Thermal Propellant Gauging at EOL,

EuroStar 2000 Implementation

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Knowledge of propellant remaining is one of the most paramount tasks which should be addressed in order to complete the mission successfully. The paper discusses a development and implementation of the thermal propellant gauging system needed for precise propellant gauging at End-of-Life (EOL). Out of the most popular methods of propellant estimation, namely, book-keeping, Pressure-Volume-Temperature (PVT), and thermal propellant gauging, the later is most accurate at EOL. Thermal methods use tank temperature respond to tank heating in order to infer propellant load of the tank. Currently, two thermal propellant gauging methods are used widely, namely, Thermal Propellant Gauging System (TPGS) and Propellant Gauging System (PGS) methods. The paper discusses difference between both methods and shows that the PGS is more useful for propellant estimation at EOL because the model is calibrated to the actual flight conditions at the time of propellant gauging. The TPGS uses the model which is calibrated during ground testing before launch. There is a big chance that such a model may not be useful at EOL due to changes of satellite conditions during long space flight. EuroStar 2000 satellite is entering last phase of its mission life. The current paper discusses implementation of the developed PGM for EuroStar 2000. The paper shows that the developed method does not require ground calibration of the thermal model and provides a high accuracy of propellant estimation at EOL. The method was used for estimation of propellant remaining on the Telstar 11 satellite. Loral Skynet used the results from PGS and TPGS analysis to make an important business decision to extend the mission of its Telstar 11 satellite. Loral Skynet continued to operate Telstar 11 in an inclined orbit at its current longitude position to provide service and to generate revenue on a limited basis. Telstar 11 was successfully de-orbited in March 2008.

I. Introduction

Three methods are typically employed in the satellite industry to estimate the propellant remaining in orbit. These are bookkeeping, Pressure-Volume-Temperature (PVT), and thermal Propellant Gauging

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System (PGS/TPGS). Basics of the modern PGS method can be found elsewhere[1,2]. The PGS method has distinct advantages over the bookkeeping and PVT methods, in particular, near end of life (EOL). Bookkeeping accuracy drops due to the accumulation of error with time. The decline of PVT accuracy is the result of decrease of sensitivity of the Helium pressure to volume change at low pressure. It takes place at EOL when the amount of the propellant in the tank is small. The accuracy of the PGS method increases with decreasing propellant mass. Fig.1 shows a general trend for an uncertainty of propellant remaining estimation for the bookkeeping and the PGS methods with time. This shows that the bookkeeping method has better accuracy then PGS at the beginning of a satellite life. The accuracies of both methods become comparable in the middle of life. The PGS method becomes typically superior to the bookkeeping between mid-life and end-of-life.

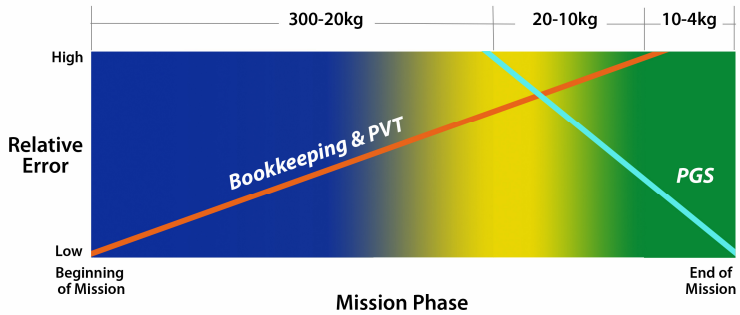


Figure 1. Error of different propellant gauging methods

Another important difference between the PGS and the bookkeeping methods is found in applications to multi-tank propulsion systems. PGS is capable of determining the fuel load in each tank while the bookkeeping method can determine only total propellant load of a satellite with a multi-tank propulsion system when interconnecting valve is open.. Any imbalance in propellant distribution between the tanks would be hidden from the user in bookkeeping method, and can thus lead to unexpected tank depletion and early decommissioning of the satellite.

A Thermal Propellant Gauging method 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[1-3]. 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. Current implementation of the PGS method is superior in numerous ways to the published initial work in 2000.

Non-uniform heater power distribution and uneven propellant distribution inside of the tank cause a temperature gradients 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 accurately to successfully compare the test flight data with calculated temperatures.

II. Thermal models

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

- Develop a thermal models of the propellant tanks and 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 and uncertainties of estimate

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 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. Development of the high fidelity of a propellant tank is discussed elsewhere[4].

A. Satellite Model

The current paper discusses development of the PGS method for EuroStar 2000 geosynchronous communication satellite. The satellite propulsion system has four spherical tanks (two fuel tanks and two oxidizer tanks). Tanks are covered with Multi Layer Insulation (MLI) blanket. 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 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 a 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 2 illustrates a developed satellite thermal model. External panels are removed for clarity. The model simulates all major elements of the EuroStar 2000 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.

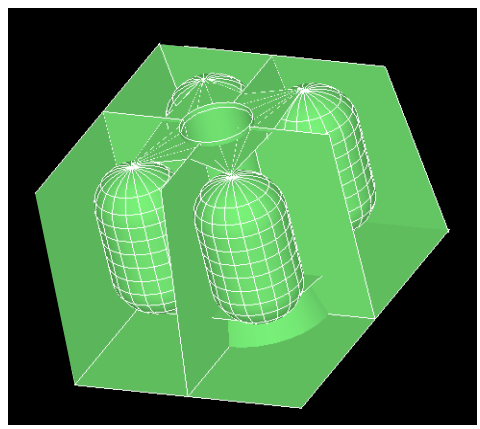


Figure 2 Satellite Thermal Model

III. Propellant Estimation

This section discusses the PGS operation that was conducted in 2007 on EuroStar 2000 satellite of Loral-Skynet Corporation fleet.

The propellant estimation was performed in several phases, namely: 1). development of models of the propellant tanks and the satellite. Results of the 1st phase are used for development of PGS operation procedure; 2) Performing the PGS operation; 3) Tank and Satellite models calibration per flight conditions; 4) Propellant estimation; 5) Uncertainty analysis.

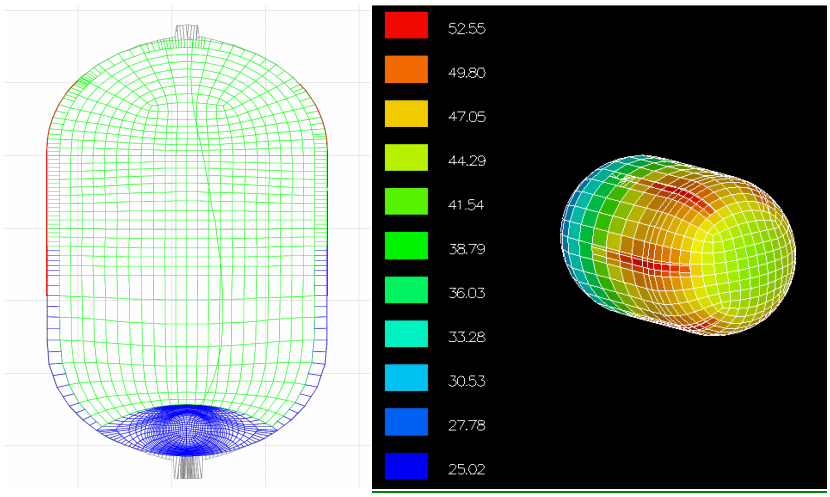
A. Tank and Satellite Models Development

The development of the Finite Element (FE) Model of the fuel tank was not a trivial task. It required the generation of a complex grid, of the FE model data, and many other specialized tasks. The tank model was integrated into the Telstar 11 satellite model to create an integrated model which is used for propellant estimation. The final model was generated in a format compatible with Systems Improved Numerical Differencing Analyzer with Fluid Integrator software (Sinda/Fluint tool - the solver of FE model).

The tank FE model is generated through combination of a number of different programs. A program called Surface Evolver was used to determine the position and shape of the liquid in micro-gravity for given tank geometry. A software package known as GridPro was used to generate the Finite Element grid. In addition to these programs, a suite of tools was developed to complement standard tools and to fulfill the specialized requirements of the integrated model. Fig. 3 shows the tank grid. An internal view of satellite model of T11 is shown in Fig.2.

B. PGS operation

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 or to reach tank temperature qualification limit, which comes first and 2) the length of time which it takes for the tanks to cool down to the initial conditions. The PGS operation could last from several hours to several days depending on the satellite design and .propellant load. The operation should not to interfere with maneuvering schedule.



3a **3b**

Figure 3 Tank FEM model; *3a- tank grid; 3b – simulated temperature distribution on tank surface*

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 (rapid change of thermal environment)
- No station-keeping maneuvers performed (change of propellant load, sloshing)
- Have enough time to cool-down the tanks after turning heaters OFF in order to reduce propellant tank pressure. Increased tank pressure might cause some variance in maneuver performance.

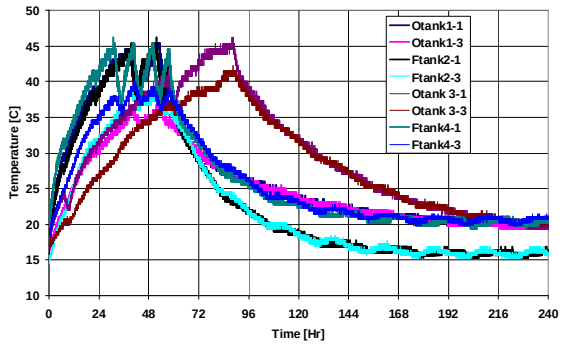


Figure 4. Temperature Sensors trend during PGS operation

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. Temperature rise during 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 of almost 30 C was sufficient to estimate the remaining propellant in the tanks.

C. Model calibration

The satellite models were calibrated using flight data. The goal of calibration was to make sure that thermal environment for tanks is modeled correctly and corresponds to current satellite conditions.

D. Propellant Estimation

Propellant remaining in all four tanks was estimated using the developed thermal models of the tanks and of EuroStar 2000 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 simulations results. Figure 5 shows an example of the comparison of the flight data with simulations results for the Fuel tank. The flight and simulation data illustrate temperature rise due to tank heating. As one can see from Fig. 5, the comparison of flight and simulation data indicates that the propellant load of the propellant tank is close to 9.4 kg with probable variation of 2 kg.

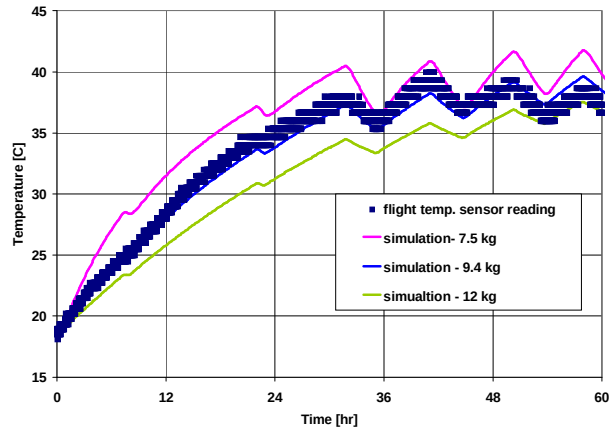


Figure 5 Results of PGS estimation for propellant tank .
Lines – simulation results; Markers – Temperature Sensor reading
Tank heaters was turned ON at t=0

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 5, 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 elsewhere[5]. There are essentially two categories of uncertainty in our analysis:

(1) A least squares curve fit and associated uncertainty: we use a non-linear curve fit to determine the propellant load. The goal of a least squares fit is to minimize the sum of the squares of the differences between given data points and corresponding model points. In theoretical terms, one minimizes

$$F = \sum_i \left[T_i - U\left(t_i; m\right)\right]^2$$

where T represents flight data, U represents simulation data, t_i represents the time of the ith data point, and m represents the propellant mass. In our case, U is known only for certain values of m, and the behavior of F must be inferred from what is known from a limited number of simulations. The standard deviation associated with this fit gives us an idea what maximum accuracy we should expect.

(2) Estimate of uncertainty due to other sources[4]: This determines how uncertainties of specific model parameters affect the accuracy. These other sources of uncertainty are largely expected to be statistically independent from each other, so they are aggregated by summing their variances. According to our estimation, the accuracy of propellant estimation was about ± 1.5 kg of fuel and about ± 2.7 kg of oxidizer per tank.

An error of estimation of the consumed propellant obtained by the bookkeeping method typically is in the range of ±2.5 % - 3.5 %, according to Ref. 3, 5, 6. Assuming the error of 3%, the bookkeeping method has uncertainty around ± 14 kg per tank at EOL based on data on EuroStar 2000 propellant tanks volume[3].

An accuracy of the PVT method was subject of several studies. The reported error of propellant estimation by the PVT method various significantly. For example, the error of propellant estimation is reported as high as 35% [7] and as low as 0.22% [8] at EOL. Such difference greatly influenced by uncertainty in reading of the pressure transducer. A high resolution pressure transducer is used in Ref.8. It is not clear, however, how reliable this pressure transducer is after 10 years in flight.

V. Discussion

E. Future Plans

Skynet-Loral 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.

F. Comparison TPGS with PGS

Both methods employ a thermal approach to estimate remaining propellant, namely, to calculate a heat capacity of a propellant tank using temperature change when known amount of the heat is applied to the tank. There are several major differences between the TPGS[3] method and our approach (PGS). One of them is fidelity of the propellant tank model. The TPGS method employs a simple thermal model of the propellant tank which consists of two nodes, one is for the gas and other is for liquid contained in the propellant tank. The PGS method uses a high fidelity tank model which takes into account tank design, liquid position in microgravity, heaters and temperature sensor locations, etc. The high fidelity model allows simulating of the temperature distribution on the tank surface with high precision during flight. It leads to high accuracy of propellant estimation.

Secondly, the TPGS method does not include directly an effect of the current satellite environment on the tank temperature. A thermal connection between tanks and satellite environment along with temperature gradients on tank surface are incorporated into model by calibration of the tank model during Thermo-Vacuum test. If satellite conditions changed significantly through the mission life or the calibration loses its validity due to some unforeseen events, propellant estimation by the TPGS method becomes questionable or even impossible. In contrary, we calibrate both, tank and satellite, models per flight current conditions which makes the PGS method is quite accurate.

Recently published data on accuracy of the TPGS method[9] indicated that the method overestimated fuel load in five satellites de-orbited from 2003 to 2006.

VI. Conclusion

Proposed paper shows that the thermal PGS method for propellant estimation can be applied successfully to a EuroStar 2000 geosynchronous communication satellite. Use of the PGS method for propellant estimation requires development tank and satellite thermal models. It is shown that the error of propellant estimation by the PGS method is less than an error of propellant estimation by the book keeping method at EOL for EuroStar 2000 satellite. Use of the PGS method allows Skynet-Loral 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.

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