

Thermal Propellant Gauging System for BSS 601

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Of the more popular methods of propellant estimation, namely, book-keeping, PVT (Pressure, Volume, Temperature) and the Thermal Propellant Gauging System (PGS) methods, the latter is most accurate at End-of-Life (EOL). The thermal method uses tank temperature responses to tank heating in order to infer the propellant load in the tank. Typically, the PGS method uses heat load from heaters which are attached to the propellant tanks. The current paper discusses a method of Thermal PGS when tanks do not have installed heaters. Specifically, this paper describes how the Thermal PGS method could be applied to an on-orbit Boeing 601 geosynchronous communications satellite. It is shown that propellant gauging is possible even when the propellant tanks do not have heaters. This paper examines an implementation of the Thermal PGS method on a Boeing 601 geosynchronous communications satellite which has been operated by JSAT Corporation of Japan. Prior to the development of a thermal model, a feasibility test was conducted in order to determine the tank temperature response to tank heating. Due to the lack of heaters on the propellant tanks, gyro (Inertial Reference Unit, or IRU) heaters were used for tank heating. During the 48-hour feasibility test, the tank temperature rose several degrees C which is sufficient for propellant estimation by the Thermal PGS method. No stationkeeping maneuvers were conducted during the period of data collection, in fact, the first maneuver was performed after a cool-down period for the tanks. High-fidelity tank and satellite thermal models were developed based on the results of the feasibility test, and those thermal models were used for propellant estimation. This paper discusses the results of the propellant estimation operations and the accuracies achieved.

Nomenclature

C_p	= specific heat
m_i	= mass of “i” component
T	= tank temperature
T_{env}	= environment temperature
Q_{load}	= heater power
U	= uncertainty of calculated or measured value
f	= generic function\
ε^*	= effective emissivity through Multi Layer Insulation (MLI)
i	= component index
p	= propellant index
g	= gas index
t	= tank index

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I. Introduction

The Propellant Gauging System (PGS) method of propellant estimation is based on a concept of measuring the thermal capacitance of a tank containing liquid fuel and pressurant gas by measuring the thermal response of the propellant tank to heating and comparing the observed temperature rise to simulation results obtained from a tank thermal model^{1,2}. Described in Ref. 1, 2 the PGS method employs a very sophisticated thermal model of the propellant tank which takes into account temperature gradients in the tank.

Non-uniform heater power distribution and uneven propellant distribution inside of the tank cause a non-uniform temperature distribution on the tank surface. Non-uniformity of heater power distribution stems from the fact that heater strips typically cover only a fraction of the tank surface. If propellant position in the tank is controlled by a vane-type Propellant Management Device (PMD) in microgravity, then at EOL the propellant is located in the sump and in the corners formed by PMD vanes and the tank wall. A significant portion of the internal tank wall is not in contact with propellant and therefore dry. All these factors lead to the formation of significant temperature gradients on the tank wall. Therefore, the temperature, which is measured by the temperature sensors on the external side of the tank wall, depends on the sensor locations. The temperature distribution on the tank surface must be determined to successfully compare the test flight data with calculated temperatures.

If satellite thermal control system does not have heaters installed on the propellant tanks, the tank temperature is controlled by internal satellite thermal control system. The BSS (former Hughes) 601 geosynchronous communication satellite is an example of such thermal control scheme³. Such a thermal control system presents a challenge for a typical PGS method because energy input into a propellant tank is done not by heaters installed on the propellant tanks but rather by external heat sources like payload or bus units which heat generation is known. An example of such unit could be TWT or one of the bus units which generate enough heat to increase tank temperature. The key is knowledge of heater power or/and surface temperature of the unit which is used to generate energy and to increase tank temperature.

If the unit in question has a temperature sensor, heat generation by the unit can be calculated. Vice-versa, knowledge of heat generation allows calculation of unit temperature which can be compared with temperature sensor reading if the unit has temperature sensor installed. In both cases, development of a high fidelity model of the satellite including payload and bus units is required.

Such a requirement constitutes the major difference for PGS method between satellites with and without heaters installed on the propellant tanks. If propellant tanks have heaters installed and the tanks are covered with thick Multi Layer Insulation (MLI) blanket, the tanks do not have much thermal interaction with the satellite environment. Knowledge of the satellite thermal environment is not so important for correct propellant estimation by the PGS method. On other hand, if payload or/and bus unit is a heat source which used for propellant estimation, the heat source is part of the satellite environment. In this case, the tank temperature rise is determined by thermal interaction between the tank and the satellite environment. Therefore, knowledge of the satellite environment becomes very important for correct propellant estimation.

II. Thermal models

Regardless of the spacecraft type, the PGS method employs the same steps:

- Develop a thermal models of the propellant tanks and the satellite
- Develop a thermal models of the satellite
- Merge the thermal models of the satellite and propellant tanks
- Prepare and conduct the PGS operation
- Simulate the PGS operation for different propellant loads
- Compare flight and simulation data
- Determine tank propellant load

The first phase of the PGS method, namely, development of the tank thermal model, the development is mostly driven by the tank design and by the fact that heaters (if installed) create a large temperature gradient on tank walls in heaters vicinity. It means that a high fidelity tank model is required to capture

temperature gradients and to determine tank wall temperature at the temperature sensor location. In absence of the heaters on the tank surface, one can expect less temperature gradient and, therefore, less stringent requirements for capturing temperature gradients.

A. High Fidelity Tank Model

If temperature gradients can not be neglected, which is a common case, temperature distribution in the tank should be determined numerically with corresponding boundary and initial conditions. Previously developed a Finite Element (FE) model of the propellant tank^{1,2} was based on grid provided by Surface Evolver⁴. The developed FEM model of the tank had several problems including difficulty of keeping the ratio of the maximum to minimum conductances of the links between nodes in the thermal model sufficiently small to avoid ill-conditioned matrices in the thermal modeling. Also, based on Surface

Evolver grid had extremely small or large conductances, which are not generally necessary. Similarly, the minimum thermal capacitance of elements affects step size in time and thus overall compute time of the modeling.

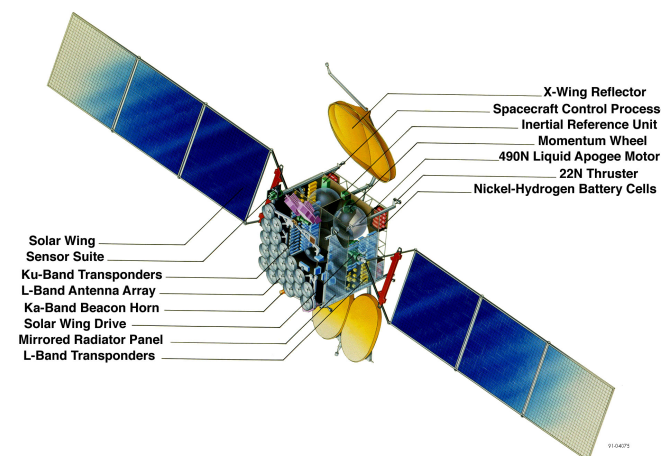
In order to avoid such problems, a new FEM was developed. Grid generation for such complex geometry like tank with gas and liquid volumes, tank wall, heaters, etc is not simple task. The grid should satisfy the following requirements:

have high enough density to simulate thermal gradients, particular at the temperature sensor location, confirm to the primary geometry of model components like, tank wall, propellant, pressurant, should confirm each other at the interfaces, confirm heater shape, etc.

GridPro⁵ was selected as the primary tool for creating the grid. It is a powerful tool designed to create computational fluid dynamics (CFD) grids. Grid generation of the tank was not simple. When the geometry is complex, it can be difficult to get a CFD style grid to converge and to model accurately the geometry. In particular, GridPro runs into problems when the geometry becomes overly complex, like, sharp edges, or a zero-degree angle between two surfaces. The gas/fluid interface model alone is of sufficient complexity to cause the GridPro to have difficulty of converging. Add to this, requirements for the grid to confirm to tank heaters shape, variations in the tank wall profile, mounting lugs, etc. and it quickly becomes extremely time consuming to develop a grid that will converge. A suite of software tools was developed in order to overcome these limitations.

Figure 1 shows several cross-sections of the final grid. As one can see, the grid has higher density next to tank wall where temperature gradients are expected.

B. High Fidelity Satellite Model



Current paper discusses development the PGS method for BSS (former Hughes) 601 geosynchronous communication satellite. Figure 2 shows a general view of the satellite which design is described in details in Ref.3.

The satellite propulsion system has four spherical tanks (two fuel tanks and two oxidizer tanks). Tanks are covered with single layer MLI³. Two temperature sensors are installed on the top and on the bottom of a propellant tank (Fig.7 Ref.3). The top temperature sensor approximates pressurant temperature. The bottom

Figure 2 BSS 601 satellite

temperature sensor senses the temperature of the propellant which is contained inside of the trap (Fig.7 Ref.3).

Such design of the propellant tanks and the satellite requires development of satellite thermal model which should describe: a). radiation heat transfer between tanks and satellite components like panels and payload/bus electrical and electronic units; b). heat transfer by conduction between the units and satellite structure, between satellite structure and propellant tanks. Due to a particular position of the temperature sensors on the propellant tank wall, heat transfer between bottom of the propellant tank and the satellite presents the greatest interest.

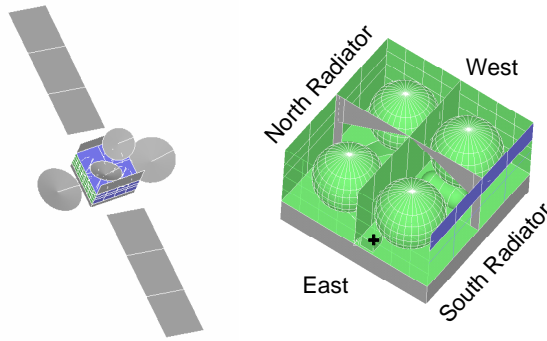


Figure 3 Satellite Thermal Model
Cross shows IRU location

Figure 3 demonstrates a developed satellite thermal model. The model simulates all major elements of the BSS 601 satellite which are important for simulation of the PGS operation and propellant estimation, like internal panels, MLI blankets, etc. All surfaces of the satellite internal panels are assumed painted black, which is common practice for communication satellites in order to increase heat rejection from the internal panels.

The satellite thermal model includes solar fluxes incident on the outer surfaces of the satellite. The radiation interaction inside of the satellite and solar fluxes were simulated by Thermal Synthesizer System (TSS) software tool. Typically, North and

South panels of communication satellites house heat producing units, like Travel Guided Tube (TWT) which usually instrumented with temperature sensors. Use of temperature sensor readings as boundary conditions simplifies the satellite thermal model because it circumvents the need to determine temperature of the North/South panels. Usually, East and West panels don't have any payload or bus units; the temperature of such panels was calculated.

III. Propellant Estimation

This section discusses the PGS operation that was performed in 2006 on one of the BSS 601 satellites of JSAT Corporation fleet. JSAT began to operate BSS 601 satellites in 1995. Five BSS601 satellites have been operated so far.

All previous experience related to propellant estimation for the satellites with tanks which have heaters. Prior to development a high fidelity models of the propellant tank and the satellite, a feasibility study was conducted. The study included simulation and flight test. The goal of the feasibility study was to determine whether the PGS method is suitable for propellant estimation due to the fact that propellant tanks do not have heaters. Due to lack of the heaters on the propellant tanks, we used IRU heaters as an external heat source. Flight experience pointed out that propellant tank temperature went up when IRU heaters were turned ON. It shows that IRU heaters can be used for the PGS operation, but an accuracy of such estimation was not known. As Figure 3 indicates, IRU units are located on the bus panel in vicinity of the propellant tanks. Therefore, the IRU heaters should have the greatest influence on the tank temperature.

A. Feasibility study

1. Simulation

In order to study an effect of heat generation by IRU heater on tank temperature, we assumed IRU temperature of 60 C when the heater is turned ON. Figure 4 shows the tank temperature trend when the heaters are turned ON and OFF. Tank temperature rises when IRU heater is ON and falling after the IRU heater is switched OFF. It supposed to take about 48 hr. to reach equilibrium with satellite environment during. The cooling period also should last about 48 hr.

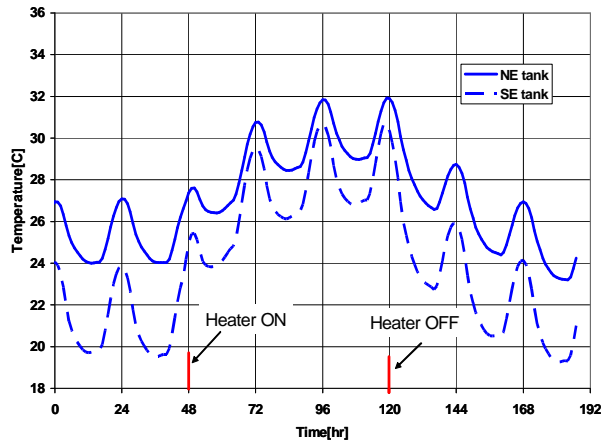


Figure 4 Tank Temperature at the bottom;

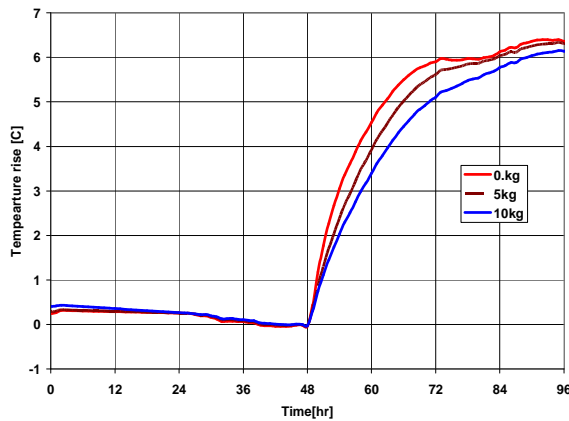
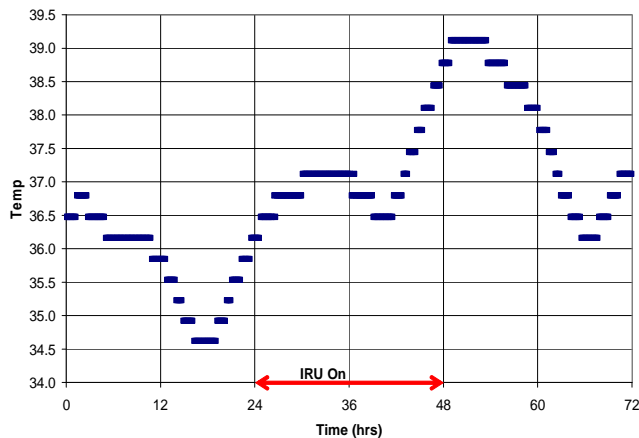


Figure 5 Normalized Tank Temperature

temperature has risen for several degrees (see Figure 6 and Table 1), which seemed to be sufficient for propellant estimation by the PGS method.



**Figure 6 Fuel Tank Temperature Sensor T3 trend
IRU on for 24 hr**

Table 1 Flight Test Results

When IRU heater is turned ON temperature of both tanks, NE and SE, increase. Heat transfer to the SE tank is conducted mostly via radiation. Heat transfers from the unit to the NE tank via conduction by base panel and via radiation across the middle wall. As expected, temperature rise of NE tank is less than temperature rise of SE tank.

Tank temperature rise due to heat input from the IRU presents the most interest, as far as the PGS method concern. Such a temperature rise has the same magnitude as tank temperature change due to daily temperature variation. This obscures temperature rise due to tank heating by the IRU heater. A normalization procedure was developed in order to extract such tank temperature change. Figure 5 shows behavior of the normalized temperature. Daily temperature fluctuations are removed and only temperature rise due to heat injection by the IRU heaters remains.

The plot also shows an effect of tank propellant load on the temperature rise, which is the most interest to the PGS method. The data clear demonstrates that temperature rise depends on the propellant load and can be used for propellant estimation by the PGS method.

2. Flight

For the feasibility test, IRU heater was turned ON for 24 hr. During this time tank

Tank Type	Temperature Rise (°C)
Fuel	2.7
Oxidizer	5.0

B. Operational Constraints

Several considerations should be taken into account in determination of the period of the PGS operation in order to minimize an influence of the spacecraft conditions on tank temperature:

- Avoid eclipse season (change of thermal condition)
- No change in payload/Bus unit configuration (change of thermal condition)
- No stationkeeping maneuvers performed (change of propellant load, sloshing)
- Enough time to cool-down for the tanks after turning heaters OFF

From station-keeping viewpoint, a period of cooling down of the propellant tanks after the heaters turned OFF should be long enough in order to reduce propellant tank pressure. Increased tank pressure might cause some variance in maneuver performance.

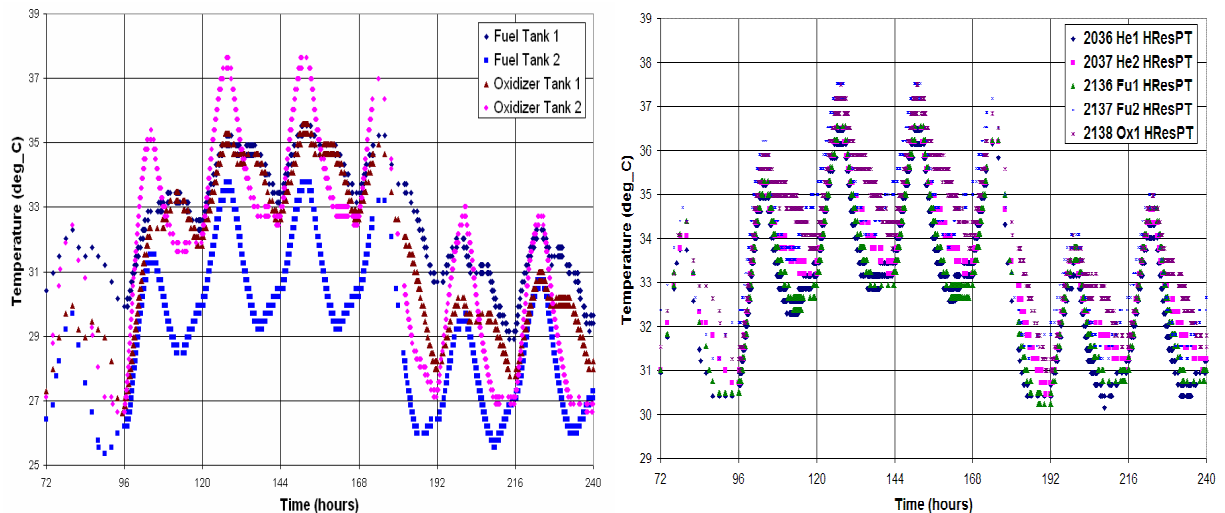
No stationkeeping manoeuvres were conducted during the PGS operation because temperature and pressure of the tanks were a little bit higher than usual due to tank heating. First manoeuvre was performed after a cool-down period which lasted for 48 hours. Temperature rise due to heating varied for different tanks. It could be explained by difference of propellant loads or/and difference in environment conditions for each tank. The observed temperature rise was sufficient to estimate the remaining propellant in the tanks.

C. Flight Test –results

The PGS operation was performed after successful completion of the feasibility study. The PGS operation consisted of two steps: PGS operation procedure preparation and a flight operation. The developed tank and spacecraft models were used in the development of the flight operations procedure. The goals of the simulation for the procedure development were to determine: 1) the length of time which it takes for the tanks to reach thermal equilibrium, and 2) the length of time which it takes for the tanks to cool down to the initial conditions. It was determined that it should take 3 -4 day for tank temperature to reach saturation and 1-2 days to cool tanks down to the initial temperature.

The IRU heaters had been turned ON for 3 days during the PGS operation. The observed tank temperature rises were: Fuel Tank 1 – 3.5 °C, Fuel Tank 2 – 4°C.; Oxidizer Tank 1- 5.5°C, Oxidizer Tank 2 - 5°C. The temperature trends for bottom temperature sensors (T3) of the propellant tanks are shown in Fig.7a.

The temperature of the propellant tanks and several bus and payload units were collected during the PGS operation. The satellite thermal model uses temperature of bus and payload units to characterize tank



a) b)
Figure 7 Flight Operation Results – a)Tank (Sensor 3); b) Pressure Controllers temperature sensors

environment. In addition to tanks, IRU heaters affect temperature of bus and payload units. An example of such influence is shown in Figure 7b. The presented data demonstrates temperature rise of pressure controllers when IRU heaters were turned ON.

D. Propellant Estimation

Propellant remaining in all four tanks was estimated using the developed thermal models of the tanks and of BSS 601 satellite and flight data. Several simulations were run with varying propellant loads for each propellant tank. Propellant remaining was estimated using normalized flight data and normalized

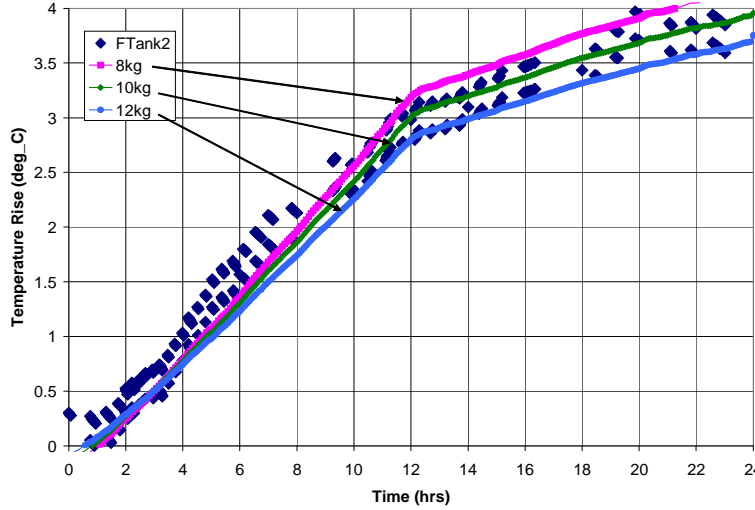


Figure 8 Results of PGS estimation for Oxidizer Tank 1.
Lines – simulation results; Markers – Temperature Sensor T3 reading
IRU heater was turned ON at t=0

simulations results. Figure 8 shows an example of the comparison of the normalized flight data with normalized simulation results for the Oxidizer tank 1. The diurnal temperature variations have been removed via data normalization procedure which was described earlier. The normalized flight and simulation data illustrate temperature rise due to tank heating without obscuring it by daily temperature fluctuations. As one can see from Fig. 8, the comparison of flight and simulation data indicates that the propellant load of Ox1 tank is close to 10 kg with probable variation of 2 kg.

We need to stress that simulated temperature variation with propellant load of a tank does not represent an accuracy of the PGS method. It rather illustrates the sensitivity of temperature rise to tank load. The accuracy of the PGS estimation is addressed in the next Section. However, we would like to mention that a sensitivity plot, like Fig 8, can only give “eye ball” estimation of the PGS accuracy.

IV. Accuracy of Propellant Estimation

Typically, a satellite operator is interested not only in estimation of propellant remaining but also in the accuracy of the propellant estimation. The review of existing methods can be found elsewhere⁶. We will use an uncertainty analysis⁷ to determine an error of propellant estimation.

In general, a propellant tank mass consist of three components, namely, propellant mass, m_p , mass of pressurizing gas, m_g , and mass of the tank itself m_t . Calculated propellant mass is function of many parameters like applied heat load Q_{load} , environment temperature T_{env} , etc. Then, the uncertainty of propellant mass estimation is defined as:

$$m_p = f(T, Q_{load}, \varepsilon^*, m_g, m_t, T_{env}, C_p, \dots)$$

$$U^2(m_p) = \left(\frac{\partial m_p}{\partial T} U(T) \right)^2 + \left(\frac{\partial m_p}{\partial Q_{load}} U(Q_{load}) \right)^2 + \left(\frac{\partial m_p}{\partial \varepsilon^*} U(\varepsilon^*) \right)^2 + \dots \quad (1)$$

Uncertainty of absolute temperature measurement T does not have an effect on PGS accuracy of propellant estimation because the PGS method uses temperature difference for propellant estimation instead of the absolute temperature.

It is convenient to express all uncertainties in terms of temperature uncertainty. For example, the second term in (Eq.1), which shows the mass uncertainty related to the heater power uncertainty, can be expressed as

$$\frac{\partial m_t}{\partial Q} U(Q) = \frac{\partial m_t}{\partial T} U(T_Q) ; \text{ where } U(T_Q) = \frac{\partial T}{\partial Q} U(Q) \quad (2)$$

Using manipulation (Eq.2) for other terms in (Eq.1), easy to present (Eq.1) in the form

$$U^2(m_p) = \left[\frac{\partial m_p}{\partial T} \right]^2 \delta^2(T)^2$$

Where $\delta(T)$ is the total temperature uncertainty, defined as

$$\delta^2(T) = \left[U^2(T) + U^2(T_{Q_{load}}) + U^2(T_{\varepsilon^*}) + \dots \right] \quad (3)$$

When a high fidelity model of the propellant tank is used for propellant estimation, the temperature distribution in the tank is determined by numerical solution of (Eq.4) by SINDA/Fluint with corresponding boundary and initial conditions.

$$mc_p \frac{\partial T}{\partial t} = k\Delta T + Q \quad (4)$$

Therefore, the closed form of solution of (Eq.4) is impossible to obtain. In order to calculate the derivatives in (Eq.1), the terms in mass uncertainty (Eq.2) are expressed in (Eq.3) form. Essentially, the derivative of tank temperature over parameter is calculated instead of finding derivative of mass over parameter. The derivative of the temperature over model parameters, like, IRU power ($\frac{\partial T}{\partial Q}$), effective emissivity ($\frac{\partial T}{\partial \varepsilon^*}$), etc is obtained by solving FE tank thermal model with varied parameters. The resulting uncertainty is summarized in Table 2 for the fuel and oxidizer tanks.

Table 2 Parameter uncertainty for oxidizer and fuel tanks

Model Parameter	Effect [kg]	
	Oxidizer	Fuel
Tank-base connection	1.47	1.72
Tank MLI ε^*	1.77	0.62
Black paint emissivity	0.23	0.15
External plume shield ε^*	1.68	0.43
Transition function	1.80	1.20
Temperature sensor (T3) resolution	2.77	2.23
Total Uncertainty [kg]	4.37	3.16

The uncertainty of each parameter is independent from each other. Therefore, the RSS method is used to determine the total uncertainty of the propellant estimation. As Table 2 indicates, the error of propellant estimation by the PGS method is relatively small.

An error of estimation of the consumed propellant obtained by the bookkeeping method typically is in the range of $\pm 2.5\%$ - 3.5% , according to Ref. 6, 8, 9. Assuming the error of 3% , the bookkeeping method has uncertainty around ± 14 kg per tank at EOL based on data on BSS 601 propellant tanks volume³.

An accuracy of the PVT method was subject of several studies. The reported error of propellant estimation by the PVT method varies significantly. For example, the error of propellant estimation is reported as high as 35% ¹⁰ and as low as 0.22% ¹¹ at EOL. Such difference is greatly influenced by uncertainty in reading of the pressure transducer. A high resolution pressure transducer is used in Ref.11. It is not clear, however, how reliable this pressure transducer is after 10 years in flight.

V. Discussion

Precise estimation of remaining propellant is needed to extend the satellite mission life as long as possible. In addition, it guarantees confident de-orbiting of the satellite at the end of its mission life.

Initially, JSAT Corporation (Japan) has used both the book-keeping and the PVT methods for estimation of remaining propellant. JSAT decided to use the PGS method for propellant estimation of one of BSS601 satellite fleet as an alternative method to the bookkeeping and the PVT methods. It allows comparing the results of all three methods in order to make more rational decision for prediction of End-of-Life of the satellite.

Each method can provide different estimation of remaining propellant and with different uncertainty. Use of different methods helps to avoid a systematic error introduced by an individual method in order to minimize a possibility of unexpected depletion. For example, the result of the comparison between the PGS and other two methods can be used for selection of pair of the propellant tank used during station-keeping maneuvers. It also helps to have a balanced consumption of remaining propellant to the rest of the satellite mission.

JSAT plans to evaluate the results of the PGS estimation and determine if it would be possible to track propellant depletion in deorbit operations in the future using the PGS method. Such an evaluation will be helpful for improvement of an accuracy of the PGS method.

VI. Conclusion

Proposed paper shows that the thermal PGS method for propellant estimation can be applied successfully to a satellite which does not have heaters installed on the propellant tanks, like BSS (former Hughes) 601 geosynchronous communication satellite. It is shown that the PGS propellant estimation can be conducted if a payload or a bus unit is used as heat source external to the propellant tank. However, use of the PGS method for propellant estimation requires development of a satellite thermal model of higher fidelity compared to the case when the propellant tanks have heaters installed and tanks are insulated from the satellite environment.

It is shown that the error of propellant estimation by the PGS method is less than error of propellant estimation by the book keeping method at EOL for BSS 601 satellite. Use of the PGS method allows JSAT Corporation execute an independent verification of the propellant estimation obtained by the bookkeeping and PVT methods, to mitigate risk of unexpected depletion and increase confidence in fleet reliability.

VII. Reference

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