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Thermal Gauging and Rebalancing of Propellant in Multiple Tank Satellites

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An unbalanced propellant load in a geosynchronous communications satellite with multiple tanks can reduce satellite life. Depending on the details of the propellant plumbing system, significant fuel may become unusable in the more full tanks when the least full tank empties. If undetected and uncorrected, such an imbalance will reduce revenue and may even cause a premature loss of service. An improved thermal propellant gauging system is applied to detect imbalances in a pair of satellites and to design and implement new technology: the thermal pumping procedures to correct the imbalances. Thermal pumping is achieved through ground-based control algorithms to create the necessary differences in the heating rates of the four propellant tanks. The ground-based algorithm uses temperature telemetry and heater status telemetry to send heater commands to the satellites. This differential heating approach was employed successfully on two satellites, which were neither designed nor built with these thermal gauging and pumping operations in mind, enabling a considerable extension of profitable operational lifetime for both satellites.

I. Introduction

A NEW technology to rebalance propellant between multiple tanks in a spacecraft is made possible by improvements over a previous thermal propellant gauging method [1]. Two highly similar satellites were launched in the spring and fall of 1991. The design life for both satellites was 12 years. The propulsion system of the satellites has four connected propellant tanks, as sketched in Fig. 1. In the summer of 2001, the operator desired verification of remaining fuel mass of the two series 3000 satellites. Until that time, propellant estimation was based solely on the bookkeeping method. The authors worked with the operator of the satellites and together they implemented a high-fidelity estimation of the fuel levels on the satellites. The authors improved a previously published thermal propellant gauging system (PGS) [1] to independently determine the fuel load of each tank. The total fuel mass measured with the PGS method matched well with bookkeeping results. However, a significant imbalance of the fuel load between the tanks was discovered. Any imbalance between these tanks prevents the efficient use of all of the onboard propellant because the depletion of one tank, while the other tanks still contain propellant, will lead to two phase fluid (fuel and pressurizing gas) mixture in the fuel lines. This would make maneuvers difficult to control if there were large attitude transients. If left undetected and uncorrected, this fuel imbalance can lead to the satellites being decommissioned while substantial fuel remains unused in three of the four tanks. This would be a costly loss of revenue. The only way to prevent the early decommissioning of the satellites was to rebalance the propellant loads of the tanks such that each tank contains one quarter of the remaining fuel at all times.

Once the imbalance of the propellant tank loads was determined, the liquid fuel had to be transported between tanks to balance the load in each tank. Fuel transfer between tanks was performed by creating temperature differences between tanks. The set points of tank heaters were changed to create the required temperature differences. The control of the tank backup heaters to rebalance the fuel was performed by ground-based software, as there is no capability in the onboard processors for a suitable programming patch of this type. The ground-based algorithm uses temperature and heater status telemetry to generate and send appropriate heater commands to the satellites to create the desired temperature differences. It is interesting that estimates made in 1972 predict that a nonuniform thermal environment could be the primary cause of an imbalance between multiple tanks [2].

This paper describes the application of an improved thermal gauging method to determine the remaining fuel mass in the four tanks in both of the satellites, the effects of the undesired distribution of the fuel on the thermal response of the tanks, a determination of the accuracy of the estimates of the end of the satellite operational lifetimes, and a thermal method to rebalance the nonuniform propellant distribution between the four tanks. The success of these efforts is seen in the agreement between the measured on-orbit thermal response of tanks and the results of the modeling, but most important, the success is proven by the extension of the profitable lifetime of both satellites.

II. Propellant Gauging System

Three methods are typically employed in the industry to estimate the propellant remaining in orbit. These are bookkeeping, pressure–volume–temperature (PVT), and PGS. Basics of the modern PGS method can be found elsewhere [1]. Current implementation of the PGS method is superior in numerous ways to the published initial work.

The PGS method has distinct advantages over the bookkeeping and PVT methods, in particular, near end of life (EOL). Bookkeeping

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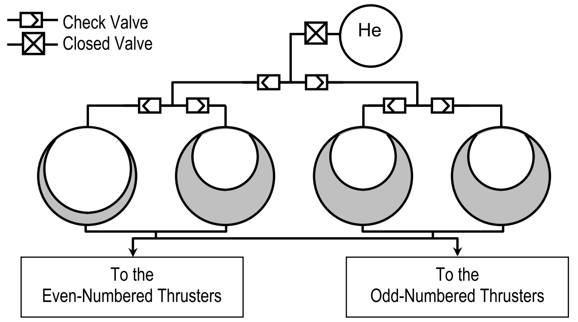

Fig. 1 Major elements of the monopropellant station-keeping propulsion system.

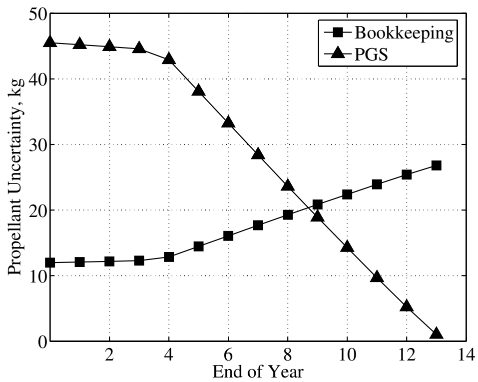

Fig. 2 Uncertainty in PGS and PVT or bookkeeping methods.

accuracy drops because of the accumulation of error with time. The decline of PVT accuracy is the result of pressure decreases when the amount of the propellant in the tank is small. However, the accuracy of the PGS method increases with decreasing propellant mass. Figure 2 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 than 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 midlife and end of life.

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

It is important to note that the PGS and rebalancing work described here is performed on satellites that were designed, built, and launched before the PGS method was developed. Unlike PVT there is no need for extreme precision in the pressure sensor, which is very difficult to achieve, in particular, for the long run. Low-resolution digitization of temperature data does limit accuracy of PGS, and yet the accuracy is sufficient to permit high-fidelity propellant estimation. When PGS is applied to the newest satellites designed with PGS operations in mind, the benefits of the high-fidelity thermal model are numerous.

The thermal PGS is based on the concept of measuring the thermal capacitance of a tank containing liquid propellant and pressurant gas by measuring the spatially varying time-dependent thermal response of the propellant tank to heating and comparing the observed temperature rise to simulation results. During a PGS test, the tank heaters apply a known amount of energy to the propellant tank and the resulting temperature increase with time is recorded. These on-orbit data are then compared with the computed temperature

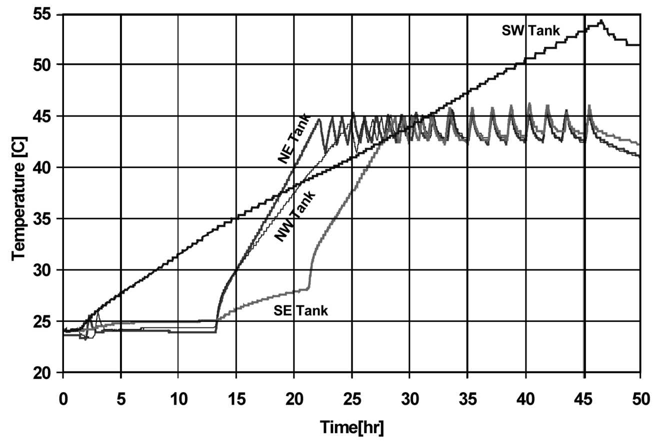

Fig. 3 PGS measurement conducted without temperature change control (data from on-orbit).

response of tank thermal model versus time for different propellant loads. The propellant load is calculated via interpolation between these propellant calibration curves. The tank thermal model includes propellant management device (PMD) vanes and sponges, spatial capillary-dominated propellant positioning in the tank, the tank wall materials, heaters, thermistors, multilayer insulation (MLI), and the satellite thermal environment in which the tanks exist. Developing a model of sufficient fidelity is the key to success. Improvements over previously published work include superior volumetric meshing, improved spatial resolution in the thermal model, increased accuracy in modeling the spacecraft thermal environment, and the multiple-tank capability.

To prevent thermal pumping between tanks during both the heating and cooling periods of the PGS measurements, the temperature rise and drop of the four tanks should have equal rates. To meet this goal, the tank heaters were turned on and off according to a specially developed algorithm that used temperature telemetry and heater status telemetry to create the necessary heater commands to be sent to the satellites. This matched the heating of all tanks to the thermal profile of the tank with the largest thermal lag (usually the tank with the largest propellant load).

Figures 3 and 4 show results of PGS measurements conducted without and with the algorithm to control the relative rates of temperature change. Note the following two symptoms of liquid transfer between tanks in Fig. 3: changes in slope of the heating curves and changes in frequency of the on–off cycles after the NE, NW, and SE tanks near 30 h. As can be seen, the improved algorithm for controlling the temperature rise was effective, resulting in little fluid movement between tanks during the PGS. This allowed for improved accuracy in PGS measurements.

The temperature distribution on the tank surface is nonuniform because of, for example, nonuniform heater power distribution and uneven propellant distribution inside of the tank. Nonuniformity of heater power distribution stems from the fact that heater strips cover

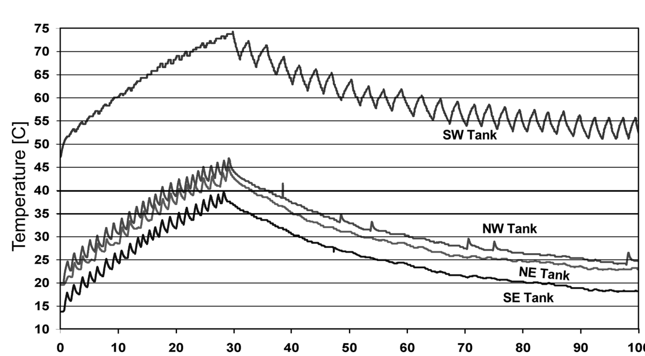

Fig. 4 PGS measurement conducted with temperature change control (data from on-orbit).

only a fraction of the tank surface. Propellant position in the tank during microgravity is controlled by a vane-type PMD [3]. At times near EOL in these two satellites, 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 dry and not in contact with propellant. All of these factors lead to significant temperature gradients on the tank wall. Therefore, the temperatures measured by the temperature sensors on the outer side of the tank wall depend on the sensor locations. The temperature distribution on the tank surface must be determined accurately to compare test data with calculated temperatures successfully.

Challenges of using PGS include the development of a thermal model of a single fuel tank that adequately simulates the propellant tank response to heating. Such a model was developed for the tanks on these two satellites. The major features of the model include three-dimensional fuel distribution in the tank in microgravity, effect of environment on tank thermal response, details of the tank design such as tank material properties, heater and temperature sensor locations, and so on.

Depending on how much detailed information about the tank is available and used in the model development, the thermal tank model can range from a high fidelity to, as previously published [1], a simplified model. The high-fidelity model typically consists of 20,000 nodes or more. It provides detailed propellant and temperature distribution in the tank including the transient temperature field on the tank outer surface where temperature sensors are located.

A. Fluid Modeling

The spatial distribution of the propellant in the tank was determined using the Surface Evolver[§] (SE) code [4]. SE can be programmed to solve for the three-dimensional positions of a liquid volume and the associated gas–liquid interface in microgravity with exceptional contact-angle fidelity. The solution is obtained through a scalar minimization algorithm and user-specified energies. SE has been validated against classical capillary instability theory and critical contact-angle theory [5]. SE is applied to determine the propellant distribution in the tank and vane-type propellant management device inside the tank [6–8]. The static equilibrium position of the propellant in weightlessness is determined by PMD and tank geometry, plus the contact angle of the liquid on the tank wall. Fluid material properties such as density and surface tension are not relevant to the static equilibrium distribution of the propellant, but are important for dynamics.

The SE code is programmed to model the interior space of the propellant tanks. The vanes of the PMD are modeled, as is the simple sponge [9] at the outlet of the tank. Creation of such geometry definitions in SE requires experience with and understanding of a variety of features of the code and the energy minimization algorithm as well as capillary fluid physics. There is no other code available that provides the excellent and very important fidelity in the contact-angle boundary condition that SE provides.

SE produces a surface grid of triangular facets representing the complex-curvature capillary interface between liquid and gas. Based on this surface grid and knowledge of the tank and PMD geometry, volumetric grids of the propellant, pressurant, and tank wall are created. The volume grid provides the spatial and connectivity information needed for the finite-element thermal model. Material properties such as densities, conductivities, capacitances, and so on, for the propellant, pressurant, and tank walls are incorporated at this point. The tank wall grid is then used to identify wall nodes that describe the heater strips and thermistors.

Some iterative effort is generally required for three items in this process. The SE grid is manipulated to align certain wall nodes of the thermal model with thermistors on the outside of the tank wall. Second, the ratio of the maximum to minimum conductances of the links between nodes in the thermal model must be kept sufficiently small to avoid ill-conditioned matrices in the thermal modeling. Interactive efforts to identify and rectify, for example, SE facets that produce extremely small or large conductances, are generally necessary. Similarly, the minimum thermal capacitance of elements affects step size in time and thus overall compute time of the modeling.

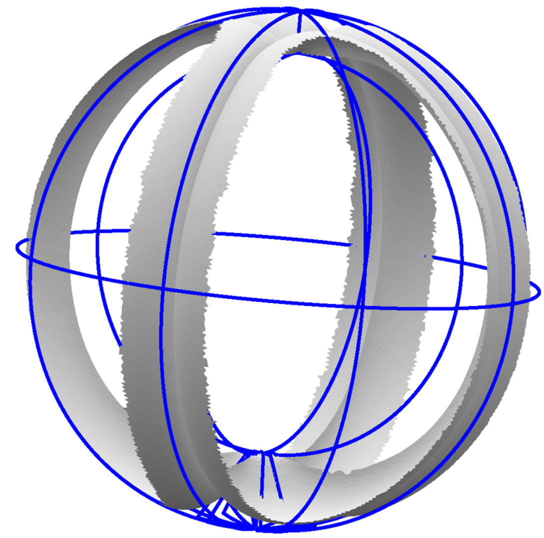

Fig. 5 Example Surface Evolver result for the propellant tanks.

Results of a SE simulation of propellant position in one propellant tank is shown in Fig. 5. Because of symmetry of the propellant tank and the PMD, the SE was used to model one-eighth of the tank. In Fig. 5, open areas indicate dry areas where gaseous helium contacts the tank wall. Any heaters situated over such dry areas tend to create hot spots during heating. Solid lines show contours of tank wall and the major vanes. The fuel is located between gray colored interface area and the tank wall. Accurate knowledge of three-dimensional fuel position is necessary to create a spatially accurate thermal model for a partially filled tank.

The purpose of the high-fidelity thermal model is to obtain detailed temperature distributions on a single tank. This model is complex and it is designed for use in off-line computing of a single-run PGS analysis. The high-fidelity model requires significant compute time and thus it is unsuitable for real-time use or for computing a large number of runs. To support large numbers of runs, a simplified thermal model derived from the high-fidelity thermal model was developed.

The simplified thermal model uses the detailed high-fidelity thermal model as a benchmark to compare against for a few cases. The simplified thermal model has significantly fewer nodes but it simulates essential features of the high-fidelity model, like the fuel distribution along the major vanes and in the sump. Use of the simplified model reduces computation time considerably. This is helpful for development of a PGS procedure when multiple simulations are required to understand the behavior and interaction of four tanks heated differently inside the spacecraft thermal environment.

B. Uncertainty

Uncertainties of the PGS method can be grouped into the following three groups: physical, measurement, and numerical. Physical phenomena that may affect the propellant gauging are thermal-capillary convection, errors or variations in tank surface and MLI emissivity, spacecraft interior temperatures, and heater power. Thermal-capillary convection is mass and energy transport generated in the liquid by a temperature-induced surface tension gradient. This process usually is negligible in most terrestrial conditions because buoyant convection generally dominates. However, in orbit, thermal-capillary convection could play a nonnegligible role at some conditions. There are presently no computational fluid dynamics

[§]The Surface Evolver manual and code are available at http://www.susqu.edu/facstaff/b/brakke [retrieved 25 April 2007].

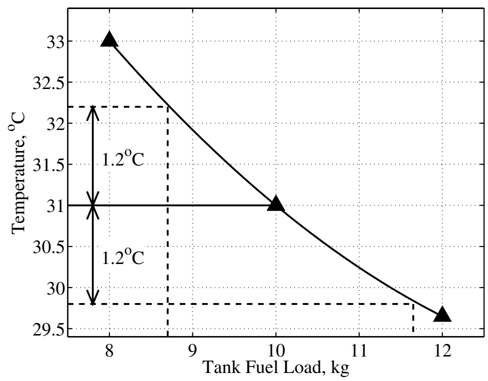

Fig. 6 Illustration of a computed uncertainty band.

codes able to compute such flows in relevant on-orbit geometries and length scales.

Uncertainties and variations of temperatures of surrounding tank structures, such as intercostal panels, and uncertainties in emissivity of the MLI also contribute to uncertainty in the fuel estimates. Radiative heat exchange between the tank and the environment, which depends on sink temperature and tank emissivity, affects the overall thermal balance of the tank. Temperatures of structures surrounding the tanks are needed to determine the sink temperature for the thermal model. The design data provide the effective emissivity, including emissivity of the MLI. These data are corrected using the flight data. That is, onboard data for heater duty cycle and tank temperature are used to infer the coefficient of effective emissivity and sink temperature. For example, if the heater duty cycle is negligibly small, then the sink temperature is very close to the tank temperature. The effective emissivity of the MLI can be verified by using the measured sink and tank temperature decays following the end of PGS heating episodes.

Sources of uncertainty include those associated with temperature measurement in orbit and the interpretation of the temperatures. Small but finite uncertainty in thermistor resistance, power supplied to the thermistor, and telemetry channel errors are items in this group. An estimate of temperature measurement uncertainty of 0.83°C was obtained for a different satellite program. The temperature measurement systems for the previous and current satellites are similar. Therefore, temperature measurement uncertainty of 0.83°C is used in this work.

The group of numerical error sources includes items such as the determination of liquid–gas surface position and errors from discretization including gridding. The volume grid produced from the SE output is used to produce the finite-element thermal model, which is solved by thermal analyzer software SINDA. Errors are also introduced when calculating the temperature at temperature sensor locations through interpolation between nodes of the SINDA model.

Studies have shown that the total temperature error from the major uncertainties is approximately ± 1.2°C. For example, if the finite-element tank thermal model predicts a temperature rise of 31°C for a 10 kg total fuel load, then an observed true temperature of 31°C $\pm$ 1.2°C indicates that the fuel load is indeed 10 kg. Therefore, for purposes of design and implementation, two loads can be distinguished only if the temperature difference on the fuel calibration curves at the end of heating exceeds 2.4°C. Figure 6 shows qualitatively a computation of the uncertainty band as an illustration, not from flight data. In the case presented in Fig. 6, the accuracy of the PGS estimate is $+1.6/-1.3$ kg at the 10 kg level, with the asymmetry inherent to the process.

III. Fuel Balancing

Initial PGS measurements indicated that the remaining fuel was distributed unevenly between the four tanks, creating lifetime-shortening problems described above. Additionally, tanks with unbalanced fuel loads exhibit nonuniform temperature rise during PGS measurements with equal heat input for each tank. Specifically, the temperature rise on a tank with larger fuel load would be less then the rise on the tank with less fuel. Temperature differences between tanks would be created during PGS and would lead to thermal pumping from the warmer tank to the cooler tank. Not only does this create ambiguity in propellant gauging, but as the warmer tank is generally the emptiest tank, this thermal pumping serves to increase existing imbalances, creating the possibility of tank depletion during a PGS measurement.

The results of the PGS testing allowed an estimation of the temperature differences between tanks which are required to balance the fuel loads in the tanks. Based on Boyle’s law, most commonly exhibited as the perfect gas equation of state, a hydraulic model of the spacecraft propulsion system with four connected tanks was developed. The parameters for the model are the initial pressure, initial and final temperatures, initial and final propellant masses, tank volume, propellant properties, and pressurant fluid properties. This model also takes into account pressurant solubility and tank stretch with pressure (in retrospect, an even simpler model also might have worked fairly well for these satellites). The physics behind the model is a simple force balance on the liquid in the four tanks. This permits the necessary temperatures to be determined to create the desired new state of equal liquid mass in each tank. The model does not predict the dynamics of the transfer.

The desired tank temperature differentials between tanks were then induced in the satellite to balance the fuel load of the tanks. This was accomplished by changing the set points of the tank heaters to maintain the new desired temperature differential. The set point of the tank with the most fuel load was chosen at the highest possible temperature.

This differential tank heating approach was employed for approximately 1.5 years, resulting in the rebalancing the tank fuel loads. As time progressed and new PGS results were obtained, the differential heating requirements were adjusted to maintain the propellant balance.

IV. Hardware and Operations

The propellant tank system uses four interconnected tanks with no isolating latch valves. There are two temperature sensors per tank. There are three heater sets that provide thermal control of the propellant tanks. There is a primary and backup differential heater control (DHC) system and a thermostatic heater control system. The DHC system maintains all four tank temperatures to within 2°C of each other, as well as providing thermostatic control to maintain a minimum tank temperature of 13°C. The thermostatic system maintains minimum tank temperatures but does not provide differential control. There is no ground control over these two systems aside from the ability to enable them. There is, however, ground override command capability on the backup heater patches for each tank. Until the implementation of the control method described in this paper, the satellites operated using the primary DHC.

The amount of fuel remaining in each tank was determined by comparing simulation and PGS data. A typical comparison is shown

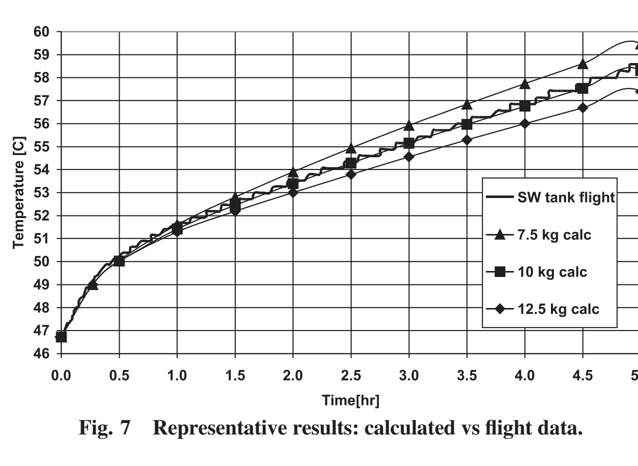

Fig. 7 Representative results: calculated vs flight data.

Table 1 Bookkeeping versus PGS fuel measurements in the two satellites

PGS test no.	Date	Bookkeeping	PGS	Delta
First satellite[a]				
4	14 Dec. 2001	73.4 kg	75.5 kg	+2.1 kg
5	8 May 2002	58.0 kg	59.5 kg	+1.5 kg
6	22 Aug. 2002	43.5 kg	48.0 kg	+4.5 kg
7	23 Oct. 2002	38.7 kg	39.0 kg	+0.3 kg
8	20 Feb. 2003	24.9 kg	23.5 kg	−1.4 kg
9	24 April 2003	23.3 kg	21.5 kg	−1.8 kg
Second satellite[b]				
7	16 May 2002	47.6 kg	52.2 kg	+4.4 kg
8	21 Aug. 2002	37.0 kg	44.0 kg	+7.0 kg
9	17 Oct. 2002	34.9 kg	41.0 kg	+6.1 kg
10	24 Feb. 2003	22.5 kg	27.5 kg	+5.0 kg
11	14 April 2003	22.1 kg	27.5 kg	+5.4 kg

[a]The average result for the first satellite PGS is 0.9 kg above bookkeeping.
[b]The average result for the second satellite PGS is 5.6 kg above bookkeeping.

in Fig. 7. The fuel estimates from bookkeeping and PGS for the two satellites is shown in Table 1. The data indicate that bookkeeping and PGS methods predict similar results for total fuel load. The PGS method estimations are above the bookkeeping ones for most cases. Analysis has shown that at 10 kg of fuel, PGS measurements can be as good as approximately ± 0.56 kg, or about $\pm 5\%$ of the fuel remaining on the spacecraft.

Both of the satellites have had major anomalies that hamper operations [10]. The first satellite had a power anomaly such that power is only available from one solar wing. This anomaly precludes using the primary north/south station-keeping thrusters in the augmented mode. Operation in the augmented mode would draw power from the batteries to augmentation heaters in the thrusters to increase specific impulse. The second satellite has lost the use of the momentum wheels and is a truly zero-momentum satellite. Attitude control is performed using magnetic torquers and various thrusters. This method of control is extremely sensitive to helium bubbles in the propellant lines.

A short series of tests was performed on both satellites to determine the health of the backup heaters, which had been unused for almost 10 years. All of the thermal components were found to be healthy, but the pressure sensors were not, however, and so a PVT crosscheck of the thermal gauging was not possible. Nevertheless, the basic components for thermal propellant gauging and fuel balancing by differential temperatures were available, namely, commandable tank heater patches and functioning tank temperature sensors.

These two satellites have very limited onboard processing capabilities compared with the current generation of spacecraft. The onboard processor controls attitude and station-keeping maneuvers. Therefore, thermal gauging and differential heating algorithms had to be developed to run on ground computers using temperature and heater status telemetry as inputs and heater commands as outputs.

It was found that three of the tanks maintain a temperature differential to the fourth tank (reference tank) for reasons described above. The reference tank was originally hard coded to be the southeast tank, as all measurements for both satellites indicated that this tank is the tank with the least fuel mass. This has subsequently been modified to allow any tank to be the reference tank, allowing for greater operational flexibility. The temperature differential from each tank to the reference tank can be varied to accommodate mass differences for each tank and to account for seasonal variations in the satellite internal thermal environment.

There is as well a thermostatic routine to ensure that individual tank temperatures are maintained above a designated user selectable minimum temperature. The thermostatic routine operates on the reference tank, because it is by definition the coldest tank.

Thermal gauging and differential heating use the same software routines. For thermal gauging the set point is the target temperature for the thermostatic routine and the reference tank is driven to that temperature. The differential heating routine maintains the temperature differential of the other tanks to the reference tank during the gauging measurement. As described earlier, this minimizes fuel movement during the gauging measurement.

The number of times that the heater relays are cycled was tracked and counted. The relays are mechanical relays and thus have a qualification limit for on/off cycles. Because of the manner in which maneuvers are managed in the operating system, the automated commanding of the differential heating software is disabled during all maneuvers. Requests for heater commands from the satellite are therefore acted on manually. Fortunately, the number of heater duty cycles is low and therefore few heater commands are required during a typical maneuver.

Monitoring of the fuel load in each tank is mandatory for a successful tank balancing. This need dictated the frequency of PGS measurements. The measurements were typically conducted one or two months apart for each satellite. A total of 20 PGS measurements have been conducted on the two satellites (9 for one and 11 for the other). The first four PGS measurements on one satellite and the first five on the other were conducted without control of the temperature rise and drop rates.

V. Results and Conclusions

Active balancing tanks lead to a significant reduction in difference of fuel loads of tanks. As data in Fig. 8 indicate, tank balancing led to a significant reduction in difference of fuel tank loads. For example, the southwest tank held approximately 45% of the total fuel load before balancing with the remaining fuel distributed approximately equally between the other three tanks. However, each tank contained between 20 and 28% of the total fuel load after rebalancing. This degree of rebalancing was sufficient for the mission.

The mission extension achieved with the fuel-balancing procedures on the propellant tanks is estimated to be approximately six months. That is, without the use of the thermal propellant gauging and thermal rebalancing procedures, the mission life of the satellites would have ended when one tank ran dry with the other tanks containing sufficient fuel for six months of operations. Approximately six months elapsed from the start of initial thermal propellant gauging activities to operational implementation of the differential heating procedure and approximately 1.5 years of thermal pumping was performed. Sensitivity of the thermal propellant gauging system appears to be $+1.6/-1.3$ kg at the 10 kg level and the operator states that end-of-life maneuvers show an end-of-life uncertainty [10] of ± 3 kg.

The successful on-orbit use of an improved thermal propellant gauging system, using low-resolution thermistor telemetry designed only for health monitoring, coupled with the newly developed thermal rebalancing technique shows that the method is a powerful tool to assist in spacecraft operations. Specifically, the thermal propellant gauging system can be applied to detect an unbalanced fuel distribution between connected tanks. A thermal pumping procedure, designed to act specifically on the unbalanced fuel load measured by the improved thermal propellant gauging system, can

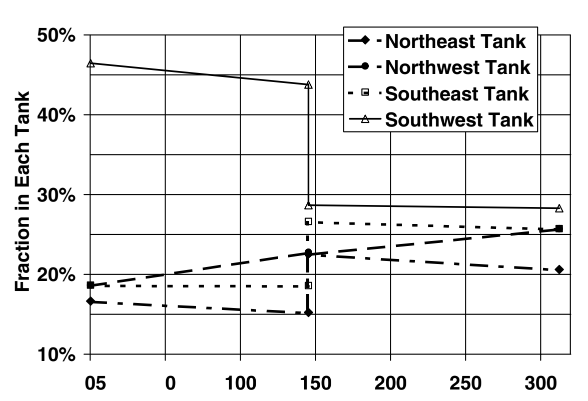

Fig. 8 Effect of rebalancing on fuel distribution in the four tanks.

then rebalance the propellant loads between tanks and also permits subsequent propellant gauging measurements to be made without depleting a tank. Implementation of the thermal pumping procedure through ground-based control of backup tank heater circuits shows that the technique likely is applicable to numerous satellites already in orbit. Because of the success of the new technique described above, the two satellites completed their nominal mission life and then entered inclined service mid-2003.

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