# **Thermal Propellant Gauging**,

## **SpaceBus 2000 (Turksat 1C) 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 of GEO satellite successfully. The paper discusses a development and implementation of the thermal propellant gauging system for Turksat 1C (SpaceBus 2000 satellite). Several techniques are typically used to measure the amount of remaining propellant. The bookkeeping, PVT (Pressure, Volume, Temperature) and thermal Propellant Gauging System (PGS) are the most popular methods. Only the thermal PGS method accuracy of propellant estimation increases as propellant load decreases due to increase of temperature rise sensitivity when the tank load decreases. The method can be used for mono or by-propellant propulsion system with one or multiple tank configuration. Implementation of the developed PGS method for Turksat 1C (SpaceBus 2000) satellite is discussed by the current paper. The method consists of several steps, namely, building Tank and Satellite Thermal Models, calibration of the model using current flight data, running the integrated model for several propellant loads for each tank under identical boundary conditions, fitting flight data to simulation results and finding propellant load of the tank. Simulation includes tank temperature change (by heater and/or from sun). Along with propellant estimation, uncertainty analysis is also required in order to determine an error of propellant estimation. The current paper shows that the developed method provides a high accuracy of propellant estimation at EOL. An accurate propellant estimation at EOL is important form business point of view. Knowledge of propellant remaining allows making correct business decisions, like, timely supersinking of a satellite, optimizing profit, avoiding gap in services, etc. The current paper discusses business implications of the PGS method.

## I. Introduction

Three methods of propellant gauging, namely, Bookkeeping, Pressure-Volume-Temperature (PVT) and thermal Propellant Gauging System (PGS) methods are typically employed in the satellite industry to estimate the propellant remaining in orbit. Each method has its advantages and problems. The bookkeeping method is quite accurate at the beginning of mission life but the accuracy decreases with time due to accumulation of error with time. The PVT accuracy declines as well with time due to decrease of sensitivity of the Helium pressure to volume change at low pressure. As one can see, both methods, Book-

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keeping and PVT, experience accuracy decline at EOL when the amount of the propellant in the tank is small. On other hand, the accuracy of the thermal propellant gauging methods increases with decreasing propellant load due to increase of sensitivity of temperature rise to propellant thermal mass at EOL.

Fig.1<sup>1</sup> shows a general trend for of an uncertainty 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 Book-keeping and PGS gauging methods

The PGS 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<sup>1-4</sup>. Described in Ref. 1-4 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 in Ref. 2.

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 (this is the case with Turksat 1C), 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.

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

Development of tank thermal model 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. Fidelity of the satellite thermal model depends on thermal connection between tanks and satellite environment. The satellite model can be a low fidelity if the connection is weak. A strong thermal connection requires development of a high fidelity satellite model due to significant influence of satellite environment on propellant tank temperature.

## II. Development of PGS method for Turksat 1C

The propellant estimation for Turksat 1C was performed in several phases, namely: 1). development of models of the propellant tanks and the satellite. Results of the 1<sup>st</sup> phase were 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 Model 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 FE model was generated through combination of a number of different programs including Surface Evolver which was used to determine the position and shape of the liquid in micro-gravity for given tank geometry and tank load. Also, a suite of tools was developed to complement standard tools and to fulfill the specialized requirements of the integrated model. Fig. 2 shows the tank grid and temperature distribution on tank surface.

Figure 3 illustrates a developed satellite thermal model. External panels are removed for clarity. The model simulates all major elements of the SpaceBus 2000 satellite which are important for simulation of the PGS operation and propellant estimation, like internal panels, MLI blankets, etc. Propellant tank models were integrated into the Turksat 1C satellite model to create an integrated model which has been used for propellant estimation. The final model was generated in a format Systems Improved compatible with Numerical Differencing Analyzer with Fluid Integrator software (Sinda/Fluint tool - the solver of FE model).

#### **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 PGS operation procedure.

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<sup>1</sup>:

- 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
- 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.

In addition to mentioned above considerations, other concerns have being addressed during PGS



**Figure 2. Tank Thermal Model.** a. FEM model ; b. temperature distribution



Figure 3. Satellite Thermal Model



#### Figure 4. PGS operation.

Fuel tank heaters and top Ox tank heater turned ON at t=72. Bottom Ox tank heater turned ON at t=80 hr.

procedure development: 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; 2) whether temperature of the bottom of the both tanks will exceed the temperature of the tank tops. In such a case, to develop heater operation

procedure to keep bottoms of a tank colder than its top; 3) the length of time which it takes for the tanks to cool down to the initial conditions.

It was determined that the heating period should last several days in order to tanks reach temperature equilibrium with environment. Also, it was found out that heaters on the bottom of the Ox tank should be turned ON with some delay relatively to the other heaters in order to keep the bottom of the Ox tank colder than the top of the Ox tank.

Temperature trends of top and bottom of the fuel and oxidizer tanks during PGS operation are shown in Figure 4. The bottom heater of the Ox tank was turned ON 8 hr later than other heaters in order to keep the bottom of the Ox tank been colder than top of the Ox tank. The bottom heater of Ox tank was turned OFF in four days while other heaters were still ON for the same reason, namely, to keep the bottom of the Ox tank colder. Both tanks heating lasted for 6 days.

#### C. Model calibration

The tank and 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. As it is well known, satellite thermal conditions change through mission, therefore, satellite thermal model should be current in order to get the highest accuracy of propellant estimation.

## **D.** Propellant Estimation

Propellant remaining in both propellant tanks was estimated using the developed and calibrated thermal models of the tanks and of Turksat C1 satellite and flight data. Several simulations were run with varying propellant loads for each propellant tank.

As data in Fig. 4 indicates, tank temperature at two locations (top of the fuel tank and bottom of the Ox tank) exhibits daily variation. In order increase accuracy of propellant estimation, daily variation was removed from flight and simulation data using normalization procedure. Propellant а remaining was estimated using normalized flight and simulations data. 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.



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

#### E. 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 including bookkeeping and PVT methods can be found elsewhere<sup>5</sup>. 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. 5, 6, 7. Assuming the error of 3%, the bookkeeping method has uncertainty around  $\pm 13$  kg of propellant at EOL based on data on Turksat C1 propellant tanks volume.

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%<sup>8</sup> and as low as 0.22%<sup>9</sup> at EOL. Such difference greatly influenced by uncertainty in reading of the pressure transducer. It is not clear, however, how reliable the pressure transducer is after 10 years in flight.

The uncertainty analysis which is used the current effort is described elsewhere<sup>1</sup>. Essentially, it considers two categories of uncertainty, namely, an uncertainty of the curve fit associated with propellant load estimation and uncertainties of specific model parameters which affect the accuracy. The standard deviation associated with former uncertainty of curve fit gives an idea what maximum accuracy should be expected. An uncertainty of heater power is an example of the latter category of uncertainty.

uncertainties are largely expected to be statistically independent from each other, so they are aggregated by summing their variances. The resulting uncertainties are 3.7 kg for the fuel and 10.6 kg for oxidizer tanks.

Analysis of the contributions into the total uncertainty indicated that propellant distribution in a propellant tank is the largest contributor to the total uncertainty. This relates to Propellant Management Device (PMD) design. In propellant tanks of Turksat 1C satellite, liquid is distributed between bottom of the tank and the baffle<sup>10</sup>. Due to the fact that the PGS operation was started immediately after E/W maneuver, the position of fuel and oxidizer was ambiguous during the PGS operation. The liquid could be on the bottom of the tank or can be next to the baffle during the PGS operation. Due to such this uncertainty, the worst case scenario for variation of liquid distribution was assumed. As the result, there is a large uncertainty in the load estimation associated with the liquid distribution. If an exact location of the fluid (fuel/Ox) in the tank were certain, the uncertainty of load estimation would be reduced significantly.

## III. Discussion

The book-keeping and PVT methods are the most popular methods of propellant estimation. As it was discussed earlier, these two approaches are quite accurate from the Beginning of Life (BOL) through Middle of Life (MOL) and, typically, provide very close estimates. However, both methods have problems which can affect the accuracy of estimates. For example, the book-keeping method requires running thrusters at specific conditions in order to satisfy requirements of the flow model which is used to calculate propellant flow through thrusters. In a case of using thruster "out of the box", results of the flow model are not accurate. As far as the PVT method concerned, the method requires an accurate initialization, particularly after all LEOP maneuvers. Otherwise the absolute precision is very poor. Also, the PVT method accuracy declines with pressure drop in the propellant tank which is usual for blow-down propulsion systems. Thermal gauging is free from all above factors which makes the method attractive even though the method requires much more efforts for implementation comparing to the book-keeping and PVT methods.

Due to decrease of accuracy of propellant estimation at EOL, propellant estimates by both methods start to deviate from each other at EOL leaving the satellite operator to wonder which number to choose. Such a situation requires employment of a third independent method in order to increase confidence in propellant estimates. The PGS method serves this purpose and is used more and more for different satellite platform including BSS 601<sup>4</sup>, LM A2100<sup>2</sup>, LM 3000<sup>11</sup> and 5000<sup>3</sup> series, Telstar 11<sup>1</sup>(this satellite is very close to EuroStar 2000 platform), etc. The method was used not only at EOL, but also was used in situations when book-keeping or PVT methods can not be used, *e.g.*, when a pressure transducer is not working.

#### F. Turksat-1C

Turksat 1C was launched in July 1996 for 12 years of service. Replacement of Turksat-1C, Turksat-3A was ordered early 2006 for a delivery early 2008. The replacement schedule needed to be perfectly managed but was not robust enough to mitigate slippage in delivery schedule of Turksat-3A due to some factors which were beyond of TAS control. It included launch payloads issues, possible last minute schedule shift because of launcher unavailability itself, etc.

All these factors increased demand to reduce uncertainties of Turksat-1C EOL prediction. The bookkeeping and PVT methods have being used for propellant estimates through mission life of Turksat-1C. The PGS method was employed at EOL to improve fidelity of the propellant estimates.

Since the satellite is in inclined orbit, Turksat-1C will be operated at 31 degree E for some years to come and will provide new services. Knowing better the remaining propellant thanks to the PGS method, it was possible significantly and with high confidence to extend Turksat-1C mission life and to propose a secure and reliable service for long time. Of cause, the ultimate prove of the PSG method accuracy will be seen at the end of Turksat-1C life, that is, after the satellite de-orbiting.

## **IV.** Conclusion

Proposed paper shows that the thermal PGS method for propellant estimation was successfully applied to Turksat 1C (SpaceBus 2000) geosynchronous communication satellite. Following usual approach of the PGS method, tank and satellite thermal models for Turksat 1C have been developed. These models were used for PGS procedure development. Based on obtained flight data, the thermal models were calibrated per current conditions of Turksat-1C satellite. Propellant remaining and uncertainty of estimate were determined using the calibrated models.

The paper shows that the PGS method is applicable to SpaceBus 2000 satellites. This platform join series of other different satellite platforms including, BSS 601, LM A2100, LM 3000 and 5000 series, Telstar 11, etc to which the PGS method has been successfully applied before.

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