**
Method 1 Spot checks	**38%** ± 12	**25%** ± 13	**43%*** ± 8	**54%** ± 8
Method 2 Statistical Analysis	**47%** ± 6	**33%** ± 6	**48%** ± 6	**52%** ± 6

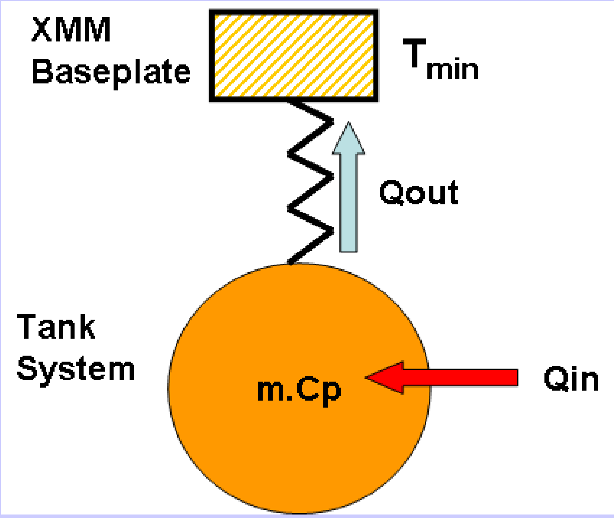
* Data taken from 2009 for Tank 3



- Methods agree within error margins
- Tank 2 supplying more Fuel?
- But 30Kg fuel missing?

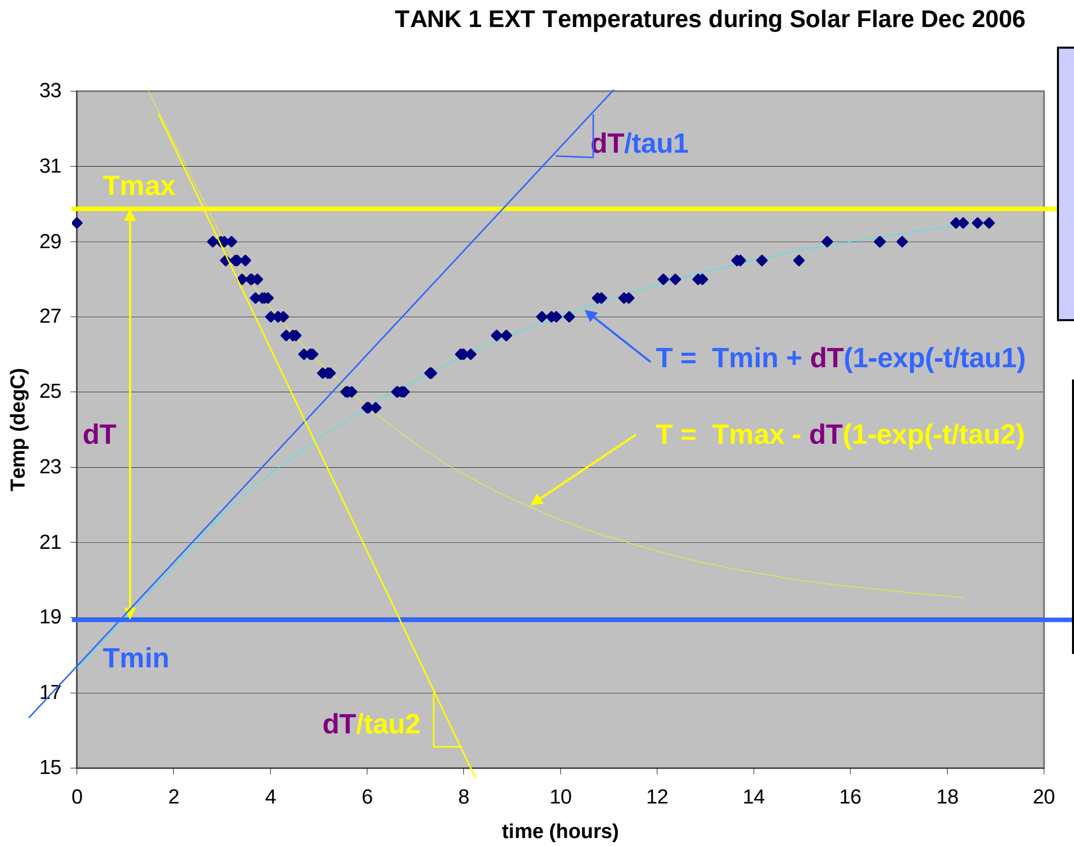


Thermal Gauging: Method 3



- In the simplest form a single tank system can be described as
  - a Capacitance (m.Cp)
  - with a Conductive coupling to the environment (the XMM base plate).
- In the steady state condition with heater off the system will be at Tmin.
- When heat is applied at a constant rate Qin the tank temperature will increase.
- The higher the temperature with respect to Tmin the higher the heat losses Qout until eventually the tank system reaches equilibrium again at Tmax with Qin = Qout.

Method 3: System Response



When heating from Tmin to Tmax:

$$T = T_{min} + \Delta T\,(1 - \exp(-t/\tau_1))$$

$\Delta T = T_{max} - T_{min}$

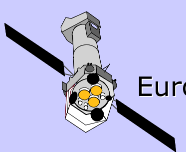
tau1 = Time constant for heating

When cooling the function is:

$$T = T_{max} - \Delta T\,(1 - \exp(-t/\tau_2))$$

$\Delta T = T_{max} - T_{min}$

tau2 = Time constant for cooling



Method 3: Analysis

- For the heating case:

Differentiating $\Rightarrow d/dt(T) = \Delta T/tau1\ (\exp(-t/tau1))$

- In the initial condition when temperature T=Tmin and time t=0 the gradient is therefore simply:

Initial gradient $= \Delta T/tau1$

- This initial gradient is shown as the blue line (previous slide)

- If it is assumed that at this instant the heat loss is zero (Qout = 0) and all heater power is therefore applied to the tank (Qin = heater power), then if we apply the energy equation (see Thermal Gauging Principle slide) we have:

$$Qin / m.Cp = \Delta T / tau1$$

Method 3: Analysis

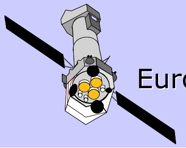
- We now have to assume the mass and heat capacity of the Helium gas in the tank can be neglected. If so then we can write:

$$\mathbf{m.Cp = [m.Cp]_{tank} + m_{fuel}.Cp_{fuel} = Qin.(tau1/\Delta T)}$$

- or rearranging:

$$\mathbf{m_{fuel} = (Qin.(tau1/\Delta T) - [m.Cp]_{tank}) / Cp_{fuel}}$$

- Simply by estimating tau1 and ΔT (Graphical best fit), it was possible to arrive at absolute values for the fuel in each tank.
- In practice it was difficult to find times where data was stable enough to make a fit: Best data from periods of Solar Flares where S/C in same pointing for number of days



Method 3: Results

2001	TANK1	TANK2	TANK3	TANK4	
dT	11	5.2	6	8.5	DegC
tau1	18	3	4.3	32	hrs
tau2	13	2.5	4	27	hrs
Qin/m.Cp	0.61	1.73	1.40	0.27	degC/hr
Qout/m.Cp	0.85	2.08	1.50	0.31	degC/hr
m.Cp	20.95	7.38	9.17	48.19	W.hr/K
Qout	17.72	15.36	13.76	15.17	W
Mass fuel	**22.49**	**6.79**	**8.88**	**54.52**	**Kg**
			Total	**92.68**	**Kg**

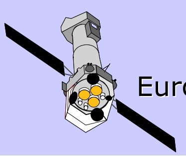
- Surprising Results

  Tank 2 (as before) appears to have least fuel

  Tank 4 has 2 to 3 times more fuel than Tank 1

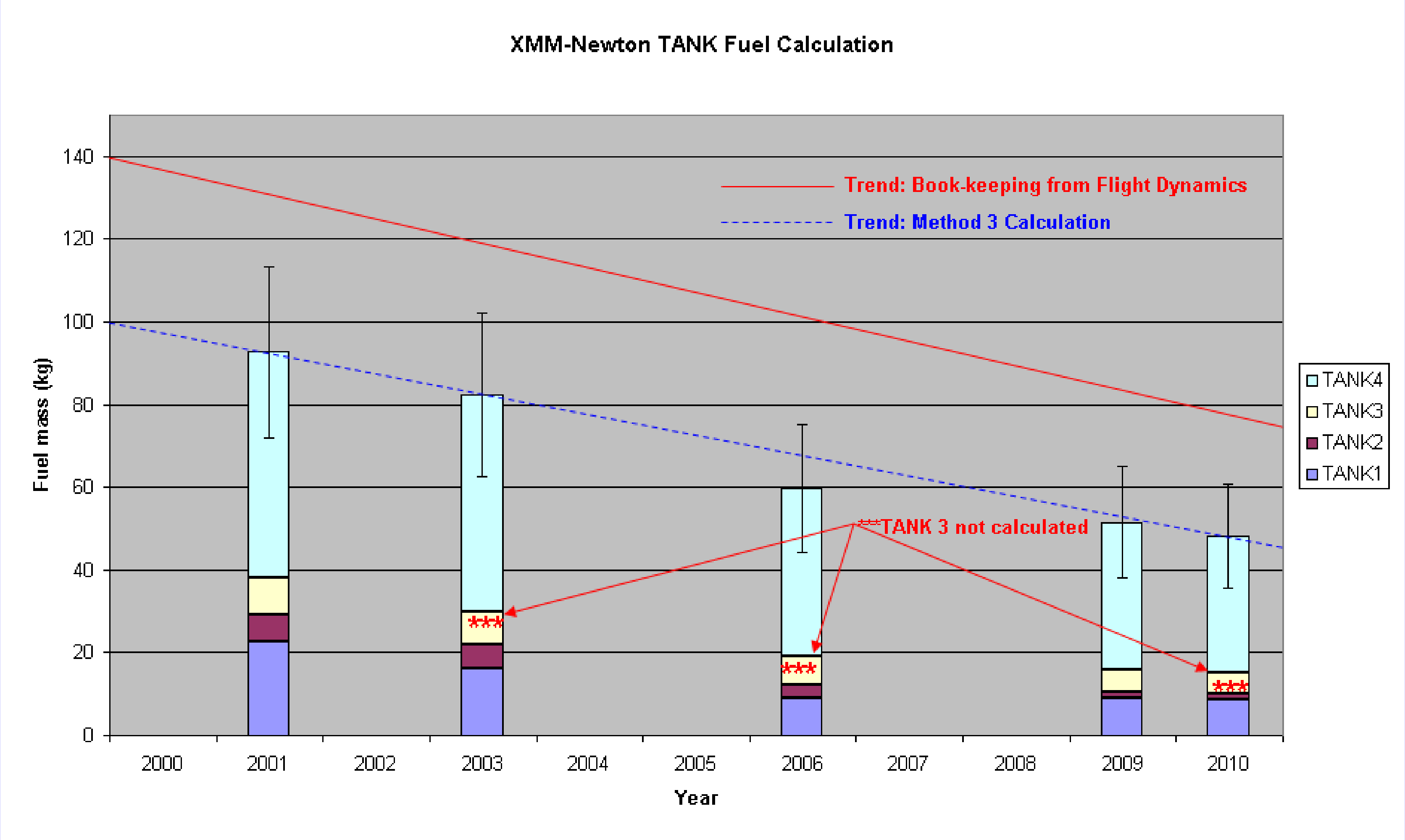
  Tank 1 (most important) looks OK

2009	TANK1	TANK2	TANK3	TANK4	
dT	13	6.5	6	6.4	DegC
tau1	9.5	1.4	3	16	hrs
tau2	5.8	1.3	2.8	12	hrs
Qin/m.Cp	1.37	4.64	2.00	0.40	degC/hr
Qout/m.Cp	2.24	5.00	2.14	0.53	degC/hr
m.Cp	9.35	2.76	6.40	32.00	W.hr/K
Qout	20.97	13.78	13.71	17.07	W
Mass fuel	**8.93**	**1.38**	**5.64**	**35.58**	**Kg**
			Total	**51.53**	**Kg**



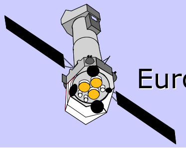
Thermal Gauging vs Book-keeping

- Still 30 Kg missing…



Astrium review

- In February 2010 FCT sent Fuel Mass Calculation document [RD-03] to Industry (Astrium) for review
- March 2010 Detailed Analysis received [RD-04]
- No need for alarm, the assymetry in fuel mass could not occur
  - Errors in initial loaded could account for ~2Kg difference between tanks
  - Fuel / pressurant gas migration between tanks during initial fuel orientation manoeuvres (LEOP) could also account for ~2Kg difference
  - Since LEOP the only way to account for more significantly fuel in Tank4 is a leakage of pressurant gas (**loss of 3bar!! Would be observable – but is not**)
  - This is ruled out since a leakage is not observable in PVT analysis nor in analysis of disturbance torques (Flight Dynamics)
- Two explanations for the assymetry calculated
  - Tank 4 is better insulated (this tank is on the cold side)
  - Temperature measurments are taken from thermistors placed near middle of Tanks (in contact with He) rather than the top (in contact with Fuel)

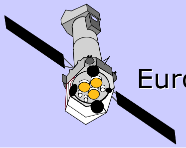


Way Ahead

- Book-keeping
  – seeking better ground calibration data for thruster performance
  - Which temperatures to use for correcting pressure variations
- Tank gauging (Thermal knocking) requires a better tank model (thermal properties, location of fuel, location of thermistors) and then calibration against flight telemetry

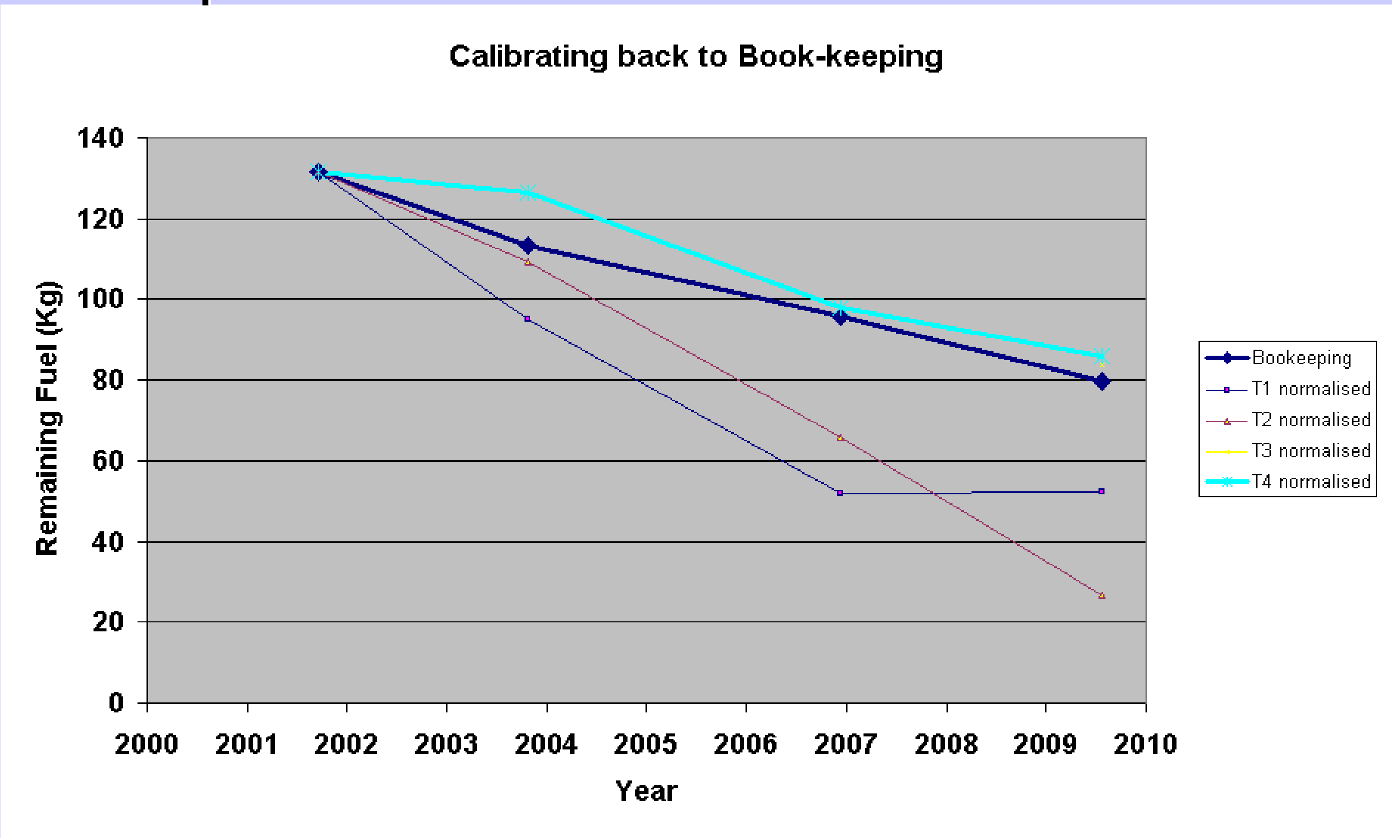
Comparison of Relative Accuracies [RD-7]

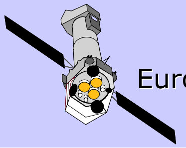
Method	Accuracy Limitation Drivers	Accuracy Trend	Accuracy 2 years before EOL	Accuracy at EOL
MEASUREMENT DURING THRUSTER FIRINGS				
Bookkeeping	• incomplete maneuver recording • mission profile has to be known well in advance to prepare for on ground calibration testing • maneuver data measurement accuracy	DECREASING	< +/- 3 %	
Flowmeter	• flowmeter accuracy • initial tank loading	CONSTANT	*< +/- 0.2 % ful scale during liquid apogee firing*	
MEASUREMENT BETWEEN THRUSTER FIRINGS				
pVT	• pressure and temperature measurement accuracy	DECREASING	< +/- 1.5 %[1]	
Thermal Knocking	• heater power stability • stability of thermal environment • accuracy of thermal model	INCREASING	*+/- 10 to 15 % of remaining propellant mass*	



Way Ahead – Thermal Knocking

- Flight Calibration?
- Perhaps TANK 4 is best suited





References

RD-1 Assessment of XMM Anomaly XMM_SC-60 and Recovery Action, Astrium, 21/07/2009

RD-2 RCS SSD - Annex B: Fuel Book-keeping Accuracy for XMM, XMM-MOC-SSD-0019-OAD, March 2002

RD-3 XMM-Newton Fuel Mass Calculation, J.Martin, Draft, 01-02-2010

RD-4 Assymetric Tank Depletion, Astrium, 11-03-2010

RD-5 XMM-Newton RCS Fluid Dynamics Analysis, XM-TN-BPD-0013

RD-6 XMM-Newton RCS Flight Model Users Manual, XM-TN-BPD-0005

RD-7 Comparative Assessment of Gauging Systems and Description of a Liquid Level Gauging Concept for a Spin Stabilized Spacecraft, Hufenbach.B. 1997ESASP.398..561H

RD-8 Flight Validation of the Thermal Propellant Gauging Method
Used at EADS Astrium, L. Dandaleix, 2004ESASP.555E...9D