A Comparison of Fuel Gauging Methods Utilising the Experience of S/C De-orbiting Operations

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(Received April 17th, 2017)

The fuel budget evaluation is an important part of the ESOC Flight Dynamics support to the ESA Earth Observation missions.

There are two basic methods – the actuators consumption integration method and the PVT method. The latter based upon the gas equation of state and measured tank parameters. Operationally, on ESOC Flight Dynamics side the actuators consumption integration method is used throughout the missions and the PVT method is used as a secondary check.

A large variety of missions with different propulsion systems have been supported in the past, the monopropellant Hydrazine RCS systems of ERS, Envisat and the Sentinel missions, the cold-gas RCS system of Cryosat and the electric propulsion system of GOCE.

For all these systems the adequate ground modelling had been developed and a substantial amount of data has been collected during the mission's lifetimes.

These data can be used to demonstrate the inherent inaccuracies of the methods and the relative evolution of the respective spacecraft fuel budget estimation. On two missions (ERS-2 and GOCE) telemetry was available until the depletion of the propellant tanks – here the achieved conformance of the two methods can be calibrated at EOL.

The paper shall give a short overview about the propellant budgeting methods, demonstrate the operational experience and try to evaluate the theoretical error margins on the results of the EOL data.

Key Words: Fuel Budget, PVT, Actuator Consumption

Nomenclature

BOL : Begin of Life (Mission start)
EOL : End of Life (Mission end)
f_{exp} : Tank expansion factor
F : force
g : Earth acceleration 9.81 m/s^2
I_{sp} : Specific Impulse
M : Mass
n : Number of actuations
N : amount of gas in moles
p : pressure
R : universal gas constant
ρ : Density
t_{pulse} : Thruster pulse length
T : temperature
V : Volume
Z : Compressibility factor

Subscripts

1bar : measured at 1 bar
f : filling conditions
pipe : pipework
press : pressurant
prop : propellant
t : time
thr : thruster

1. Introduction

One if the tasks performed by the Flight Dynamics division at ESA's operations center ESOC is the book-keeping of the propellant on-board to predict the satellites operational lifetime and plan the end-of-life operations.

1.1. Thruster Consumption Integration Method

This fuel book-keeping method uses as starting point the pre-launch fueling data. From the initial propellant mass the amount used by every thruster actuation is then subtracted. Pre-requisite is a permanent monitoring of the thruster actuations and the parameters required by the ground modeling of the thrusters to compute the individual consumption. Additionally, algorithms have to be developed to cope with intervals where no telemetry is available.

In most cases, qualification data of the thrusters are available which allow to define a polynomial best fit curve of the thrust vs. the propellant inlet pressure, which is the main factor of this relation. As secondary effects the thruster temperature or e.g. catalyst bed temperatures may influence the thrust vs. inlet pressure function. Alternatively direct measurement of the propellant mass flow might be available, as in the case of electric propulsion systems.

1.2. PVT Method

The PVT method is based on the ideal gas equation

$$pV=NRT. \quad (2)$$

The measured values of temperature and pressure in the RCS are used to compute the volume of a gas, which can either be directly the propellant (as in the case of cold gas systems or electric propulsion) or the volume of a pressurant from which the volume of the propellant can be deducted.

Depending on the type of propulsion system, the pressurant might be treated as ideal gas or the specific properties are used. The tank volume might be assumed to be constant or – in the case of high-pressure systems – its volume is a function of the pressure inside. Additionally the volume of the connected pipework can be taken into account.

2. Monopropellant Hydrazine RCS Missions – ERS and Envisat

The ERS satellites were the first ESA Earth observation satellites, with a launch mass of approx. 2400 kg. ERS-1 was launched in 1991 and ERS-2 in 1995, both into Sun-synchronous orbits with an altitude of 785 km. They were equipped with a monopropellant Hydrazine thruster RCS, equipped with two redundant branches of 4 15.6 N orbit control and 4 3.5 N attitude control thrusters, fed by two Hydrazine propellant tanks with 314 kg of propellant in total, pressurized with He at a BOL pressure of 32 bars. They has a blow-down RCS system, used for orbit control and attitude control in non-nominal S/C modes. In normal operations, the attitude was controlled by reaction wheels and magnetotorquers and no propellant was used.

ERS-1 operations ended in 2000 after a gyroscope failure. ERS-2 was operated until 2011 when it was decided to use the remaining propellant for a controlled de-orbiting exercise to limit the remaining lifetime in orbit to less than 25 years, in compliance with international agreements on space debris mitigation. This de-orbiting exercise is described in detail in chapter 5.1.

The successor Envisat was a much larger platform with a launch mass of 8200 kg, however the ERS RCS was re-used and the same ground modelling could be used. Envisat was launched in 2002 and remained operational until 2012 when an on-board failure ended the S/C to ground-communication.

2.1. Thruster Modeling

The thrust force of each of the N thrusters is modelled by a polynomial

$$F_{thr} = a_{thr} + b_{thr}{}^{p}, \quad (2)$$

valid for hot thrusters, with a constant specific impulse I_{sp} = 229.36 sec for all thrusters. Cold thrusts (attitude control thrusting and orbit manoeuvres < 20 sec) are modelled with a fixed propellant consumption increase by a factor of 1.27. From the S/C telemetry the number n_{thr} of fired thruster pulses for each thruster is available following orbit manoeuvres or periods in which the S/C attitude is controlled using the thrusters. The thruster pulse length t_{pulse} is fixed to 0.125 seconds. The propellant mass consumed, $M_{,}$ is then derived from the thrust using the equation

$$M = F_{thr} * (n_{thr} * t_{pulse}) / (I_{sp} * g). \quad (3)$$

2.2. PVT Method

The Helium pressurant is treated as an ideal gas, the tank volumes are assumed to be constant and the pipework volume is neglected, leading to an equation for the pressurant mass as function of tank temperature and pressure. As the total volume of propellant and pressurant is constant, one gets

$$V_{prop,f} + V_{press,f} = V_{prop,t} + V_{press,t}. \quad (4)$$

The ideal gas equation leads to

$$V_{press,t} = V_{press,f}\ (p_f T_t)/(T_f p_t) \quad (5)$$

and thus to the equation of the propellant volume at time t as function of the tank filling conditions and the measured temperature and pressure at time t:

$$V_{prop,t} = V_{prop,f}\ V_{press,f}\ (1 - (P_f{*}T_t)/(T_f{*}P_t)) \quad (6)$$

The propellant mass can then be computed using the (also temperature-dependant) propellant density ρ as

$$M_{prop,t} = V_{prop,t}\ \rho(T_t) \quad (7)$$

The temperature sensors mounted on the tank surfaces have a resolution of 0.3 deg K, the pressure sensors a resolution of 0.2 bars. This leads to an initial accuracy limit of the PVT method of 1% at BOL and an expected accuracy of 4% at EOL, as demonstrated by X. Marc in its working paper “On The Fuel Gauging During The ERS-1 Mission: Algorithms & Accuracy” (Ref. 1)

2.3. Operational Results

From the ERS-2 mission the thruster pulse and PVT method results are available from launch to end of life which show a good agreement of both methods with differences < X kg up to fuel depletion. As visible in the fig. 1, the PVT results were initially not derived automatically from the housekeeping telemetry but computed later at the start of the de-orbiting operations for selected times during the past mission. Only in the later part of the mission the PVT results are continuously available. The pulse counting methods results – which are the ones used in operations - prove to be more “conservative” than the PVT results.

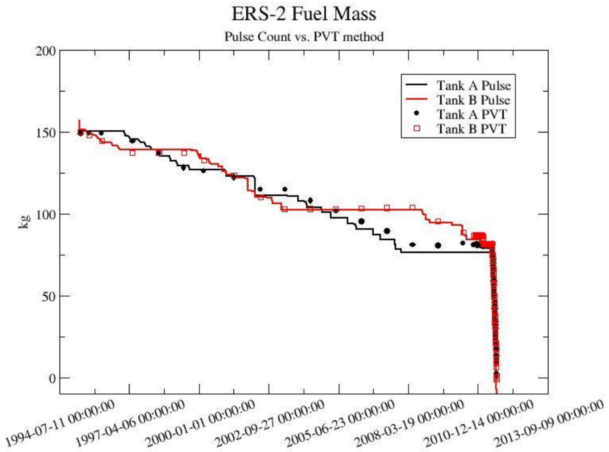

Fig. 1. ERS-2: fuel mass from launch to EOL – pulse count and PVT results.

After 2002 a systematic under-estimation of the pulse count method for tank system A is visible, which was later tracked back to human processing error when data from both methods were available.

For Envisat the same fuel book-keeping algorithms were implemented as for the processor ERS S/C, however here larger difference between the two methods of approx. 15 kg at end of mission can be spotted in fig. 2, detailed in fig. 3. The unfortunate loss of contact with the S/C in 2012 prevented a deeper analysis of this feature.

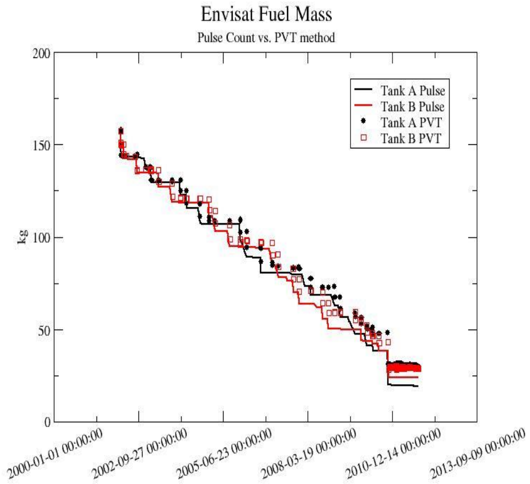

Fig. 2. Envisat: fuel mass from launch to EOL – pulse count and PVT results

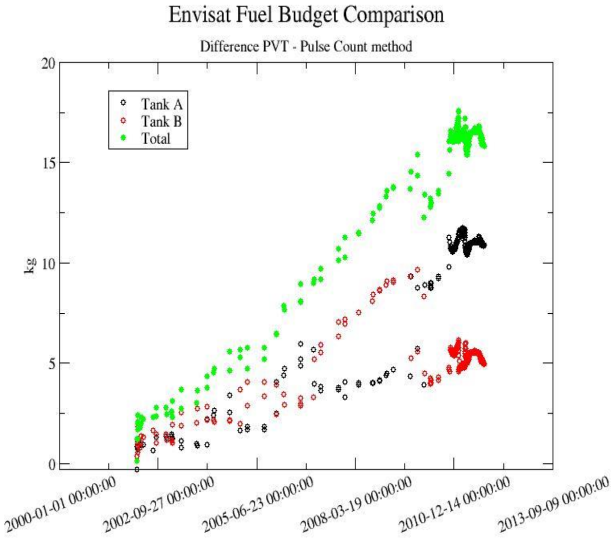

Fig. 3. Envisat: difference evolution between pulse count and PVT results

3. High-Pressure Cold Gas RCS Missions – Cryosat-2

The Cryosat-2 satellite is an Earth explorer mission S/C with a launch mass of 500 kg. It was launched in 2010 (following the launch failure of Cryosat-1 in 2007) into a Sun-synchronous orbit with an altitude of 780 km. It has a cold-gas RCS with two redundant branches of 2 40-mN-orbit control thrusters and 8 10-mN attitude control thrusters, operated with high-pressure Nitrogen gas at a BOL pressure of 270 bars. A pressure regulator provides the propellant gas to the thrusters at an operating pressure of 1.2 – 1.4 bars.

3.1. Thruster Modeling

The Cryosat thruster model used by ESOC Flight Dynamics for the operational fuel book-keeping is described in detail in ref. 2. It was developed by X. Marc in 2005 based on the assumptions

- cold-gas assumed to be ideal Nitrogen, with constant specific heats
- gas flow is isentropic (i.e. no friction, no heat transfer)
- constant thermodynamics properties on surfaces normal to streamlines
- in the volume comprised between the Pressure-Regulator and thruster inlet: uniform
- thermodynamics properties, gas velocity (and linear momentum) assumed to be zero
- no boundary layers and transient are considered

The thrust delivered by the thrusters depend in this model only on the gas inlet pressure and the nozzle geometry (different between attitude and orbit control thrusters). The S/C telemetry contains the activation times for all thrusters, allowing to compute the integrated mass flow from orbit and attitude control.

As described in the reference paper, this model was later enhanced using thruster qualification data.

3.2. PVT Method

The propellant mass can be derived directly from the housekeeping telemetry which contains measurements of the tank temperature and the tank Nitrogen pressure. The tank volume was measured at 1 bar and is then scaled linearly with the propellant pressure by an expansion factor f_{exp}. The additional volume of the pipework is assumed to be constant. As here the propellant clearly cannot be treated as an ideal gas, the compressibility factor Z is computed iteratively following the Benedict-Webb-Rubin method modified by Lee-Kesler, as described in ref. 3.

As result the relation

$$M_t = (p_t \quad V_t) / (R \quad T_t \quad Z(p,t)) \tag{8}$$

is determined by the measured pressure and temperature, with the tank volume being a direct function of the Pressure:

$$V_t = (V_{1bar} + f_{exp} (p_t - 1 \text{ bar}) + V_{pipe}) \tag{9}$$

3.3. Operational Results

Cryosat uses the RCS also for the attitude control in its nominal modes, therefore a continuous monitoring of the thruster actuations was implemented. The results of the monitoring of pulse count and PVT method since launch are available and shown in fig. 4 to 6. After the intensive use of the RCS in the first 2 months after launch to acquire the operational orbit, the propellant usage remains rather constant and the difference between pulse count and PVT method is constant at <0.2 kg up to 2016. Since then, a divergence between the methods can be noted (fig. 6), which is presently analyzed by D. Suen at ESOC Flight Dynamics. An improvement of the thruster model of the manufacturer, based on qualification data of the used thruster type, has shown a better fit of the estimated mass flow values, and the re-processing of the complete mission housekeeping telemetry will hopefully result in a better fit of the two methods.

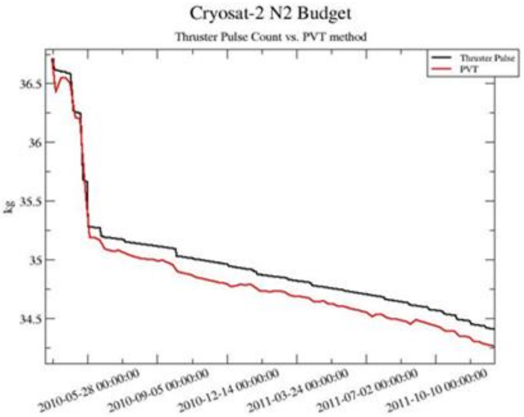

Fig. 4. Cryosat-2: fuel mass from launch to 2012 – pulse count and PVT results

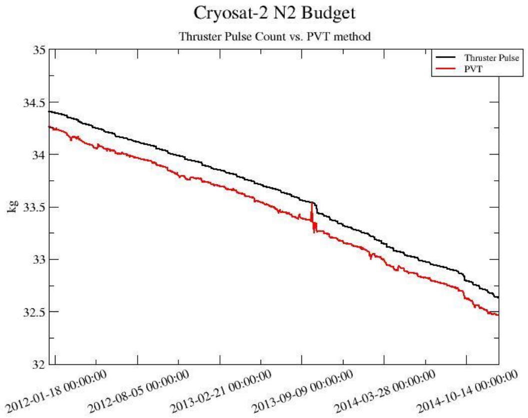

Fig. 5. Cryosat-2: fuel mass from 2012 to 2015 – pulse count and PVT results

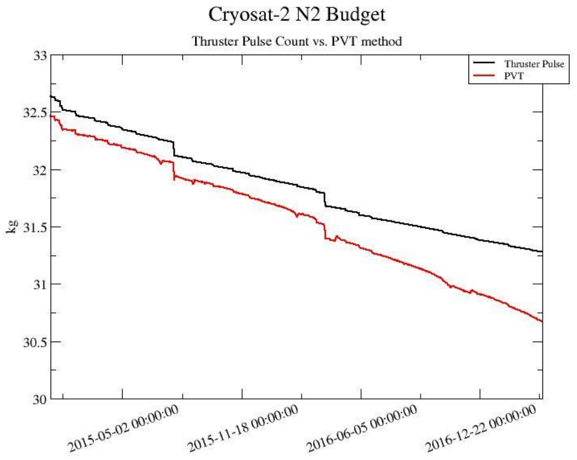

Fig. 6. Cryosat-2: fuel mass from 2015 to 2017 – pulse count and PVT results

4. Electric Propulsion RCS Missions - GOCE

The GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) satellite was a low-Earth mission, launched in 2010 and flying at an altitude of 254-224 km in a sun-synchronous orbit. In its operational phase the atmospheric drag was counterbalanced by a Xenon-propelled electric thruster, in open-loop control by the on-board accelerometers, resulting in an orbit free from external forces to allow the high precision gravitation measurements. When the Xenon supply was depleted, the S/C quickly re-entered into the atmosphere and burned up in October 2014.

The Xenon propellant of 40 kg is contained on-board in one tank with a volume of 28 m3 at a BOL pressure of 125 bar, a pressure regulator then provides the Xenon to the electric thruster at an operating pressure of 2.5 bar.

4.1. Thruster Modeling

Here the usual method of thrust modeling and mass flow computations cannot be applied. The prime Xenon mass flow though the electric thruster is measured on-board by a dedicated sensor, additionally the thruster uses Xenon gas to supply its Cathode and Neutralizer assemblies. Here a linear dependence of the mass flow from the operating pressure of the thruster is recommended by the manufacturer and respective 1st order polynomial models are given.

4.2. PVT Method

The Xenon gas at the high pressure persistent in the storage tank is clearly not behaving as an ideal gas. Therefore an algorithm which uses the measured Xenon temperature and pressure to compute the density ρ_i using tables available from the US National Institute for Standards and Technology, ref. 4, was implemented. With this density, the tank volume as function or the gas pressure and the tank temperature the remaining Xenon mass can be derived using Eq. (9) and Eq. (7).

4.3. Operational Results

Flight Dynamics did run a daily retrieval and processing of the GOCE housekeeping telemetry, resulting in a complete history of the Xenon budgeting from both methods (fig. 7 and 8). Here one can see that the PVT method returns a fluctuating result, resulting from the tank temperature variation. This fluctuation results in a change of the estimated Xe mass by 60 grams in 2012. This variation is quite small, compared with the variation in the early mission phases (fig. 7), and indicates that GOCE in 2012 was a Xe high pressure regime favorable for the PVT method accuracy.

The Xe mass fluctuations have developed such:

Date	average tank Pressure (bar)	Xe mass from PVT (kg)	Δ (kg)
2010/10/10	69.2	32.7 – 34.4	1.7
2011/07/03	68.2	26.4 – 28.4	2.0
2011/11/27	65.3	21.8 – 23.0	1.2
2012/08/19	56.9	14.26 – 14.56	0.3
2013/05/02	35.3	6.57 – 6.63	0.06

Comparing the mass flow and the PVT results, one arrives for 2013/05/02 at the following results:
Xe mass from PVT: 6.57 – 6.63 kg
Xe mass from mass flow Integration: 6.89 kg

This corresponds to a difference in the Xenon mass estimation of 300 g or 4.5% of the propellant mass.

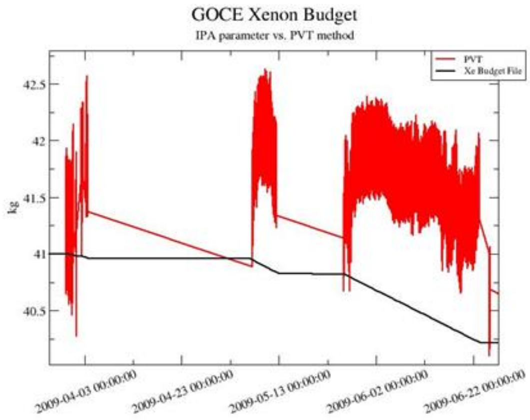

Fig. 7. GOCE: fuel mass after launch 2009 – mass flow integration and PVT results

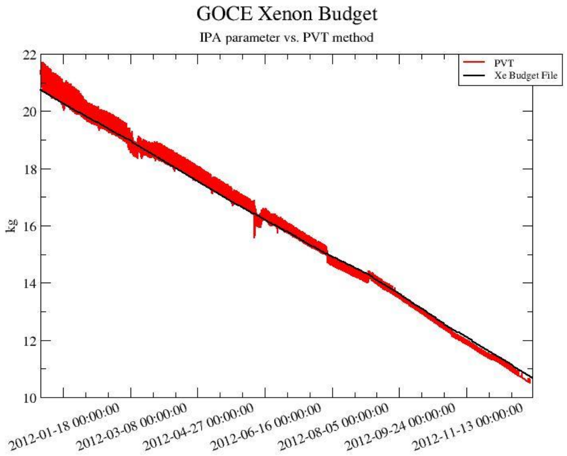

Fig. 8. GOCE: fuel mass in 2012 – mass flow integration and PVT results

5. End-of-Life Operations – ERS-2 and GOCE

5.1. ERS-2 De-Orbiting

In 2011 it was decided to de-orbit ERS-2 with the remaining fuel to limit its life time in orbit after passivating the S/C. With the remaining fuel of approx. 160 kg the predicted time to burn-up in the atmosphere was brought down from 150 years to 25 years.

At the beginning of this operation the up to then separated tank systems were connected by opening the respective latch valves, removing the need for regular thruster branch switches. Subsequently, the pulse count method returned only one unique result for the two tank systems, while the PVT results from the temperature and pressure measurements of the branch A and B tanks returned slightly different values due to the different individual thermistor and pressure transducer parameters. In fig. 9 the results of the two methods are compared, from the beginning of the de-orbiting operations (series of large orbit manoeuvres against the flight direction) up to the end when the depletion of the tanks was detected and the spacecraft passivated.

It can be noted that the pulse count method remained conservative and crossed the zero fuel mass line already before the last series of orbit manoeuvres started, while the PVT results accurately return the zero value at the end of spacecraft lifetime. However, the difference between the two methods of 10 kg at EOL shows that both can be used during the operational phase of the mission to estimate the on-board supply of propellant.

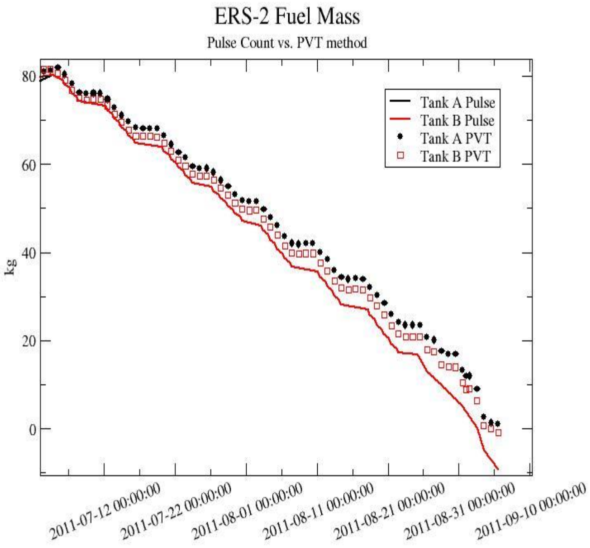

Fig. 9. ERS-2: fuel mass evolution during the de-orbiting operations – pulse count and PVT results

5.2. GOCE End-of-Life

The GOCE electric propulsion was switched off when the Xenon tank pressure reached the lower operational limit of 5 bars, which was the lowest value for the pressure regulator assembly to provide the electric thruster with a constant Xenon supply. At that time the Xenon budget values from the PVT method indicated a remaining Xe mass of 239 g, while the book-keeping using the on-board mass flow sensor and the regulated low-pressure measurements to estimate the mass flow of the side Xe flow to Cathode and Neutralizer gave a remaining Xe mass of 733 g. This agreement in the order of 500 g indicated that the operational PVT results are well in line with the mass flow integration results, as depicted in fig. 10.

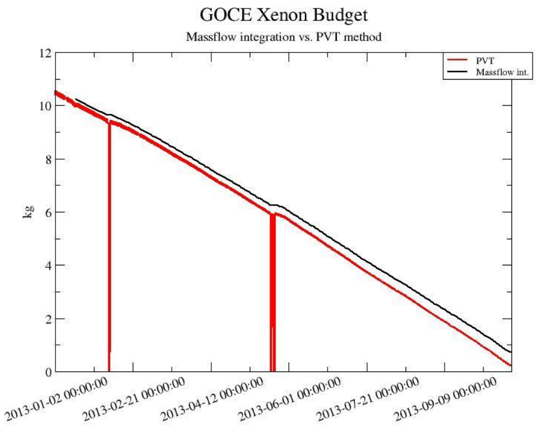

Fig. 10. GOCE: fuel mass evolution up to EOL – mass flow integration and PVT results

7. Conclusion

The operational experience shows that both the PVT and the actuator consumption integration methods are valid and verified methods for assessing the propellant supply on board of a spacecraft. Each method has its downsides – the thruster count or mass flow integration methods might accumulate systematic errors, and the PVT method is due to the limited resolution of the available pressure sensors difficult to use for the monitoring of small consumptions, e.g. orbit manoeuvres. As the PVT method depends heavily on the fueling conditions, here clear procedures which data are sampled and when are requires. Additionally, a time series of tank pressure and temperature data before launch is helpful to get a steady-state set of measurements as start point. Both rely on a variety of S/C manufacturer specifications, and in case of difference a retrospective re-assessment of the results might be required. It is highly recommended to have the respective input data from S/C telemetry archived and readily accessible for such exercises. As well the results of the two methods should be both routinely compared to spot divergences or questionable results on short notice. The operational results from the PVT method show a cyclic fluctuation of the results in sync with on-board tank heating cycles which deserve a dedicated analysis whether delays or biases on the on-board temperature and pressure measurements might improve the method.

As all flying and future ESA missions will comply with the space debris mitigation standards, especially an end-of-life propellant bookkeeping will gain in importance, not only for the actual EOL operations but also to plan the preceding mission phases such that the limited propellant amount if most effectively used.

Acknowledgments

The author thanks the European Space Agency for its permission to use the operational data of the various missions discussed in this paper. Special thank go to my colleagues X. Marc, S. Pessina and D.Suen for their valuable inputs and discussions to this papers area of expertise. Spacecraft operations are team efforts, and the author wants to express his sincere thanks to the whole ESOC Flight Dynamics team for professional support, making the collection of the presented experiences possible.

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