Enhancement of the PVT (pressure, volume, temperature) method for xenon gauging of electric propulsion by the use of an EMA (exponential moving average) method

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Abstract: This paper describes the PVT method used to provide an estimate of the available propellant mass of an electric propulsion system during the whole life of the spacecraft. The thermal control system produces oscillations on the measurements of skin temperature and pressure, especially when the pressure is higher than 40 bar. Because the thermal transfers are not instantaneous during a thermal cycle, there is a shift between the observed temperature and pressure maxima, inducing oscillations in the mass estimated with the PVT method. It is clear that the mass inferred from the averaged values of temperature and pressure presents much less oscillations.
In order to get a straightforward method that is valid along the entire operational mission, the averaged values can be assessed by moving average methods over enough thermal cycles in order to smooth the oscillations. The Exponential Moving Average (EMA) relies on a weighting factor "alpha" that is a function of the number of samples having a significant weight into the moving average. The EMA definition is a very simple recurrence equation that can be applied to temperature and pressure measurements. However, the choice of the weighting factor for each new data α must be carefully performed, taking into account the physical process of the selected oscillations to be filtered and the corresponding sampling rate.

Nomenclature

α	=	weighting factor for the recurrence of EMA
M	=	mass (kg)
N	=	the number of significant samples in the EMA

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P = pressure (bar or Pa)
T = temperature (K)
V = volume (m^3)
Z = compressibility factor (-) modifying the perfect gas equation ($P \cdot V/M = Z \cdot 8.314/m_{mol} \cdot T$)
m_{mol} = molecular mass(kg/mol)

I. Introduction

THIS paper describes the method Pressure, Volume & Temperature (PVT) that provides the mass assessments of available propellant in an electric propulsion system during the whole life of the spacecraft.

The SMART-1 probe using electric propulsion for travelling from GTO to the Moon was in 2003 a pioneer mission with the main propulsion relying only on a xenon Hall Effect Thruster **[R 1]**, **[R 2]**. It still serves as a reference for many purposes because the measurements during the propulsive phase are easily available. The paper presents (again) the propulsion system and the results of the PVT mass on SMART-1.

It will be shown that the estimated mass in the case of xenon (with bang-bang thermal control) oscillates quite largely during the course of the mission. The paper presents then the possible methods for removing the oscillations, and particularly the Exponential Moving Average (EMA) and its settings for enhancing the PVT method.

II. SMART-1 electric propulsion sub-system

The functional diagram of SMART-1 is shown in Figure 1 from ref. **[R 3]**. Of particular interest here is the xenon subsystem comprising the xenon tank and the tubing reaching the valve input to the electronic pressure regulator. The sensors used in PVT (pressure and temperature) are highlighted in the sketch. For detailed information on the other parts of the system (BPRU, PRE Card, PPU/TSU, FU, XFCs and thruster PPS1350 of Snecma/Safran) see ref. **[R 1]**, **[R 2]** as well as their own references.

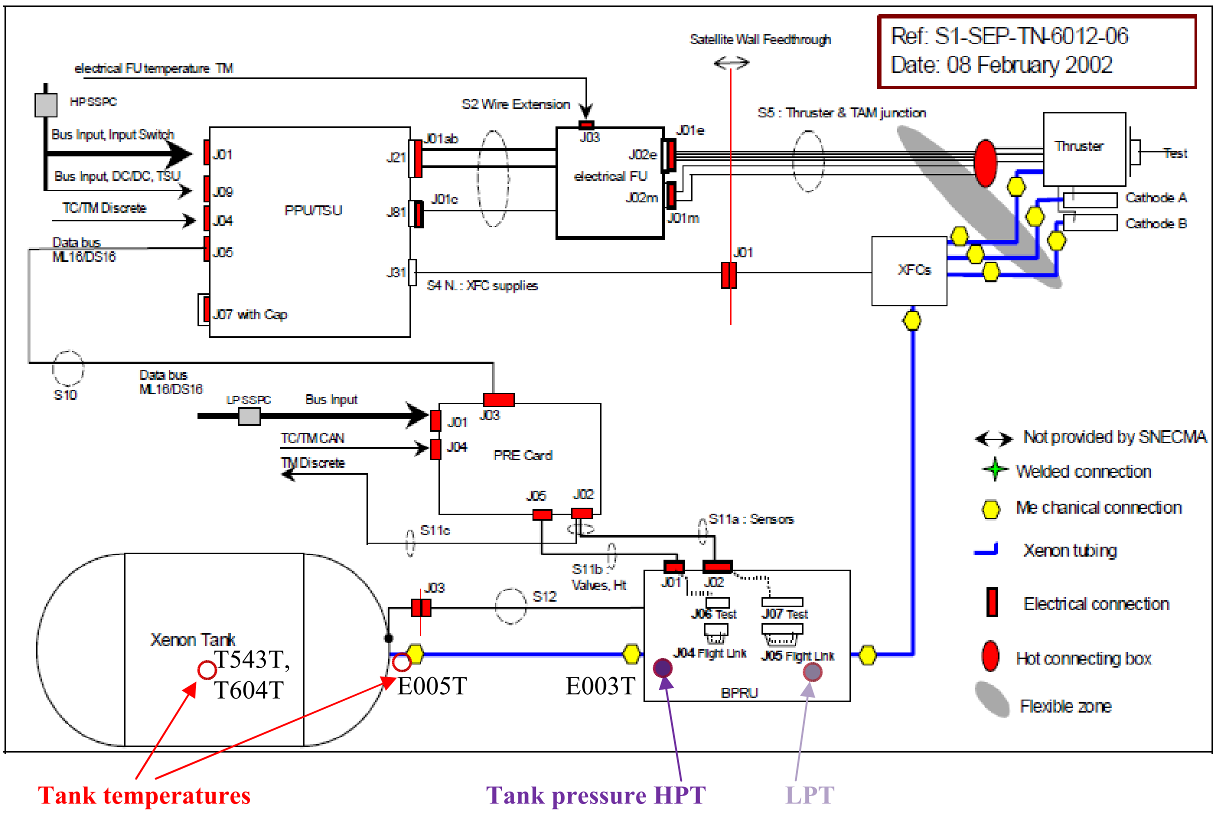

Figure 1 EPS functional diagram: the xenon system feeds the thruster cathodes and anode.

A. Pressure sensors

The xenon gas pressure is measured with a pressure transducer located at the pressure regulation unit input (E003T) in the Electric propulsion system. No significant pressure losses exist since the connection to the tank is performed with tubing of large diameter (6.35 mm), ref. **[R 4**].

B. Temperatures sensors

The temperatures sensors labelled as T543T and T604T are glued on the carbon skin of the tank, as shown in Figure 2. Both sensors are used in the bang-bang control of the thermal conditioning of the xenon tank by turning on or off the heaters glued on the tank skin.

An additional temperature sensor named E005T is implemented in the electric propulsion system. It is located on the outlet tubing of the tank and is directly glued on the aluminium liner end of the composite carbon over-wrapped tank, see Figure 3. It is primarily used in the pressure regulator, to enable redundancy with respect to the single pressure transducer (HPT) implemented in the system, through the xenon state equation and the duration between bang-bang valves openings.

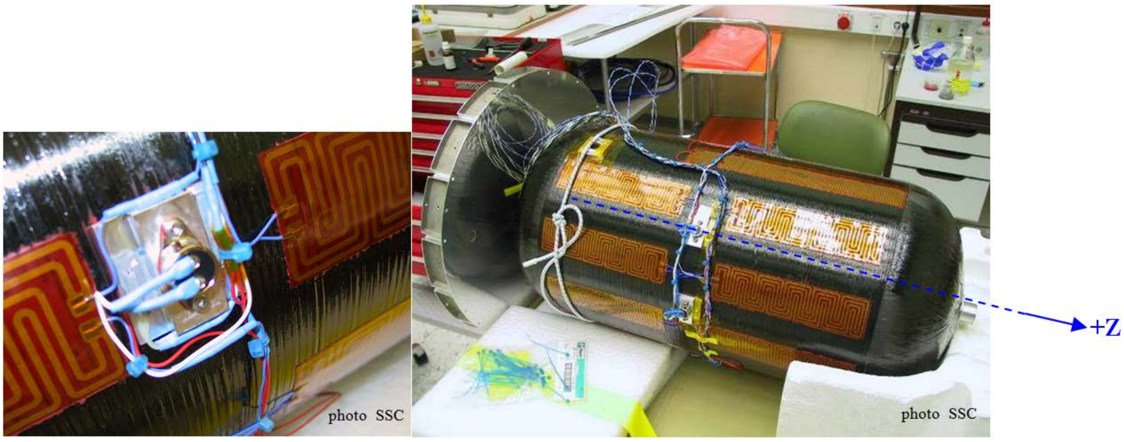

Figure 2 Left: temperature sensors T543T and T604T located on the tank skin. Right: skin heaters (30 W)

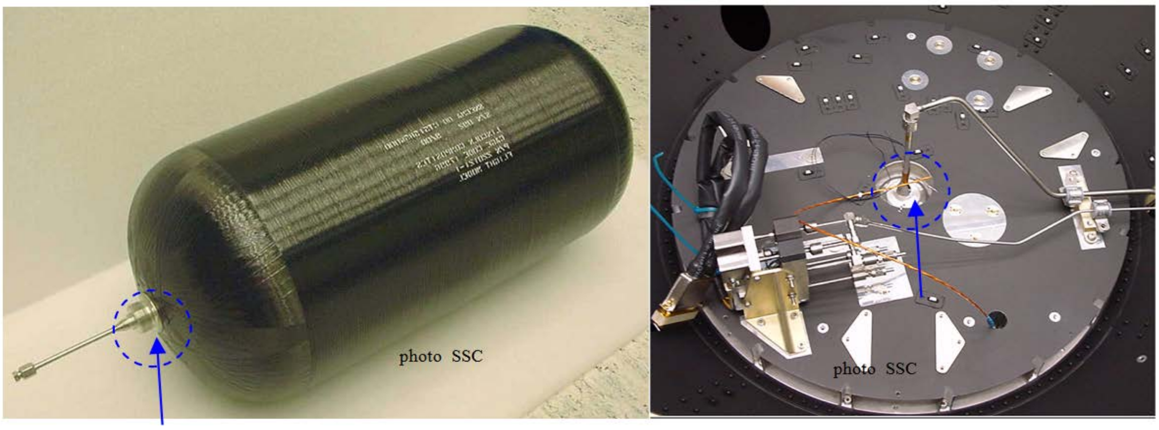

Figure 3 Left: Temperature sensor E005T located at the tank outlet tubing. Left: structure "tank support deck" (location –Z)

C. Overall volume

The overall volume at high-pressure is formed by the high pressure (HP) side of the xenon system, i.e. the volume of the tank itself and the HP line connecting the tank to the pressure regulation HP valve inlet.

1) The tank is delivered by Lincoln Company (from US, now belonging to General Dynamics Armament and Technical Products). Its volume is subject to a slight dependence to pressure, but no dependence to temperature, i.e. the thermal expansion of the tank is zero.
2) Vessel volume: 0.04929 at 0 gauge pressure, i.e. at 0 bar in vacuum, see **[R 5**]
3) Volume expansion with Pressure, coefficient: 5.935E-6 m^3/bar from **[R 5**]

The HP line from the tank to the pressure regulation is a simple tube with 6.35mm external diameter, 0.71 mm thickness and 616 mm length.

D. Xenon real gas

When data for pressure P and temperature T is available simultaneously, the compressibility factor Z can be obtained by means of a look-up table of xenon real gas compressibility (Figure 4) from NIST ref.[R 6], interpolating for both P and T variables.

	303.2	304.2	305.2	306.2	307.2	308.2	309.2	310.2	311.2	312.2	313.2	314.2	315.2	316.2
	30 °C	31 °C	32 °C	33 °C	34 °C	35 °C	36 °C	37 °C	38 °C	39 °C	40 °C	41 °C	42 °C	43 °C
50 bar a	0.682	0.687	0.692	0.696	0.701	0.705	0.709	0.714	0.718	0.722	0.725	0.729	0.733	0.736
51 bar a	0.673	0.678	0.683	0.688	0.693	0.697	0.702	0.706	0.71	0.714	0.718	0.722	0.726	0.73
52 bar a	0.664	0.669	0.674	0.679	0.684	0.689	0.694	0.698	0.703	0.707	0.711	0.715	0.719	0.723
53 bar a	0.654	0.66	0.665	0.671	0.676	0.681	0.686	0.691	0.695	0.7	0.704	0.708	0.712	0.716
54 bar a	0.644	0.65	0.656	0.662	0.667	0.673	0.678	0.683	0.687	0.692	0.697	0.701	0.705	0.709
55 bar a	0.634	0.641	0.647	0.653	0.659	0.664	0.669	0.675	0.68	0.684	0.689	0.694	0.698	0.702
56 bar a	0.624	0.631	0.637	0.644	0.65	0.655	0.661	0.666	0.672	0.677	0.682	0.686	0.691	0.695
57 bar a	0.614	0.621	0.628	0.634	0.64	0.647	0.652	0.658	0.663	0.669	0.674	0.679	0.684	0.688
58 bar a	0.603	0.61	0.618	0.624	0.631	0.637	0.644	0.649	0.655	0.661	0.666	0.671	0.676	0.681
59 bar a	0.591	0.6	0.607	0.614	0.621	0.628	0.635	0.641	0.647	0.652	0.658	0.663	0.669	0.674
60 bar a	0.58	0.588	0.597	0.604	0.612	0.619	0.625	0.632	0.638	0.644	0.65	0.655	0.661	0.666
61 bar a	0.568	0.577	0.586	0.594	0.601	0.609	0.616	0.623	0.629	0.636	0.642	0.647	0.653	0.659
62 bar a	0.555	0.565	0.574	0.583	0.591	0.599	0.606	0.613	0.62	0.627	0.633	0.639	0.645	0.651
63 bar a	0.542	0.553	0.563	0.572	0.58	0.589	0.597	0.604	0.611	0.618	0.625	0.631	0.637	0.643
64 bar a	0.529	0.54	0.55	0.56	0.569	0.578	0.586	0.594	0.602	0.609	0.616	0.623	0.629	0.635
65 bar a	0.515	0.527	0.538	0.548	0.558	0.567	0.576	0.584	0.592	0.6	0.607	0.614	0.621	0.627
66 bar a	0.5	0.513	0.525	0.536	0.547	0.556	0.566	0.574	0.583	0.591	0.598	0.605	0.612	0.619
67 bar a	0.484	0.499	0.512	0.524	0.535	0.545	0.555	0.564	0.573	0.581	0.589	0.596	0.604	0.611
68 bar a	0.468	0.484	0.498	0.511	0.522	0.533	0.544	0.553	0.563	0.571	0.58	0.587	0.595	0.602
69 bar a	0.451	0.468	0.483	0.497	0.51	0.521	0.532	0.543	0.552	0.561	0.57	0.578	0.586	0.594
70 bar a	0.433	0.452	0.468	0.483	0.497	0.509	0.521	0.532	0.542	0.551	0.56	0.569	0.577	0.585
71 bar a	0.414	0.434	0.452	0.469	0.483	0.497	0.509	0.52	0.531	0.541	0.551	0.56	0.568	0.576
72 bar a	0.394	0.417	0.436	0.454	0.469	0.484	0.497	0.509	0.52	0.531	0.541	0.55	0.559	0.567
73 bar a	0.375	0.399	0.42	0.438	0.455	0.47	0.484	0.497	0.509	0.52	0.53	0.54	0.55	0.558
74 bar a	0.358	0.381	0.403	0.423	0.441	0.457	0.471	0.485	0.497	0.509	0.52	0.53	0.54	0.549
75 bar a	0.343	0.365	0.387	0.407	0.426	0.443	0.459	0.473	0.486	0.498	0.51	0.52	0.531	0.54
76 bar a	0.332	0.351	0.372	0.392	0.411	0.429	0.445	0.46	0.474	0.487	0.499	0.51	0.521	0.531
77 bar a	0.323	0.34	0.358	0.378	0.397	0.416	0.432	0.448	0.463	0.476	0.488	0.5	0.511	0.522
78 bar a	0.316	0.331	0.347	0.365	0.384	0.402	0.42	0.436	0.451	0.465	0.478	0.49	0.501	0.512
79 bar a	0.311	0.324	0.339	0.355	0.372	0.39	0.407	0.424	0.439	0.454	0.467	0.48	0.492	0.503
80 bar a	0.308	0.319	0.332	0.346	0.362	0.379	0.396	0.412	0.428	0.443	0.456	0.469	0.482	0.493
81 bar a	0.305	0.315	0.326	0.339	0.354	0.369	0.385	0.401	0.417	0.432	0.446	0.459	0.472	0.484
82 bar a	0.303	0.312	0.322	0.334	0.347	0.361	0.376	0.391	0.406	0.421	0.436	0.449	0.462	0.475
83 bar a	0.302	0.31	0.319	0.329	0.341	0.354	0.367	0.382	0.397	0.412	0.426	0.44	0.453	0.465
84 bar a	0.301	0.308	0.317	0.326	0.336	0.348	0.361	0.374	0.388	0.402	0.417	0.43	0.444	0.456
85 bar a	0.3	0.307	0.315	0.323	0.333	0.343	0.355	0.367	0.381	0.394	0.408	0.421	0.435	0.447
86 bar a	0.3	0.306	0.313	0.321	0.33	0.34	0.35	0.362	0.374	0.387	0.4	0.413	0.426	0.439
87 bar a	0.3	0.306	0.312	0.32	0.328	0.337	0.346	0.357	0.368	0.38	0.393	0.406	0.418	0.431
88 bar a	0.3	0.306	0.312	0.319	0.326	0.334	0.343	0.353	0.363	0.375	0.386	0.399	0.411	0.423
89 bar a	0.3	0.306	0.311	0.318	0.325	0.332	0.341	0.35	0.359	0.37	0.381	0.393	0.404	0.416
90 bar a	0.301	0.306	0.311	0.317	0.324	0.331	0.339	0.347	0.356	0.366	0.376	0.387	0.398	0.41
91 bar a	0.302	0.306	0.311	0.317	0.323	0.33	0.337	0.345	0.353	0.362	0.372	0.382	0.393	0.404
92 bar a	0.302	0.307	0.312	0.317	0.323	0.329	0.336	0.343	0.351	0.36	0.369	0.378	0.388	0.399
93 bar a	0.303	0.308	0.312	0.317	0.323	0.329	0.335	0.342	0.349	0.357	0.366	0.375	0.384	0.394
94 bar a	0.304	0.308	0.313	0.318	0.323	0.328	0.334	0.341	0.348	0.355	0.363	0.372	0.381	0.39
95 bar a	0.305	0.309	0.314	0.318	0.323	0.328	0.334	0.34	0.347	0.354	0.361	0.369	0.378	0.387
96 bar a	0.306	0.31	0.314	0.319	0.323	0.329	0.334	0.34	0.346	0.353	0.36	0.367	0.375	0.384
97 bar a	0.308	0.311	0.315	0.319	0.324	0.329	0.334	0.34	0.345	0.352	0.359	0.366	0.373	0.381
98 bar a	0.309	0.312	0.316	0.32	0.325	0.329	0.334	0.339	0.345	0.351	0.358	0.364	0.372	0.379
99 bar a	0.31	0.314	0.317	0.321	0.325	0.33	0.335	0.34	0.345	0.351	0.357	0.363	0.37	0.377
100 bar a	0.312	0.315	0.318	0.322	0.326	0.33	0.335	0.34	0.345	0.35	0.356	0.362	0.369	0.376

Figure 4 Partial look-up table for the xenon compressibility factor from NIST, ref. [R 6]

E. Simultaneous PVT measurements in flight

Pressure is measured by the single high pressure transducer E003T, and it is equal at the tank and HP line. This measurement is available in flight through the pressure regulator (BPRU) and its electronics (PRE Card), and the transmitted data is time stamped. But when that electronic is off, the last measure is still recorded and transmitted to the ground station. This "memory effect" does not have any negative impact on operations, but it makes the analysis of the data more complex.

Thus, it is to be highlighted that relevant measurements of pressure are only available when the Electric propulsion system (EPS) is turned on (i.e. the electronics card of the pressure regulator is turned on). The ground treatment of those pressure data takes care of that feature by eliminating the data points that are identical within any given time interval.

The shift affecting the zero of the high pressure transducer, known only at the end of the mission by comparison with the low pressure transducer, has been removed from the pressure data (under the hypothesis of constant shift rate over time); hence the pressure presented here can be considered an exact reference.

The tank skin temperatures T543T, T604T acquired by the S/C are available most of the time, but due to eventual TM issues, both signals are not always available simultaneously. For this reason, both T543T and T604T have been taken into account in order to cover the whole lifetime while minimizing the loss of telemetry data. It has been checked that no visible offsets occur between the two temperature measurements, their mean value over the entire mission being 39.17°C for T543T and 39.20°C for T604T. The two temperature signals have not been averaged, since the measurements do not occur in an exact simultaneous time. Instead, the two whole datasets of T543T and T604T has been merged over time in order to get a single continuous set of chronological data.

For the HP line, the temperature measurement E005T is available through the pressure regulator (BPRU) electronic card. The synchronisation of all the measurements is performed by linear interpolation of the temperatures for each time stamp of any given pressure. A huge amount of data are available, see ref. **[R 7]** for the EPS SMART-1 (polling every 2 s, that is 9 000 000 points for each EPS measurement when the EPS is ON). The pressure and temperature signals over the entire duration of the SMART-1 mission are shown in Figure 6. The temperature at the outlet of the tank (Figure 6-c; E005E) present considerably larger perturbations than the tank skin temperatures (Figure 6-b T543T, T604T), which are most of the time within the control range of (37.5 to 42.5°C). Only some exceptions occur: during LEOP due to the fact that a test was performed to change to a lower control range, and during certain eclipses of long duration. The pressure, Figure 6-a, also presents oscillations induced by the changes in the thermal control range during LEOP, but no effect is observed due to long eclipses since the EPS was turned off then, and no pressure measurements were possible.

III. The PVT xenon mass assessment

A xenon mass assessment is obtained by applying the modified perfect gas equation $P \cdot V/M = Z \cdot 8.314/m_{mol} \cdot T$ to the whole available dataset. The plot in Figure 5 shows the xenon mass assessment using the measurements of pressure and skin temperature with the right volume of the pressure vessel and the outlet tubing temperature for the high pressure tubing part of the xenon sub-system. The mass computed by this method starts with oscillations. The oscillations culminate with about ±10% of the xenon mass around its mean value in the middle of the mission (March 2004). Such large uncertainties lead to search for a better method for removing the oscillations.

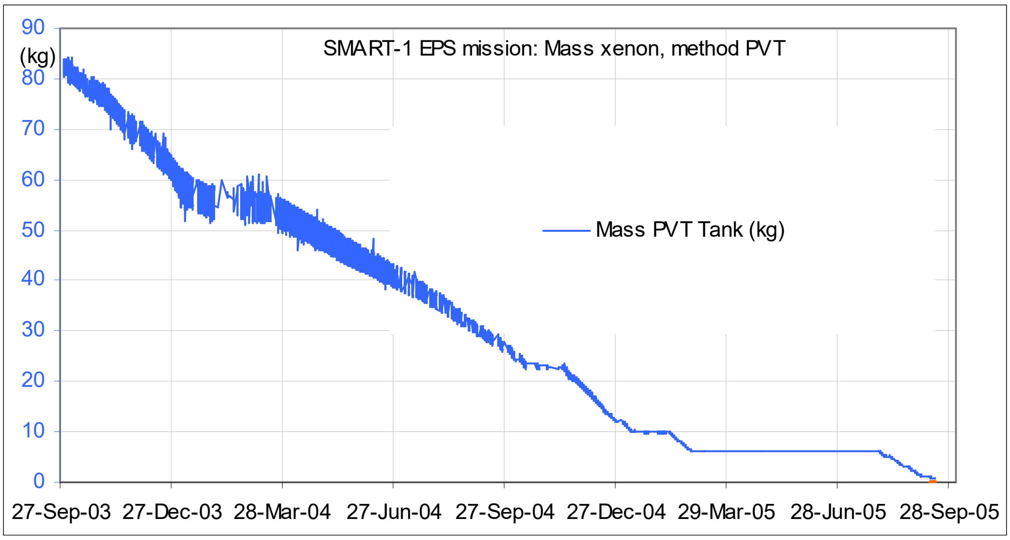

Figure 5 Mission SMART-1: Xenon mass in the tank assessed via PVT method (from [R 7])

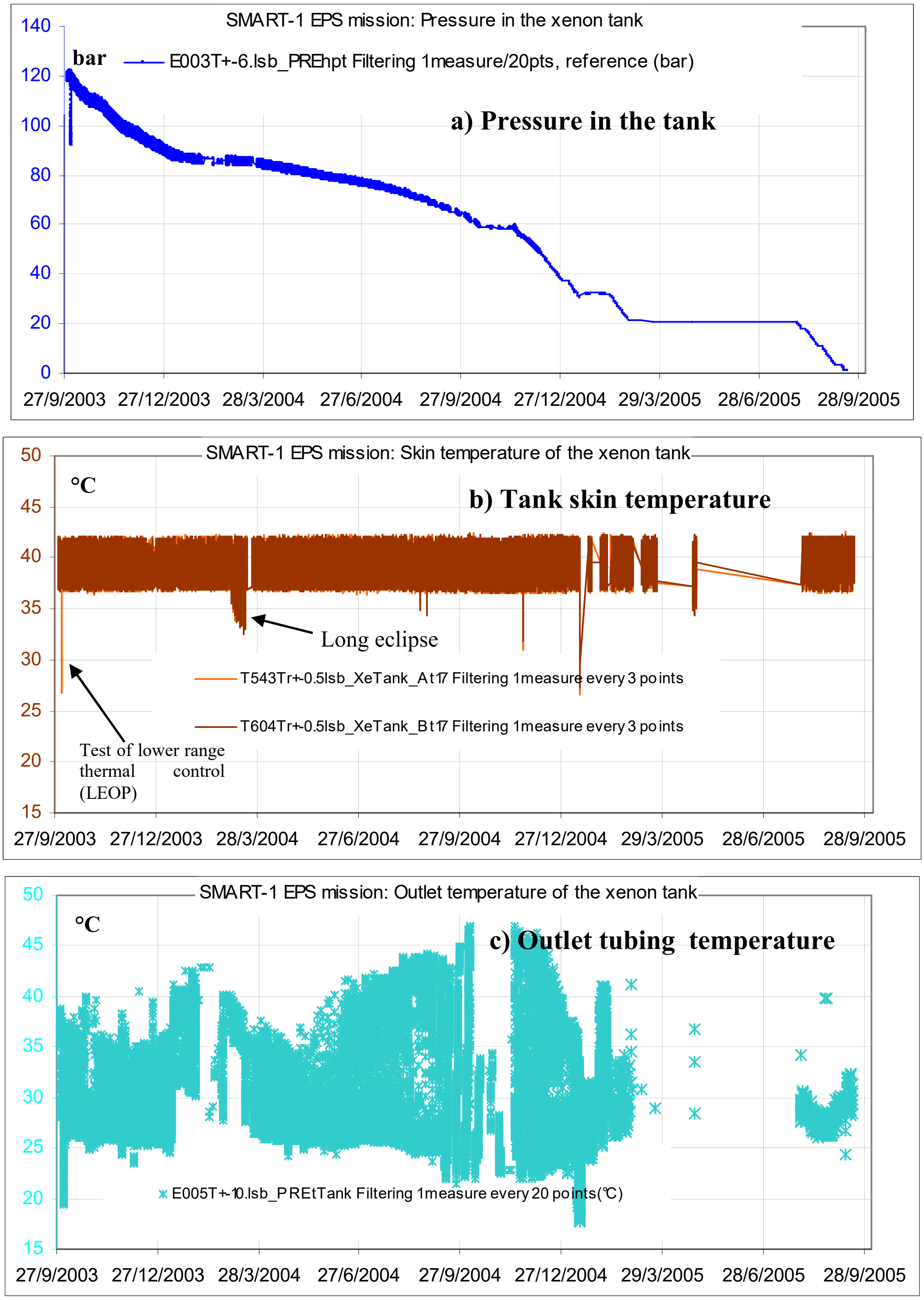

Figure 6 Mission SMART-1: a)Pressure in the tank, b)Skin tank temperature and c)Outlet tubing temperature (from [R 7])

IV. Averaging method suited for the PVT mass assessment

The aforementioned PVT method provides xenon mass assessments during the whole life of the spacecraft, but the bang-bang thermal control system produces oscillations in the skin temperature and pressure measurements, especially when the pressure is higher than 40 bar.

Since thermal transfers are not instantaneous during a thermal cycle, and due to the low thermal conductivity of xenon, there is a shift between the observed maximum temperatures and pressures, and this shift in turn induces the mass oscillations in the PVT method described above.

It is clear that a mass assessment based on the average values of pressure and temperature should not present any oscillations. But it is not so easy to find automatically the average values:

1) Normally this would mean the detection of a full thermal cycle on the mass, which is within some period of time, detection of the mini-maxi or the maxi-mini of the mass and then making the average.

Such method presents several practical difficulties for its implementation:

2) The duration of the thermal cycles is not constant,
3) Some cycles are not complete (because the pressure measurements occur only when the EPS is turned on)

Hence the use of a straightforward method valid along the operational mission has been investigated. A filter-like approach has been selected in order to smooth the oscillations, by assessing the averaged values via moving average methods over a sufficient amount of thermal cycles. Among several possible methods, the following EMA method has been found suited for its implementation in operations.

A. The Exponential Moving Average

The Exponential Moving Average (EMA) definition is a very simple recurrent equation, see Eq. (1). The EMA relies on a weighting factor $\alpha = \frac{2}{N+1}$, where N is the number of samples having a significant weight into the moving average (86% of the total). For example, the EMA of temperature is calculated as follows:

$$T_{EMA} = \alpha . T + (1-\alpha) . T_{EMA\_previous} \, , \tag{1}$$

where T is the new temperature measurement and T_{EMA} is the new average temperature and $T_{EMA\_previous}$ is the variable's previous value.

The choice of N (or the weighting factor α for each new value) relies on the physical process of the oscillations to be filtered and the associated sampling rate.

B. Choice of weighting factor for the EMA (Exponential Moving Average)

For the case of SMART-1 in flight, we have the following characteristics:

1) The period of the thermal cycle is between 4000 s and 6000 s long.
2) The sampling period for the pressure measurements taken into account is about 400 s *(in flight a measurement is taken every 2 seconds, and for ground assessment one data point is taken from every 20 points: that is a period of 2 x 20 =400 s).*
3) The sampling period for the temperature measurements is 1 to 2 minutes, i.e. 120 s.
4) Hence for smoothing over at least **10 thermal cycles** (60 000 s):
   - The number of pressure samples to be taken is N=150, i.e. α = 1.3%.
   - The number of temperature samples to be taken is 500, i.e. α = 0.4%.

C. Operational weighting factor for the EMA

In order to get a common value of the weighting factor for both pressure and temperature, the number of measurements shall be the same for both variables. This is done by synchronisation, selecting temperature data points for each time-stamped pressure data.

Hence with such set of synchronised consistent data of pressure and temperature, a common weighting factor of 1.3 % (N=150) has been applied for the EMA on both pressure and temperature.

However, when the pressure oscillations vanish by the end of the mission (pressure lower than 40 bar) it has been found that that the weighing factor needs to be adjusted so that the previous measurements cancel out rapidly with α = 4% (N=50) in order for the EMA pressure to follow more closely the actual pressure.

D. Results with EMA method

The results of the xenon mass computed via the EMA method are shown in Figure 7.

The details of the EMA method presented in Figure 8 show that the EMA pressure and EMA temperature (T543 and T604) are well within the original measurements of pressure (above 40 bar) and temperature. Thus, the effect of the EMA method to remove the oscillation for providing a smooth evolution of both parameters is working as expected.

Note: The EMA of the temperature measured at the high-pressure tubing (E005) is not very smooth because its data is poorly synchronised with the valid pressure timestamp. This has very little influence on the total mass, since the volume of the HP line is much smaller than the tank volume.

The obtained smooth EMA pressure and EMA temperatures provide a stable computation of the xenon mass. The xenon mass provided by the EMA method is also within the xenon PVT mass oscillations, as expected.

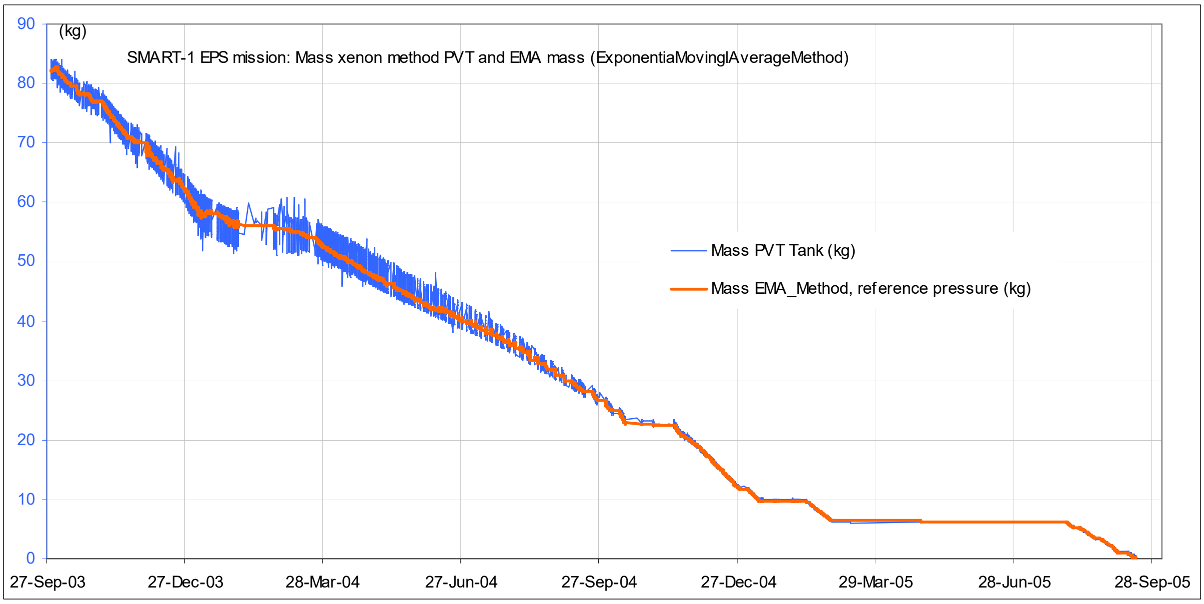

Figure 7 Xenon mass from PVT method and xenon mass from EMA method during SMART-1 mission (from [R 7])

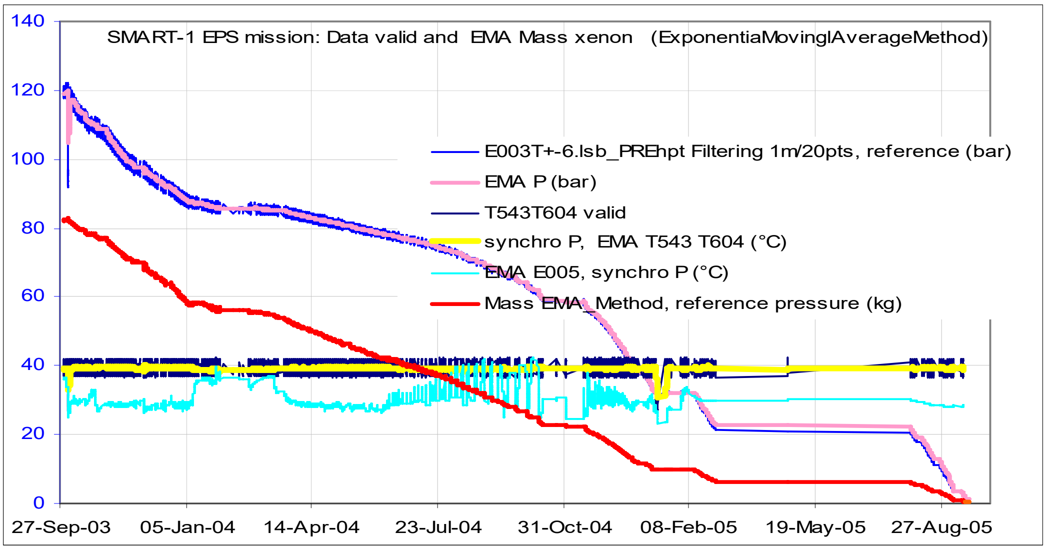

Figure 8 Details of the EMA method: Pressure, temperatures and mass of xenon (from [R 7])

V. Conclusions

The direct use of the Pressure, Volume & Temperature (PVT) method for xenon mass assessment has been presented. The low thermal conductivity of xenon and the particularities of the bang-bang thermal control induce considerably large oscillations in the mass assessment (up to ±10%). A filtering process is required on the measurements in order to allow for the retrieval of stable results from the PVT method.
On the SMART-1 mission, such enhancement of the PVT method has been successfully performed by implementing the Exponential Moving Average (EMA) on each measurement prior to applying the PVT method.
The settings of the EMA consist only in the selection of one weighting factor, which depends on the oscillation period and the sampling rates of each measurement. For the case of the SMART-1 mission, a weighting factor of 1.3% produces satisfactory results for pressures above 40 bar.

Acknowledgments

The overall SMART-1 EPS activities have been performed in the frame of an ESA/ESTEC/TOS-MPE TRP contract, and the EPS has been delivered to the Project as Customer Furnished Equipment.

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