Criticality of the fuel consumption estimation towards the EOL of a satellite

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***Abstract* – With the increasing number of satellites being launched, it has been recommended by the Inter-Agency Space Debris Coordination Committee (IADC) that LEO satellites be commanded to re-enter Earth's atmosphere within 25 years of mission completion to reduce the space debris growth rate and consequently the collision probability. An important part of the end-of--life disposal of spacecrafts is passivation, during which, all latent energy reservoirs are to be depleted to prevent an accidental post-mission explosion. Such passivation measures may include depletion burns, fuel and/or pressurant venting, as well as the discharging of batteries and the inhibiting of pyro devices.**

This is why it has become essential for any mission that the pre-launch fuel budget estimate considers not only the initial transfer requirements, and the orbit control manoeuvres once the spacecraft has reached its operational orbit, but also the fuel required for the end-of--life disposal.

It follows that in the frame of the orbit control - incl. deorbiting - of a satellite, it has become crucial to be able to rely on an accurate approach for fuel estimation to predict the satellite's operational lifetime and plan the end-of-life operations. Throughout the mission, the calculation of the satellite's lifespan is indeed based on the estimation of the remaining fuel and the evaluation of the actual performances of the executed manoeuvres. These estimates rely on dedicated algorithms, like the ones presented in this article, which will focus on two different approaches to calculate the fuel consumption for satellites in near circular orbit.

The First method is a theoretical one known as the PVT method, using the perfect gas law based on conservation of pressurant mass, and relying on the initial conditions to derive the evolution of the mass of the propellant. Among other requirements, this article will emphasize the importance of accurately estimating the fuel consumption from the very beginning of life of the spacecraft.

Second method is more empirical and is called the Pulse Count Method, as it is integrating the actuators consumption. Using the telemetry retrieved from the spacecraft, this method is using the accumulated number of thruster pulses to derive the amount of fuel Δm consumed by each thruster for a given manoeuvre. This mass of fuel Δm can then be used to recursively update the fuel mass left.

Resulting fuel consumption estimations are then compared for the particular example of the Sentinel-1 mission, part of the European Copernicus programme, and the relevance of the corresponding methods analysed for different steps throughout the spacecraft's lifetime.

Finally, the accuracy of both methods is assessed, as this information is of the utmost importance for the operations towards the end of life of the satellite. One needs indeed to assess as accurately as possible when the full fuel depletion of the tanks will be reached. This will be illustrated through the example of data collected for Sentinel-1, aiming at highlighting the criticality of the fuel consumption estimation towards the EOL of a spacecraft, while trying to evaluate the relative accuracy of these methods.

Abbreviations and Acronyms

The following abbreviations and acronyms are used throughout this paper:

BOL	Beginning Of Life
EOL	End Of Life
ESOC	European Space Operations Centre
da	Delta in semi-major axis
dv	Delta in velocity
FD	Flight Dynamics
FS	Full Scale
FDDB	Flight Dynamics Data Base
FOM	Flight Operation Manual
IADC	Inter-Agency Space Debris Coordination Committee
IP	In-Plane manoeuvre (IPP: IP Prograde, IPR: IP Retrograde)
MEOP	Maximum Expected Operating Pressure
MEOT	Maximum Expected Operating Temperature
NAPEOS	Navigation Package for Earth Orbiting Satellites
OCM	Orbit Control Manoeuvre
OOP	Out-Of-Plane manoeuvre
PCM	Pulse Count Method
PVT	Pressure-Volume-Temperature
SFM	Safe Mode
YOL	Years Of Lifetime

NOTATIONS

The following notations are used throughout this paper:

P	tank gas pressure corresponding to a mass *m* of left fuel (in bar)
V	tank gas volume corresponding to a mass *m* of left fuel (in m^3)
T	measured gas temperature (in K)
m	estimated mass of left fuel (in kg)
M_{sc}	current total spacecraft mass (in kg)
I	thruster specific impulse
g	Gravitational acceleration
F	thruster current thrust level (in N)
Δt	thrust duration (in s)
M_p	Mass of the propellant (in kg)
ρ_p	Density of the propellant ()
$P_g, V_g T_g$	P,V,T of the pressurant
$P_p, V_p T_p$	P,V,T of the propellant
$P_{g_i}, V_{g_{i,}} T_{g_i}$	Initial conditions of the P,V,T for the pressurant
δM_p	Error made on the mass of the propellant
$\frac{\partial M_p}{\partial T}$	Derivative of the mass of the propellant wrt the temperature
$\frac{\partial M_p}{\partial P}$	Derivative of the mass of the propellant wrt the pressure
dT_{LSB}	Temperature sensor LSB
dP_{LSB}	Pressure sensor LSB

I. INTRODUCTION

As the number of satellites launches increases, the Inter-Agency Space Debris Coordination Committee (IADC) has advocated for the re-entry of Low Earth Orbit (LEO) satellites into Earth's atmosphere within 25 years of mission completion to mitigate catastrophic collisions. This recommendation of deorbiting within 25 years necessitates precise fuel estimation, particularly for end-of-life operations. Accurate fuel estimation is indeed vital for end-of-life operations of satellites due to its direct impact on mission planning and execution. Precise knowledge of remaining fuel enables efficient manoeuvres, such as deorbiting or repositioning, to minimize space debris and comply with international regulations. Inaccurate estimations can lead to unexpected mission terminations or failures, jeopardizing satellite assets and contributing to space debris accumulation. Moreover, it influences decisions regarding resource allocation and the sustainability of space operations, ensuring responsible space utilization and long-term orbital safety. Therefore, precise fuel estimation is essential for optimizing satellite end-of-life strategies and safeguarding space infrastructure.

A crucial aspect of spacecraft end-of-life disposal involves passivation, wherein all latent energy reservoirs are to be depleted to avert potential post-mission explosions. Such passivation measures may encompass depletion burns, fuel and/or pressurant venting, battery discharging, and pyro device inhibition. Consequently, precise estimation of fuel consumption from the onset of a spacecraft's life, and notably the accuracy of these estimates, has become paramount, particularly in the context of a deorbiting. This article explores two methodologies for this purpose and evaluates their applicability through the lens of the Sentinel-1 mission and to compare the results of these assessments to the ones provide by the industry.

II. MISSION BACKGROUND

The Sentinel-1 mission performs radar imagery of the Earth from a dusk-dawn, frozen eccentricity, sun-synchronous orbit and consisted of 2 satellites (Sentinel-1A, launched on April 3, 2014, and Sentinel-1B, launched on April 25, 2016) separated by an argument of latitude difference of 180 degrees.
After the unfortunate Sentinel-1B on-board failure in December 2021 that led to the declaration of end-of-mission in spring 2022 for that satellite, it was decided to move the spacecraft away from its nominal operational orbit to reduce its impact on the Sentinel-1C launch and orbit acquisition that was planned at that time for January 2023. With the delay of the Sentinel-1C launch, it became desirable to start de-orbiting the Sentinel-1B and complete the passivation process before the new launch date of Sentinel-1C. Initially good progress was made, but due to thruster performance issues, this slowed down. Current predictions indicate re-entry into the Earth's atmosphere will take place within the next 25 years. With the on-going de-orbiting activities, the re-entry is expected to transpire sooner.

III. FUEL BOOK-KEEPING METHODS

One of the tasks performed by the Flight Dynamics division at ESOC is the book-keeping of the propellant on-board the satellites to assess the operational lifetime and plan the accompanying end-of-life operations. As emphasis is placed on accurate fuel estimation from spacecraft commissioning to end-of-life operations, two alternative fuel gauging methods are used. Based on different inputs, they can be cross checked against each other, thus strengthening their relevance and correctness.

A. Theoretical approach

The Pressure-Volume-Temperature (PVT) method is based on the perfect gas law and conserves pressurant mass to estimate fuel consumption. In the case of the Sentinel missions, the propulsion system is a monopropellant Hydrazine RCS system. The measured values of temperature and pressure in the RCS are used to compute the volume of the pressurant from which the volume of the propellant can be deducted. The pressurant is modelled as an ideal gas and the tank volume is assumed to be constant. However, the volume of the connected pipework is neglected in this study.

$$\frac{dV}{V} = \frac{dT}{T} - \frac{dP}{P} \quad (1)$$

Initial conditions can then be used to project propellant mass evolution throughout the lifetime of the spacecraft. However, the spacecraft's remaining fuel mass can be calculated at any point in the mission without relying on prior determinations, only relying on the pressure and temperature sensor readings. Tank temperature and pressure values, obtained from telemetry, are processed alongside tank filling conditions using the perfect gas equation, from which is derived (1). This computation yields the volume occupied by gas within the tank system. Subtracting this volume from the total internal volume of the tank system provides the volume occupied by propellant. Consequently, utilizing the propellant density, which is temperature-dependent, yields the remaining propellant mass.
At ESOC, the PVT method is used for the routine operations as a basis for comparison as a benchmark for verifying the accuracy of the other implemented method, presented hereafter.

B. Empirical approach

In the telemetry retrieved from the spacecraft, one can also find the accumulated number of thruster pulses (per thruster). By differentiating these values over the manoeuvre duration (i.e. before the first and after the last thruster burn), one can hence derive the number of pulses triggered for the concerned manoeuvre, for each thruster of the used branch.
The Pulse Count Method (PCM) integrates actuators' consumption, utilizing this telemetry to derive thruster pulse counts and associated fuel consumption. This method iteratively updates remaining fuel mass based on accumulated thruster pulses.
Using the specific impulse I of each thruster and the thrust level F of this thruster, one can then derive the amount of fuel Δm consumed by each thruster for a given ΔV :

$$\Delta m = M_{sc} \frac{\Delta V}{I.g} \quad (2)$$

where the velocity increment ΔV is related to the thruster thrust level through:

$$\Delta V = \frac{F}{M_{sc}} \Delta t \quad (3)$$

assuming that over the duration of a pulse a certain quantity of fuel is expelled from the tank, which depends only on the current pressure in the tank. This mass of fuel Δm can then be used to recursively update the fuel mass left.
Continuous monitoring of thruster operations and necessary parameters for ground modelling is essential for this method. Furthermore, algorithms must be able to handle intervals with no telemetry available. Typically, qualification data permits the creation of a polynomial curve correlating thrust with propellant inlet pressure. Secondary factors like thruster temperature or catalyst bed temperatures may also influence this relationship but will not be considered in this paper.
Unlike the PVT method, which provides absolute computations of the mass of the propellant, based on its volume, the pulse counting accumulates errors over time. By comparing results from both methods, discrepancies can be identified, helping to ensure the reliability and consistency of pulse counting measurements.

IV. Comparison and application to Sentinel-1 mission

Fuel consumption estimates from both methods are compared using the Sentinel-1 mission as a case study. The relevance of each approach throughout the mission lifecycle is evaluated, highlighting their applicability and limitations.

A. PVT method

Evolution of the mass of the propellant

The mass of propellant can be modelled as follows:

$$M_p = \rho_p . \left(V - \frac{P_{g_i} . V_{g_i}}{T_{g_i}} . \frac{T}{P} \right) \quad (4)$$

with P_{g_i}, V_{g_i}, T_{g_i} describing the initial conditions of the tank. In this context, the initial mass of propellant would be 154.57 kg, assuming the initial conditions given in Table 1 and Table 2 and would thus be slightly over-estimated wrt the reference value found in the Flight Dynamics Data Base (FDDB). The reason is that in the FDDB, the mass of the propellant is *computed* in a way that enables the different values to be consistent with each other.

Table 1 Assumptions at BOL for the pressurant

Parameters	Initial conditions
Mass M_g	1.315 kg
Pressure P_g	21.88 bar
Volume V_g	51.1 L
Temperature T_g	20 ºC

Table 2 Assumptions at BOL for the propellant

Parameters	Initial conditions
Mass M_p	153.65 kg
Pressure P_p	21.88 bar

Volume V_p	153.3 L
Temperature T_p	20 ºC
Density ρ_p@20 ºC	1008.27 kg/m³

The evolution of the mass wrt the pressure is depicted in Fig. 1, with the density also depending on the temperature.

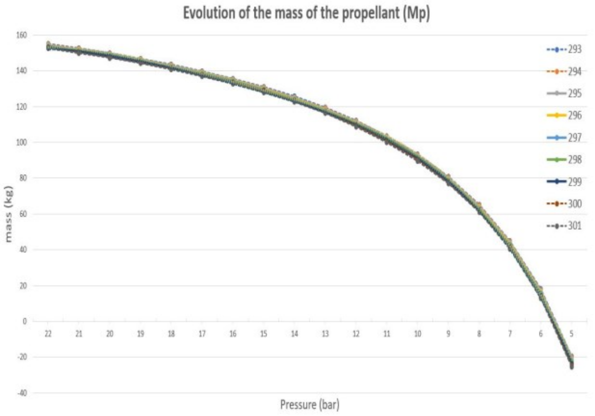

Fig. 1 Propellant mass prediction for different temperatures (in K)

Evolution of the pressure in the tank

From the results of the previous section, the pressure in the tank can be computed as follows:

$$P = \left(\frac{P_{g_i} \cdot V_{g_i}}{T_{g_i}} \cdot \frac{T}{V - \frac{M_p}{\rho_p}} \right) \quad (5)$$

Under the current assumptions, for a temperature in the range of [22-26] ºC, when the propellant is to be fully depleted, the pressure would be between 5.51 and 5.59 bar, as illustrated in Table 3.

Table 3 Pressure at fuel mass depletion (initial conditions from FDDB)

T in the tank (deg)	P_{min} at fuel mass depletion (bar)
22	**5.51**
23	5.53
24	5.54
25	5.56
26	**5.59**

Note that the results fit the inputs received from the industry (see Table 4) about the predicted pressure at fuel mass depletion (i.e. an instant before the tank is emptied and the pressure drops to 0).

Table 4 Pressure at fuel mass depletion (Source : TASI)

T [°C]	P_{MIN} [bar]	P_{MEAN} [bar]	P_{MAX} [bar]
22	5.54	5.62	5.70
25	5.59	5.68	5.76

Evolution of the mass uncertainty for the propellant

According to [4] and [5], after considering inaccuracy factors like the calibration errors, the non-linearity factors, the power supply variation, the hysteresis, the lifetime aging or the end-of-life errors of electronics, the total error on the output signal for the pressure and the temperature can be characterized as described in Table 5 and Table 6.

Table 5 Error characterization of the pressure

Parameters	Value
dP_{LSB}	EOL: ±0.32% FS
FS	MEOP + 5%
MEOP	24.7 bar
dP_{LSB}	0.083 bar

Table 6 Error characterization of the temperature

Parameters	Value
dT_{LSB}	EOL: ±0.20% FS
FS	MEOT + 5%
MEOT	50 ºC
dT_{LSB}	0.105 ºC

Assuming a first order approximation of the error made on the mass, as modelled in (6), together with an uncertainty of ± 2K for the thermistor, leads to the results illustrated in Fig. 2.

$$\delta M_p = \frac{\partial M_p}{\partial T} dT_{LSB} + \frac{\partial M_p}{\partial P} dP_{LSB} \quad (6)$$

This error model yields towards the EOL an uncertainty of 4.63kg @5.5bar for T=22 ºC, and to an initial uncertainty of 0.369kg @21.88bar for T=20 ºC (which corresponds to the initial conditions at BOL), which is consistent with the estimations given in the FOM and illustrated in Fig. 3.

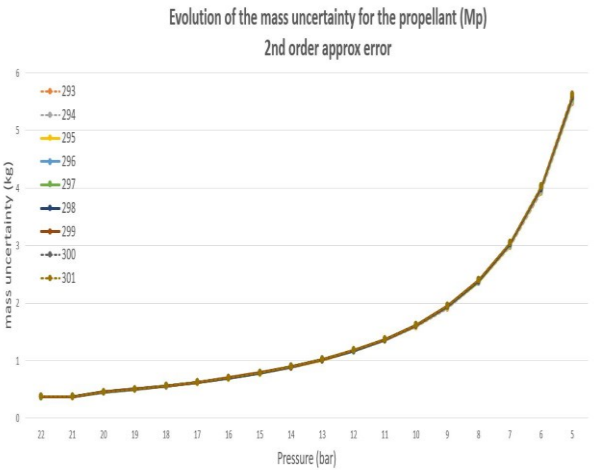

Fig. 2 Mass uncertainty assessment for different temperatures – 2nd order estimation (PVT method)

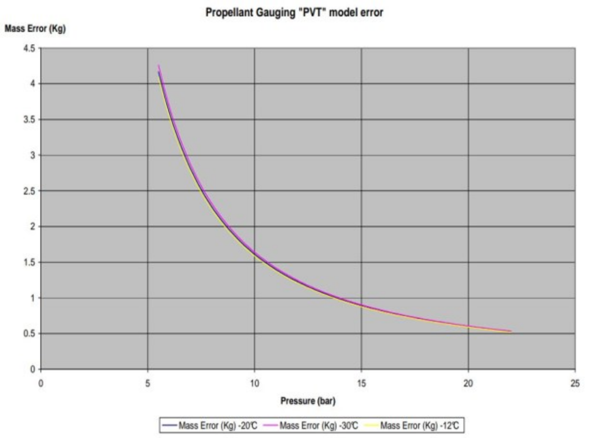

Fig. 3 Estimation of the propellant gauging error for the PVT model (Source: FOM)

To underpin this statement, one could read in [2] that for the ERS mission, which was also equipped with a monopropellant Hydrazine thruster RCS, the temperature sensor LSB was about 0.3K for a typical tank temperature of 15 ºC (288K), and that a typical order of magnitude for $\delta T/T$ was consequently expected to be around 0.1%. In the case of Sentinel-1B, an uncertainty of 2K for a typical temperature of 20 ºC (293K) yields a ratio $\delta T/T$ of ~0.7% which is consistent with the ERS mission.

B. PCM method

To model the uncertainty of the pulse counting method, a perturbation method is applied for the estimation of the residual hydrazine on board.

Evolution of the mass of the propellant

Since the duration of a pulse lasts only 125ms, it is assumed in this paper that the mass expelled over one single burn is only depending on the current pressure in the tank, thus resulting in the thrust being a linear function of the pressure. Thanks to (2) and (3), the mass of fuel required by a thruster can be modelled as follows:

$$\Delta m = \frac{F}{I.g}\Delta t \tag{7}$$

The thrust itself is related to the tank pressure as follows:

$$F = \alpha.P^{\beta} \tag{8}$$

where the constants α and β are physical characteristics of the thruster. If one considers the propagation of some initial error δm made on the fuel quantity and δI made on the specific impulse I_{sp} of the thruster firing, with

$$m = m_0 + \delta m$$
$$I = I_0 + \delta I$$

then, through an iterative application of this method while differentiating (8), the thruster thrust can eventually be modelled as follows:

$$F = F_0(1 + \beta\frac{\delta m}{\rho.V_0} + \frac{\delta I}{I_0}) \tag{9}$$

and the fuel mass consumption over one single burn could be assessed as follows:

$$\Delta m = \Delta m_0(1 - \frac{\delta I}{I_{sp}}) \tag{10}$$

where Δm is the estimated mass of left fuel, Δm_0 is the true mass of left fuel, I_{sp} is the thruster specific impulse and δI is the uncertainty of the thruster specific impulse. Over the whole mission, the final error made on the mass estimation could subsequently be assessed as:

$$\delta m_{fuel}^{EOL} = m_{fuel}\frac{\delta I}{I_0} \tag{11}$$

as described in [2]. The main difficulty at this stage would then be to estimate the error δI since it cannot be measured directly.

Assessment of δ I/I

An initial, simplistic approach to estimating the error in I_{sp} could involve correlating it with the performance of the thrusters, though this physical correlation would still need to be proven. The preliminary evaluation of I_{sp} error based on RCT performance was however deemed irrelevant within the scope of the study and thus abandoned.

A second approach is to model $\frac{\delta I}{I}$ as a function of the pressure inlet. In the FOM, the industry has collected some datasets for the different thrusters to model the behaviour of the force and the mass flow for the different RCT wrt the inlet pressure. The performance models are here predicted as second order polynomial functions of the pressure, as stated in the following equations:

$$\begin{aligned} F &= a_1.P^2 + b_1.P + c_1 \\ \dot{m} &= a_2.P^2 + b_2.P + c_2 \end{aligned} \tag{12}$$

The values of the coefficients are given in the FOM and reported in Table 7.

Table 7 Performance model coefficients

S/N	RCT	Thrust (N)			Flow rate (g/sec)		
		a_1	b_1	c_1	a_2	b_2	c_2
f045	1A	-0.000595	0.061754	0.036131	-0.000224	0.026023	0.035996
f040	1B	-0.00036	0.055561	0.033375	-0.00019	0.025419	0.022628
f036	2A	-0.000853	0.066406	-0.005965	-0.000415	0.030014	0.006562
f043	2B	-0.000476	0.060661	0.002602	-0.000206	0.026884	0.010397
f042	3A	-0.000349	0.056361	0.029262	-0.000237	0.026656	0.016695
f032	3B	-0.000233	0.053343	0.044232	-0.000129	0.024383	0.02518
f031	4A	-0.000664	0.061858	0.03113	-0.000408	0.029585	0.017921
f044	4B	-0.000606	0.062508	0.014692	-0.000299	0.027577	0.026562
f033	5A	-0.00066	0.064455	-0.004756	-0.000247	0.027317	0.015583
f034	5B	-0.00039	0.05588	0.036594	-0.000145	0.024279	0.031051
f038	6A	-0.000521	0.060186	0.019362	-0.000321	0.029212	0.008055
f046	6B	-0.000409	0.057187	0.037777	-0.000324	0.029535	0.009842
f039	7A	-0.000221	0.052838	0.039824	-0.000155	0.024892	0.023216
f029	7B	-0.000551	0.061666	0.012825	-0.000230	0.027153	0.017669

Since only 3 points of pressure were considered for these models, 4 distinct methodologies were experimented with to characterize the evolution of the specific impulse I_{sp} concerning pressure to try to match the dataset provided by the industry: a linear model, a polynomial model, a power model and a logarithmic model. The results are presented in Fig. 4, where it clearly appears that the quantity of available data proved insufficient to determine the most suitable mathematical model for modelling the evolution of the I_{sp} as a function of the pressure inlet. Consequently, it was necessary to incorporate additional variables to accurately model the physical dynamics governing the evolution of specific impulse I_{sp} concerning tank pressure. Naturally, the initial and final conditions of the satellite's operational lifespan have emerged as prominent factors in this regard.

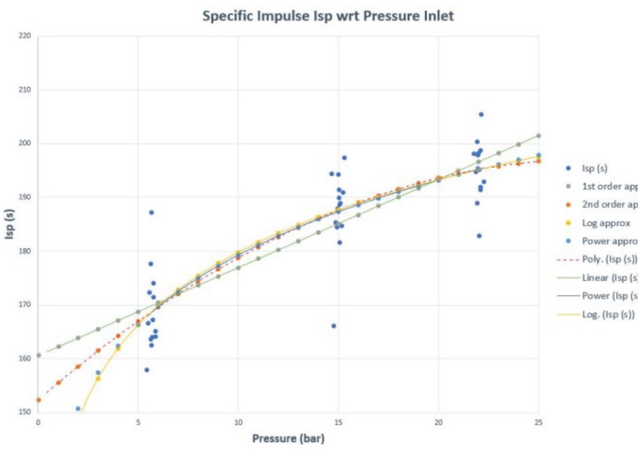

Fig. 4 Specific impulse characterisation wrt pressure input

Considering the latter case, the error made on the mass for the propellant towards the EOL for an initial mass of propellant m_{fuel} =153.65 kg (as stated in the FDDB) and a transducer inaccuracy δP = 0.073 bar (see [4]), would be assessed as summarized in Table 8 for the different models considered in this study.

Table 8 Mass error assessment for the propagation approach

Reference	P (bar)	Mass error (kg)
1st order approx.	5.5	0.122
2nd order approx.	5.5	2.901
Power approx.	5.5	2.257
Log approx.	5.5	2.532
Perf. model	5.5	4.273

By relying on the physical meaning of these representations, it is possible to put aside some of these models and to retain only the two which allow us to see the error made in the estimation of the mass tending towards 0 for the initial conditions at BOL, and has the same error of taking very large values when the pressure in the tank approaches the EOL limit conditions. The errors resulting from these two simplified models are plotted in Fig. 5, and are reminiscent of the results obtained for the theoretical method discussed previously, without fully satisfying the boundary conditions at EOL.

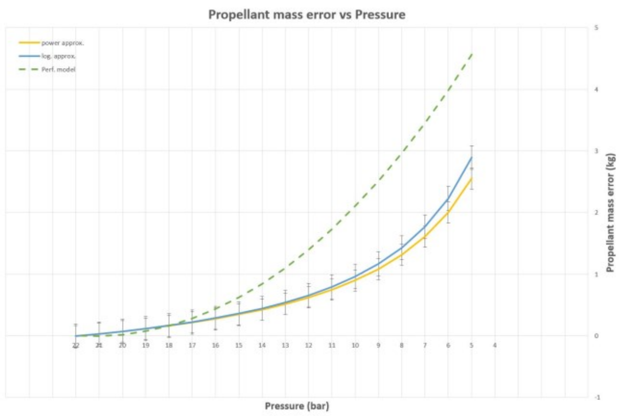

Fig. 5 Evolution of the propellant mass error for the power and the logarithmic models (PCM method)

Therefore, 1st order approximations are not suited for modelling for the specific impulse I_{sp} and employing higher-order models is necessary. The performance model delineated in the FOM and described in (12), yields a polynomial function of degree 3 for the mass estimation error:

$$\delta m = a_m . P^3 + b_m . P^2 + c_m . P \qquad (13)$$

This model gives more realistic results towards the EOL and aligns more accurately with the results obtained from the PVT as illustrated in Fig. 5 and Table 8. This is therefore the one which is implemented in the Flight Dynamics system used at ESOC.

V. IMPLEMENTATION

Both the PVT and the pulse counting methods have been

integral components of the Flight Dynamics system since the beginning of the mission, consistently yielding comparable results as illustrated in Fig. 6, with a mass difference smaller than 1kg until April 2023. The pulse counting method results – which are the ones used in operations - proved to be more conservative than the PVT results, in the sense that tend to overestimate the fuel mass used for each manoeuvre implemented.
However, as the deorbiting phase commenced, disparities between the two methods have become more pronounced. This widening gap can be attributed to several factors, notably the inherent inaccuracies in telemetry data concerning the temperature and the pressure in the tank which affect subsequently the PVT estimations for the left fuel mass and increase towards EOL because of the dropping pressure. Additionally, the aging of thrusters presents challenges, as predicting their performance becomes increasingly unreliable over time, which leads to larger errors made on the PCM side. But most of all, the main rationale for the growing disparity lies in the cumulative error inherent in the PCM, which not only progressively builds up throughout the mission duration, but also gets larger with larger manoeuvres as it has been the case since the deorbiting phase started. These cumulative uncertainties highlight the need for continued refinement and adaptation of methodologies to ensure accurate monitoring and management throughout the mission's lifecycle.

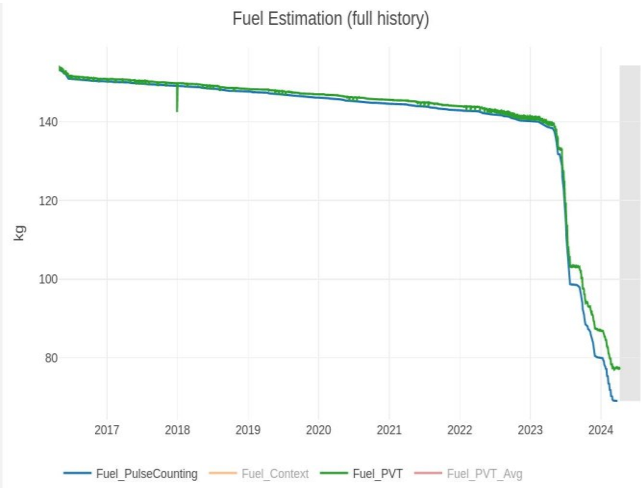

Fig. 6 S1B fuel estimation since BOL

VI. Accuracy assessment

The accuracy of both methods has been assessed, focusing on their criticality for end-of-life operations planning. The findings have been condensed into Table 9, which includes industry-reported figures to provide a comprehensive overview of all available data concerning the anticipated mass and pressure at EOL.

Available data from the Sentinel-1 mission has been thoroughly analysed to gauge the relative accuracy of these fuel estimation techniques. As illustrated in Fig. 7, the difference between the masses of remaining fuel estimated by the 2 methods have been accentuated since July 2023 and is now approaching 9kg. The variances can be rationalized by the models outlined in this paper.

Table 9 Overview of the expected mass and pressure at EOL

	FD	FOM	Industry
Mass error PVT	4.47 kg [5.5bar,12 ºC] **4.60 kg** [5.5bar,20 ºC] 4.76 kg [5.5bar,30 ºC]	4.1 kg [? bar, 12 ºC] **4.2 kg** [? bar, 20 ºC] 4.3 kg [? bar, 30 ºC]	
Mass error FBK	**4.27 kg** @5.5 bar	**4.3 kg** @5.5bar	**4.25 kg** @5.5bar
Pressure PVT	**[5.28,6.24]** bar for T in [22,26] deg C		**[5.62,5.68]** bar for T in [22,26] deg C

For instance, in April 2023, just prior to the primary deorbiting phase, the tank pressure stood at approximately 17.4 bar, resulting in an estimated mass error of 593g for the PVT method and 390g for the PCM. This result is consistent with the difference of approximately 1 kg illustrated in Fig. 6.
However, by April 2024, the pressure had decreased to 9 bars, leading to an estimated error of 1.927 kg for the PVT absolute method and 2.168 kg for the incremental PCM, as per the models presented. The residual variability can be partly ascribed to the simplified depiction of thruster-specific impulse, considered temperature-independent in this study. Nonetheless, the primary cause for the growing disparity lies in the cumulative error inherent in the pulse counting method, which progressively builds up throughout the mission duration. In contrast, the accuracy of the PVT method is contingent upon the changes in pressure and temperature evolution, thus showing a different error pattern as illustrated in Fig. 7.
As the spacecraft approaches its EOL, the disparity between the two methods is anticipated to widen further, with both the PVT method and the PCM expected to exhibit an error of nearly 4.5kg. Consequently, this would result in a relative error exceeding 10kg. Nevertheless, given that Sentinel-1B is currently assessed to have surpassed the orbital limit for re-entry within 25 years, the current aim is to expend as much fuel as feasible to expedite the deorbiting process. This objective serves to mitigate various risks, including the potential for an explosion in the event of a critical situation that triggers the satellite to enter a Safe Mode (SFM), from which recovery may be impossible. It is crucial to note at this juncture that the SFM of S1B does not facilitate activation of the thrusters.

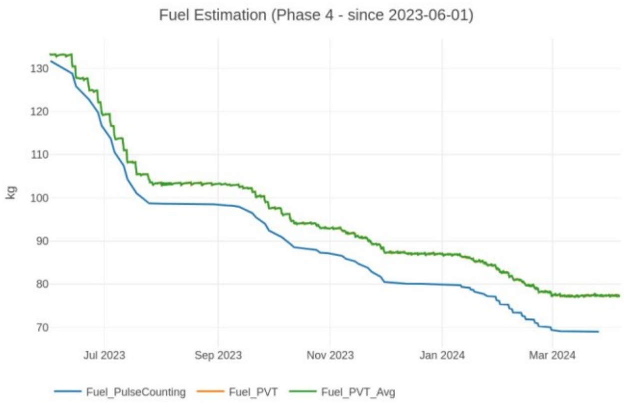

Fig. 7 S1B fuel estimation since the beginning of the deorbiting operations

VII. CONCLUSION

Accurate fuel estimation is crucial for end-of-life operations of satellites. The PVT and Pulse Count Methods offer distinct approaches, each with its merits and limitations. Through application to the Sentinel-1 mission, their relevance and accuracy are demonstrated, underscoring their importance in spacecraft lifecycle management.

In conclusion, the findings of this study align with industry-provided figures, albeit not with pinpoint accuracy, but rather within the same order of magnitude. This suggests a degree of reliability in our estimations, though room for improvement remains. Future research endeavours could focus on refining these estimations by implementing advanced methods, incorporating variables like mass flow and firing duration with varying time increments over the de-orbiting phase.
Notably, the absence of thrusters in safe mode diminishes the urgency for precise fuel mass assessments. However, enhancing accuracy remains pertinent for comprehensive mission planning and resource allocation. Despite encountered challenges during the deorbiting process, the spacecraft continues its descent, and current projections place it below the 25-year re-entry orbit, thus meeting the stringent requirements outlined by the IADC. This underscores the mission's success in adhering to regulatory standards and mitigating space debris risks.

VIII. FUTURE DIRECTIONS

As of now, Sentinel-1B has not fully undergone deorbiting procedures. Consequently, the analysis will require updating or refining once the deorbiting process for Sentinel-1B is completed. This deorbiting, expected to conclude in 2024, will necessitate adjustments to the current analysis to reflect the overall mission of Sentinel-1B.

Future research could explore advanced fuel estimation techniques, incorporating more parameters or even machine learning algorithms for enhanced accuracy. Additionally, collaboration among space agencies could lead to standardized methodologies for fuel estimation, streamlining end-of-life operations planning.

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