Implementation of Thermal Gauging Method for SpaceBus 3000A (ArabSat 2B)

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The current paper discusses the Thermal Gauging Method (TGM) developed and employed for the propellant estimation of ARABSAT 2B satellite. ARABSAT 2B is a commercial geostationary telecommunications satellite owned and operated by the ARABSAT organization based in Riyadh Saudi Arabia. The satellite was built by Thales Alenia Space (Cannes, France) and launched in November 1996. It employs a standard bi-propellant chemical propulsion system. ARABSAT 2B completed its design life of 12 years in 2008 with full functionality and is currently still in operation. The life limiting factor for this satellite is available propellant, hence the importance of a gauging method that determines propellant. It is shown that the TGM provides more accurate estimation of propellant remaining now than methods such as bookkeeping and PVT (Pressure-Volume-Temperature). The TGM (as other thermal methods) 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. The current paper discusses the difference between different thermal methods, namely, TPGS, PGS and TGM. The TGM employs a very sophisticated thermal model of the propellant tank which takes into account fuel distribution in the tank, temperature gradients in the tank, etc. While the method consists of several steps, the current paper discusses problems related to finding load of a propellant tank, *e.g.*, how to isolate tank temperature rise due to tank heaters from temperature change due to other heat sources: sun, equipment, etc. An accuracy analysis of propellant estimates is also discussed in the current paper. The paper discusses different ways of calculating the error of propellant estimation and shows the most precise approach for calculation. Advantages and weaknesses of TGM are discussed. Accuracy of different methods of propellant estimations is also compared and an area of applicability for each method is determined.

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Nomenclature

σ	=	standard deviation
m	=	propellant load/mass
p	=	model parameter which affects heating
i	=	parameter index
tot	=	total uncertainty
fit	=	uncertainty related to curve fit
TGM	=	Thermal Gauging Method
TPGS	=	Thermal Propellant Gauging Technique
PGS	=	Propellant Gauging System
EOL	=	Satellite's end-of-life

1. Introduction

ARABSAT 2B satellite was launch on Ariane 4 in November 1996 with a launch mass of 2636 Kg (loaded propellant mass of 1523 Kg). The satellite was placed at 30.5º East, where it delivered services in C and Ku Band to customers over the Middle East, North Africa and Southern Europe regions.

Over its operational life the satellite maintained full functionality with minimum reduction in subsystem redundancies. After serving its mission at 30.5º East, the satellite was relocated to 20º East were it went into full operation up to the arrival of its replacement satellite, ARABSAT 5C. Since then the satellite was relocated to 34.5º East were it is still operational.

With 2B being a fully functional, revenue-generating satellite, ARABSAT was interested in acquiring better knowledge of its remaining propellant in order to plan further utilization of the satellite.

The Thermal Gauging Method (TGM) was identified as a superior technical option for estimation of the remaining propellant compared to the book keeping and PVT (Pressure-Volume-Temperature) methods, especially at EOL. This method was used on ARARBSAT 2B in collaboration with YSPM, LLC, a leading provider of this service. The main goal of ARABSAT in pursing this service was to obtain better accuracy of remaining operational life in order to update the business plan for the satellite. The possible discovery of more propellant than what was originally estimated was considered an added bonus.

2. TGM Basic

Currently, three methods of propellant estimation are commonly employed to estimate the spacecraft propellant remaining in flight: bookkeeping, PVT, and thermal estimation methods. Employed in this effort the Thermal Gauging Method (TGM) is one of the existing thermal methods, like TPGS, PGS, etc. As noted in Ref. 1, 2, the thermal methods for propellant estimation have distinct advantages over the bookkeeping and PVT methods near a satellite's End-of-Life (EOL). Bookkeeping accuracy decreases due to error accumulation with time. PVT accuracy declines due to weak sensitivity of a gas's pressure according to volume change when the amount of propellant in the tank is small. However, the accuracy of thermal methods actually increases near EOL due to an increase in temperature's sensitivity in change with the amount of the propellant in the tank.

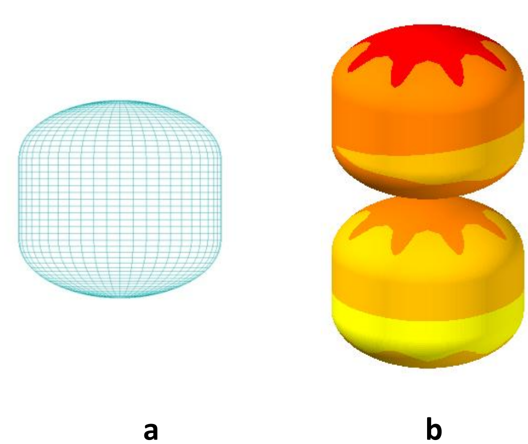

Figure 1. High Fidelity Tank model (a) and Temperature Distribution during heating (b)

Thermal gauging methods involve measuring the thermal capacity of the propellant tank by heating it and comparing the observed temperature rise to simulation results obtained from a tank thermal model. Telemetry and simulation results show that substantial temperature gradients exist within the propellant tanks[1]. Thus, in practice, this estimation must be accomplished by creating detailed computational models of the tanks and the spacecraft itself.

This paper illustrates the TGM method and describes our models and TGM techniques used for the propellant estimation. The TGM method consists of several common steps that are regardless of the spacecraft platform. Firstly, the thermal models of the propellant tank(s) and satellite are developed and calibrated using existing flight telemetry data. Secondly, a test procedure is prepared using a calibrated spacecraft thermal model. The flight test is conducted, using heating of the propellant tanks using available heat sources like tank heaters, heaters installed on spacecraft units, etc. Thirdly, estimation of propellant load of each tank and evaluation of the accuracy of the propellant estimations are conducted.

A. Tank Model

The tank thermal model is one of the most important components of the satellite thermal model. The tank model must contain enough details to accurately predict temperature distribution on the tank surface. Such a distribution depends on many factors, including the position of the propellant as well as heat exchange between the tank and the environment. To accurately capture temperature distribution on the tank surface, the high fidelity tank model [Fig. 1a] was developed using an industry-standard software package, Thermal Desktop. The tank model is comprised of the following major components: a titanium wall with an external multi-layer insulating (MLI) blanket or black exterior in specified regions; propellant (fuel or oxidizer); and helium (pressurant) and tank mounting tabs. The tank model also includes liquid distribution in the tank in micro-gravity, determined by the Surface Evolver software tool[4]. The tank model is developed for both fuel and oxidizer tanks.

The temperature gradients on the surface of propellant tanks of the AS-2B spacecraft are depicted in Fig. 1b. Temperature gradients on the surface of the tank are caused by a non-uniform heat load placed upon the tanks and a non-uniform propellant distribution. As Figure 1b illustrates, the maximum temperature gradients can be observed on the tank along the earth/anti-earth direction.

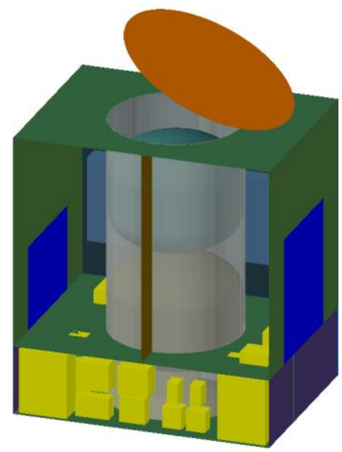

Figure 2. The spacecraft model

B. Spacecraft Model

The spacecraft model (also assembled with Thermal Desktop) accurately models radiative connections between spacecraft components, spacecraft, and space, as shown in Figure 2.

The tank and satellite thermal models form an integrated thermal model. The integrated thermal model includes heat generation by heaters of propellant tanks, by bus and payload units, and heat load from the sun.

3. TGM test

TGM uses tank temperature data obtained during all three stages of the test: heating, saturation and cooling for propellant load estimation. For example, the temperature rise portion is used to determine tank loads. The temperature saturation portion is used to characterize thermal connection between tank and environment, etc. It is essential to run the test long enough to reach the point when tank temperature pattern does not change and stays for at least two days. However, if tank temperature reaches its heat limit before it goes to saturation, the heaters should be turned OFF at a pre-determined level below temperature limit in order to provide a safety margin.

C. Preparation for the test

The test procedure has been developed to satisfy the following objectives:

- provide safety margin for all parameters, such as: tank pressure, tank temperature, payload and bus temperatures, etc.
- meet constraints such as: the maximum tank temperature, temperature differential between propellant tanks, etc.
- fit test into the station while keeping maneuvering schedule.
- collect all data which is needed for the propellant estimation.

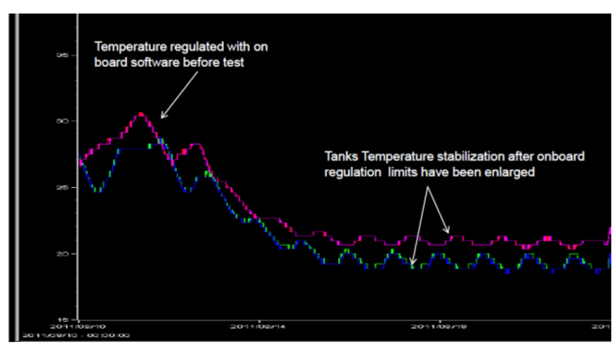

Figure 3. Tank temperatures before the TGM test

The nominal tank temperatures before the test-- between 27° and 30°C for the fuel tank and between 25° and 28°C for the oxidizer tank--are controlled by tank heaters. The tank heater control limits are lowered, allowing tank temperature to drop to around 20°C before the test starts as Fig. 3 indicates.

D. TGM test execution

The test started when both primary and backup heaters for Fu and Ox tanks were turned ON. A preliminary analysis has shown that it would take a considerably long time to reach saturation if the initial heater configuration were to be used throughout the test. Also a window of only 10 days was allowed to conduct the test due to station keeping constraints. In order to shorten the duration of the test, it was decided to turn OFF fuel tank backup heater after 36 hrs of heating while keeping the other three heaters (backup Fu tank heater and primary and backup Ox tank heaters) ON, after looking at preliminary analysis. It took three days to stabilize tank temperature pattern after the backup Fuel tank heater was turned OFF. All heaters were turned OFF after tank temperatures were at saturation for 3 days. The entire test took 12 days. The data in Fig.4 shows tank temperature behavior during the test. Noticeably, both fuel and oxidizer tanks exhibited significant daily temperature fluctuations.

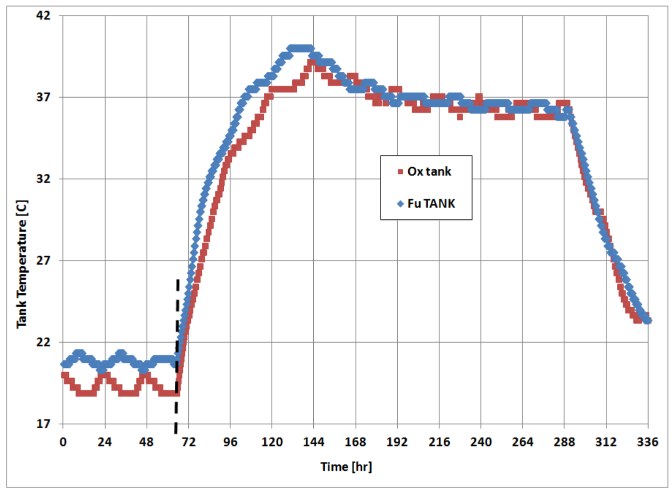

Figure 4. Tanks Temperature. *Markers - Flight Data. Heating start time - 65 hrs*

4. Tools Development

Flight telemetry data obtained during the test and the developed integrated satellite model were used for propellant estimations. A suit of software tools was developed to conduct propellant estimation and accuracy analysis. The following chapter discusses some details of the developed tools.

E. Computational environment

All tools used were developed with two major principles in mind. Firstly: to provide all necessary means to make a knowledgeable decision based on all available data sources and information processing techniques, and secondly, to create a user friendly and intuitive Graphic User Interface (GUI).

One of the defining aspects of the software tool design is a multiuser, collaborative environment for all team members, which allows access to all the data and analysis tools from any geographic location. Team members should be able to work at different locations and time-zones. Flight test support and flight data acquisition might be conducted on ground control station situated anywhere in the globe.

In order to satisfy these requirements, the analysis and data presentation tools have been developed to be web based and accessible from any on-line computer without prior software installation. The GUI of the website is shown in Fig. 5.

Figure 5. Graphic User Interface

Another defining aspect of the tools and supporting framework design is the elimination of all labor intensive, repetitive, error-prone data conversion, and pre/post processing tasks.

All flight data and simulation results must be preprocessed. Due to the large size of data sets to be processed, traditional general purpose tools such as spreadsheets or preprocessing scripts are inconvenient, slow and incapable of handling large volumes of information. Genetic tools as well do not provide necessary functions for specific data mining.

Instrumentation and software framework for quick processing, storage and retrieval of large data sets have been developed. The back-end framework consists of a distributed and scalable network of computers. Unlike traditional weakly connected set of workstations, this framework allows automatically handle of such demanding tasks as:

- large number of heavy numeric computational jobs such as parallel simulation runs
- distributed storage of large volumes of data
- data duplication for backup and redundancy
- access to all needed computational resources on demand by all team members

F. Invalid data filtration

Raw flight data may come in many different structures, forms and file formats. The automated tool set for data preprocessing used in this project detects and conditions any data sources and structures of all incoming telemetry. Such conditioning includes: automated glitch removal; out-of-pattern telemetry detection, and conversion of raw data into uniform compact structure suitable for further processing. In contrast to traditional ad-hoc, case-by-case telemetry preprocessing, this approach offers a significant improvement in speed and quality of data handling of all incoming telemetry streams.

G. Approximation of original analog data based on available telemetry data

A typical downlink telemetry stream provides only low quality, low bandwidth stream of sensor readings with rough discretization and sampling. An integral part of the telemetry preprocessing used in TGM is an adaptive raw data smoothing. This algorithm approximates the telemetry original analog signal before discretization. Such a step is necessary to improve accuracy and significantly mitigate any uncertainty introduced by discretization and a low bandwidth data transmission. Recovery of the original analog telemetry signal increases the accuracy of propellant estimation.

H. Removal of temperature diurnal variation

One of the important instruments in the toolbox used is a tool to remove temperature diurnal variation. Removal of daily variation allows extraction of tank response to tank heating by known heat source. This process is one of the key components of estimation. There are several possible ways of removing daily data variations. One of them is to subtract daily patterns before the heat test from the daily patterns during heat test. This approach has obvious limitations yielding low quality results; it does not consider difference in patterns from day-to-day fluctuations. It also does not consider seasonal variations due to constant orbital beta-angle change. Furthermore, it cannot be automated, This approach is very sensitive to choice of initial pattern by tool user. Essentially, it is very error prone.

The other possible method would be to use Fourier analysis in frequency domain. This method also does not produce a desirable outcome. A typical signal often contains exponential sections and sharp angles. It produces a very wide and high amplitude spectrum which is not suitable for selective daily pattern filtering. It also does not offer a universal algorithm which could be adopted for automatic filtering.

A new approach was developed using "sliding window" filtering which produces very smooth telemetry curves with no human interaction. It works well for both flight data trend analysis and flight-to-simulation data comparison.

I. Surface Evolver

The Surface Evolver software tool[4] is used in TGM to determine the position of propellant (liquid) and Helium (gas) interface inside the propellant tank for pre-determined loads. A special interpolation tool has been developed to determine the position of liquid-gas interface for intermediate loads. The tool is integrated into the data processing flow, providing better load resolution and accuracy of propellant estimation.

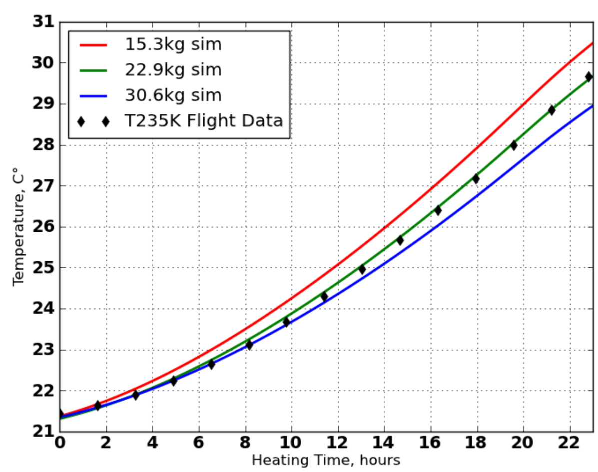

Figure 6. Simulation results and flight data for the fuel tank. *Markers- temperature sensor reading; curves - simulations for different Fu loads*

J. Finding estimation - optimum curve fit

As it was described before, the tank load is determined by comparison of flight data with simulation curves using a curve fit procedure[5].

There are many different ways of performing least squares regression fit. It could be a linear or a non-linear fit. One of the popular approaches is the 'weighted' approach based on the principle that a weighted sum of squared residuals should be minimized, if each weight is equal to the reciprocal of the variance of the measurement[6].

Another curve fit procedure was used in TGM: the tank load was found analytically using curve fit between preprocessed flight data and simulations that formed a multi-parameter space. This approach is quite different from traditional approaches of weighted or generic approximations.

The approach developed here does not introduce any additional error associated with the methodology of traditional approaches which significantly affect model quality.

K. Accuracy analysis

As discussed earlier, an evaluation of the accuracy of propellant estimation is included in the TGM approach. A special tool has been developed to provide an automated report on accuracy estimation based on selected subset of all available simulations and all known major variability contributors such as source telemetry and satellite model.

5. Load estimation

Simulation was conducted using an industry-standard solver/SINDA. Figure 6 and Figure 7 demonstrate comparison of simulation results and temperature sensor reading during the heating phase of the TGM test. The sensors are situated on the bottom of each propellant tank. Diurnal temperature variations have being removed in Fig.6 and Fig.7 in order to show only an effect of tank heaters on the tank temperature. The removal procedure of tank diurnal temperature variation is described in Section H. The simulations depicted in Fig.6 and Fig.7 do not encompass all of those used for the propellant estimation; some simulation runs have been omitted for clarity only.

The propellant estimation indicates that the Fuel tank has a load of 24.2 kg while Ox tank has load of 43.3 kg at the time of TGM operation in August 2011. The Ox load includes 5.6 kg of NTO vapor.

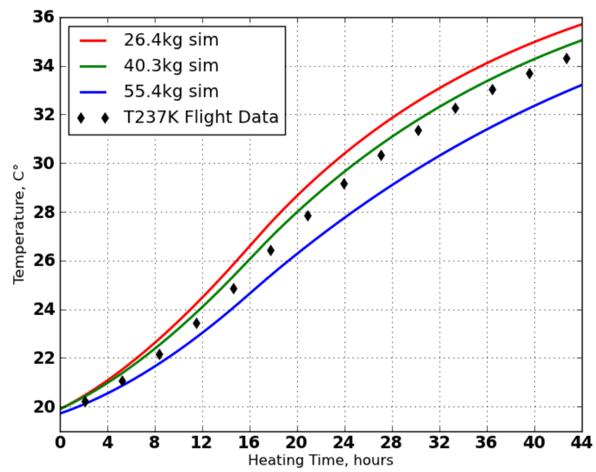

Figure 7. Simulation results and flight data for oxidizer tank. *Markers- temperature sensor reading; curves - simulations for different Ox loads*

6. Accuracy estimation

The accuracy of the propellant estimate increases as the propellant load decreases due to increased temperature sensitivity to the load. Thus at EOL, the TGM method provides a better accuracy than traditional bookkeeping and PVT methods.

There are two sources of uncertainty of propellant estimations[1]. One of them is inaccuracy of the thermal model itself. The other source is uncertainty of physical parameters used in the model. Physical parameters like optical properties of MLI, panel and tank surfaces, heater power, etc. do affect the propellant estimation. Variations in measured parameters, particularly, in temperature, also contribute to the uncertainty. The effect of all reasonable sources of uncertainty on propellant estimation is considered in this effort.

Two sources of uncertainty have been evaluated separately:

(1) Model Accuracy. The model accuracy was determined based on results of a least squares curve fit of the model to the flight data. Following Ref. 5 a non-linear curve fit was used to determine the propellant load. The procedure of curve fit is explained in Section J.

(2) Parameter Uncertainty. The effect of uncertainties of model parameters on the total accuracy has been determined. These uncertainty were assumed to be statistically independent from each other, so they were combined by summing their variances[7]

$$\sigma_{tot}^2 = \sigma_{fit}^2 + \sum_i \left(\frac{\partial m}{\partial p_i} \right)^2 \sigma_{P_i}^2$$

The partial derivatives were computed from simulation results, and the variances were obtained from experimental sources when it is possible and from all available information otherwise.

Another issue is how many terms to include. Only a certain number of parameters have a significant effect, and only a certain number of parameters can be tested in a reasonable amount of time. Only parameters that have significant effects were selected. This choice is based on engineering judgment and on experience with the SB 3000A platform. Comparison of the contributions of different parameters into the total uncertainty shows that the most important contributors are: tank heater power, propellant distribution within the tank, and emissivity of the MLI covering the central cylinder and satellite panels. Since the SB 3000 platform is relatively new for the TGM approach, a larger uncertainty of parameters was assumed in order to "be on the safe side."

Based on the analysis, it was concluded that the resulting uncertainties which correspond to 3 σ are 4.25 kg for the fuel and 4.2 kg for oxidizer tanks. Oxidizer load estimation is more accurate than fuel estimation due to the ArabSat-2B satellite design. One should distinct between theoretical error/uncertainty-which is defined in Section 6 and is over-conservative by design-and actual error/uncertainty, which is defined as the difference between predicted and actual propellant loads. The actual error/uncertainty is usually treated as having 3 sigma or higher. The actual error can be determined only after the tank(s) is depleted which usually occurs when the satellite is de-orbited. So far, flight data for satellites of different platforms which were de-orbited indicate that the uncertainty of thermal methods depend on satellite design and can range from 10% (if propellant tanks have heaters) to 20% (if propellant tanks don't have heaters, e.g., BSS 601[7]). The ArabSatB-2B satellite has heaters on the propellant tanks therefore we should expect that the actual uncertainty will be lower than what was theoretically determined here.

7. Discussion

Any method of propellant estimation is based on underlining physical phenomena and consists of a set of tools to estimate the remaining propellant. For example, the PVT (Pressure, Volume, and Temperature) method is based on the Gas Law and employs a set of equations describing different phenomena inside the propellant tank, like, solubility of Helium in propellant as a function of pressure and temperature.

L. Comparison of the Gauging Methods

1. Effect of time of the mission on choice of gauging method

Choice of a gauging method depends on many factors most significantly of which are cost and accuracy. The least expensive and, therefore, the most desirable is the book-keeping method. The thermal method is much more complicated and the most expensive. However, comparison of accuracies of different gauging methods reveals that the accuracy of any method depends on the elapsed time of the mission life when the estimation is made.

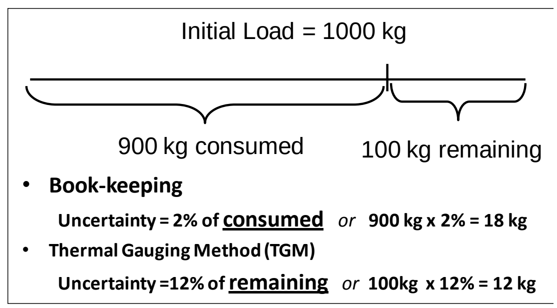

Figure 8. Book-keeping vs TGM *(Example)*

To illustrate this point consider a case of the tank filled initially with 1000 kg of fuel. It is required to estimate tank load at some point of mission life when 900 kg of fuel was consumed and 100 kg of fuel is remaining. The book-keeping method accuracy[8,9,10] is in the range of 1 - 3% of <u>consumed</u> propellant. It means that for 900 kg of consumed propellant, the uncertainty of the book-keeping method will be 18 kg, assuming a 2% accuracy. That is, the book-keeping method would give estimation of 900 kg ± 18 kg. It means that remaining load is estimated as 100 kg ± 18 kg, or the accuracy of the estimation of the remaining fuel is actually 18%' by the book-keeping method at this particular time of the mission life. It is clear that the later in the mission life estimation is made by the book-keeping method, the less accurate the estimation becomes.

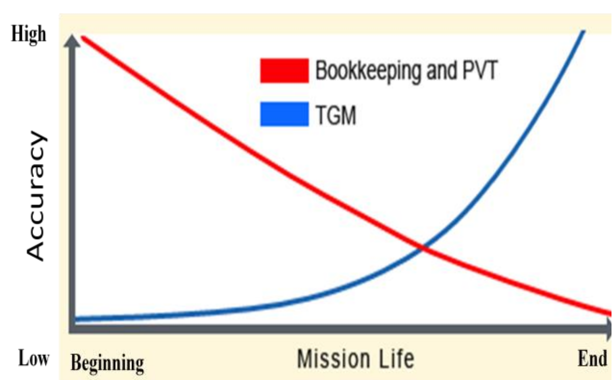

Figure 9. Comparison of different methods

The accuracy of the thermal method is calculated using the <u>remaining</u> propellant. Let's assume that the accuracy of the TGM is about

12 % of propellant remaining (12% is based on experience of estimation by thermal gauging). It means that the uncertainty of fuel estimation by the TGM will be 12 kg or the remaining load will be estimated as 100 kg ± 12 kg by the TGM. One can deduct that accuracy of the TGM estimation will increase with mission life. Fig.8 illustrates the calculations of the accuracy for each gauging method.

The PVT method accuracy is also decreasing with mission life due to decrease sensitivity of the Helium pressure to volume change with Helium volume increase. Qualitatively, the accuracy of the method vs. mission is shown in Fig. 9. Both the book-keeping and PVT methods are more accurate than the TGM at the beginning of the mission life up to roughly the middle of the mission life. After this point the accuracy of the book-keeping and PVT methods is less than the TGM accuracy. Therefore, the best approach is employment of the different methods throughout the mission life in order to obtain the highest possible accuracy of propellant estimation.

2. Thermal Methods

Several methods like, the Thermal Propellant Gauging Technique (TPGT), the Propellant Gauging System (PGS) and the Thermal Gauging Method (TGM) employ thermal physics to estimate propellant remaining. All these methods calculate heat capacity of a propellant tank using temperature change when known amount of heat is applied to the tank. The tools and approach, however, are quite different for each method. The differences are in tank model (simple vs. high fidelity), modeling thermal link between tank and environment (simple linear function vs. high fidelity satellite model), tools for pre and post processing.

The TPGT method[10] uses a simple thermal model of the propellant tank which consists of two nodes, gas and liquid. The thermal link between a tank and the environment is defined by a linear function with coefficient determined during Thermo-Vacuum test. Change of the coefficient with time is defined by a predetermined curve.

The PGS method employs a high fidelity tank model[1,2,3,7] which takes into account tank design, liquid position in microgravity, heaters and temperature sensor locations, etc. The PGS method uses satellite thermal model to determine thermal connection between tank and environment. The TGM uses a similar approach but employs different techniques in processing flight data and pre and post processing of the simulation data. The details of TGM technique are highlighted in Section 4.

M. Business benefits of using TGM

As an outcome of TGM employment, ARABSAT received an improved estimate of remaining propellant with an error of around 15%. This result has effectively delayed the end of life of the satellite by more than one year assuming worst case estimates. Obviously this result has significant business implications, more so given the fact that the satellite is fully functional.

Also for the specific case of Arabsat 2B, the cost of TGM service comes to about 0.6% of the potential profit that could be accumulated over this extra year of operation. This estimate is of course subject to several business considerations.

8. Conclusion

Current paper shows that the Thermal Gauging Method for propellant estimation was successfully applied to ArabSat 2B (SpaceBus 3000) geosynchronous communication satellite. Tank and satellite thermal models for ArabSat 2B have been developed, calibrated and used for propellant estimations and the accuracy analysis.

In the case of Arabsat 2B, the remaining propellant estimates indicate an additional 12 months of in-orbit operation for the satellite. A functional in-orbit satellite in the telecom industry is an extremely valuable asset. In addition to this positive result, the high accuracy of the result obtained by the TGM gives good confidence in the propellant estimations and allows more accurate planning for the future of this satellite.

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