Anik E Spacecraft Life Extension

A. Yip[1], B. Yendler[2], T. A. Martin[2], S. H. Collicott[3]

[1]Telesat Canada, Gloucester, Ontario, K1B 5P4, Canada.
[2]Lockheed Martin Commercial Space Systems, Newtown, PA 18940 USA.
[3] Purdue University

Background

Lockheed Martin and Telesat Canada have a long history of technical excellence going back to the early 1970s. Telesat Canada is a satellite operator based in Ottawa, Ontario, Canada. It operates a fleet of nine satellites, of which Lockheed Martin manufactured four of these satellites. The Anik E spacecrafts are owned by Telesat Canada and is their fifth generation series of satellites. The satellites use the series 5000 BUS with the C-band and Ku-band transponders supplied by Spar Aerospace. Anik E2 was launched on April 4, 1991 and Anik E1 was launched on September 26, 1991. The design life at launch for both satellites was 12 years and they both entered inclined service July 1, 2003. The Nimiq satellites are A2100 BUS spacecrafts built by Lockheed Martin, designed to provide telecommunications coverage of Canada and CONUS. Nimiq-1 was launched on May 20th 1999 and Nimiq-2 was launched on December 26, 2003. Both of the Anik satellites are very low on fuel at this point in time. Operationally, Lockheed Martin has been able to help Telesat Canada understand how much fuel is available on both of these satellites, thus providing a level of assurance in their de-orbiting estimations. Lockheed Martin and Telesat Canada have been working under technical assistance agreement authorized by OTDC CASE TA 661-99C.

Operational Summary

Lockheed Martin's Customer Response Center (CRC) provides direct technical support to nineteen worldwide customers operating a fleet of fifty spacecraft including twenty-two A2100 and twenty-eight heritage spacecraft, consisting of Series 3000, Series 5000 and Series 7000. Support is provided for the contract life of the spacecraft. The CRC is on call 24/7 through the A2100 Satellite Operations Center (ASOC). The CRC has been deeply engaged with Telesat Canada's operations team over the last two years. Together we have been able to create a high fidelity estimation of the fuel levels on the Anik satellites using the Propellant Gauging System

The station-keeping thrusters are monopropellant and use hydrazine. The primary north/south thrusters operate in EHT mode and the east/west thrusters operate in REA mode. In the summer of 2001, Telesat contacted Lockheed-Martin regarding verification of fuel mass that up to then was based solely upon the book-keeping. The total mass as measured thermally matched well with bookkeeping, but the hydrazine is contained in four tanks and the fuel imbalance between these tanks leads to complications in the efficient utilization of all of the on-board propellant. The ensuing efforts to gauge the remaining propellant and then to subsequently rebalance the propellant load in each tank via thermal approaches led to the recent thermal on-orbit spacecraft control developments discussed in this paper. The Anik spacecrafts propulsion system has four connecting propellant tanks. The bookkeeping method while capable of estimating the total propellant mass is not capable of determining a propellant load of each tank. Uneven propellant distribution between tanks can lead to a premature formation of two-phase fuel/pressurizing gas mixture due to depletion in the tank with the lowest propellant level. Such an event can significantly impact the spacecraft mission life and lead to premature decommissioning of the spacecraft. The only way to prevent tank early is to re-balance propellant load of the tanks. Fuel remaining estimation for each tank was done by using the thermal Propellant Gauging System (PGS); which includes development of tank thermal models, conduction of in-flight tests, and fuel remaining determination. The PGS method has distinct advantages over the bookkeeping method particularly for a spacecraft with a multi-tank monopropellant propulsion system. Firstly, the accuracy of the PGS increases with time becoming typically superior to the bookkeeping at EOL. Secondly, the PGS approach is capable of determination of fuel load of each tank while the bookkeeping can determine only total fuel load of the spacecraft.

Once the propellant load in each tank had been determined, the next step was to balance the load in each tank. Temperature differentials between tanks were induced in order to balance the fuel load of the tanks. The set points of tank heaters were changed in order to create the required temperature differentials. The control of the tank back-up heaters to re-balance the fuel is performed by ground software, as there is no on-board processor patch capability. The ground-based algorithm uses temperature telemetry and heater status telemetry to send heater commands to the satellites. This differential heating approach was employed for more then 1.5 yr. on both spacecraft allowing for considerable life extension.

Results of propellant remaining estimation and tank load balancing are discussed in the current paper.

Propellant Gauging System

Currently, three methods are typically employed to estimate the propellant remaining in flight, namely, bookkeeping, Pressure-Volume-Temperature (PVT) and thermal Propellant Gauging System (PGS). Description of PGS method could be found elsewhere [JA, 1999]. The PGS method has distinct advantages over the bookkeeping and PVT methods. Firstly, the accuracy of the bookkeeping and PVT methods is declining with time. The bookkeeping accuracy drops due to an accumulation of error with time. Decline of PVT method accuracy is the result of pressure decrease when amount of the propellant in the tank reduces. On other hand, the PGS method accuracy is increasing with time. Presented in Fig.1 data shows a general trend for an uncertainty of propellant remaining estimation for the book-keeping and the PGS methods with time. As Fig.1 shows, the book-keeping method has better accuracy then PGS at the beginning of a s/c life. The accuracies of both methods become comparable in the middle of life. The PGS method becomes typically superior to the bookkeeping at EOL.

Secondly, PGS is capable of determination of fuel load of each tank while the bookkeeping method can determine only total fuel load of the s/c with multi-tank monopropellant propulsion system. Any imbalance in fuel distribution between the tanks remains hidden from the user and can lead to earlier decommission of the s/c.

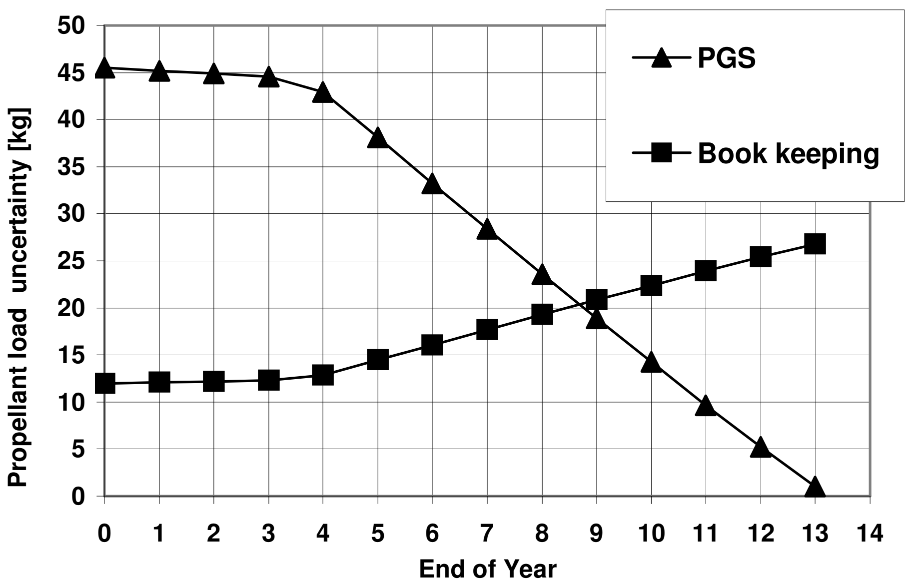


Figure 1. Propellant mass uncertainty vs. end of the Year. Triangle –PGS method. Square – Book-keeping method.

The PGS is based on the concept of measuring the thermal capacitance of a tank filled with liquid fuel and a pressurizing gas by using the thermal response of the propellant tank to heating. During PGS test the tank heaters apply a known amount of energy to the propellant tank, the resulting temperature increase with time is recorded. This on-orbit data is then compared to curves of temperature versus heating time calculated for different propellant loads (propellant calibration curves). The resulting actual load is calculated via interpolation between the propellant calibration curves.

The temperature distribution on the tank surface is not uniform due to several factors including non-uniform heater power distribution and uneven propellant distribution inside of the tank. Non-uniformity of heater power distribution stems from the fact that heater strips cover only fraction of the tank surface. Propellant position in the tank is controlled by Propellant Management Device (PMD) in microgravity. At EOL in Anik E s/c, propellant is located in the sump and in the corner formed by PMD vanes and the tank wall. All these factors lead to a non-uniform temperature distribution on the tank surface. Therefore, temperature shown by the temperature sensor depends on the sensor location. The temperature distribution on the tank surface should be determined in order to compare the test data with calculated results.

A finite element (FE) thermal model of the hydrazine tank is developed using the spatial propellant distribution. This model allows the estimation of temperature response of a tank to heating for various fill fractions (corresponding to remaining propellant masses). These calculations result in a series of curves that relate tank temperature rise to heating time for various amounts of propellant in the tank. A family of such curves is generated for different masses of hydrazine in the tank. The amount of propellant remaining is determined by comparing analytically calculated temperature rises to the curves generated on-orbit .

Challenges of using PGS include the development of a thermal model of a single fuel tank, which adequately simulates the fuel tank response to heating. Such a model has been developed. The major features of the model include 3-D fuel distribution in the tank in mcrogravity; effect of environment on tank temperature behavior, non-uniformity of temperature distribution in the tank; details of the tank design like tank material properties, heater and temperature sensor locations, etc.

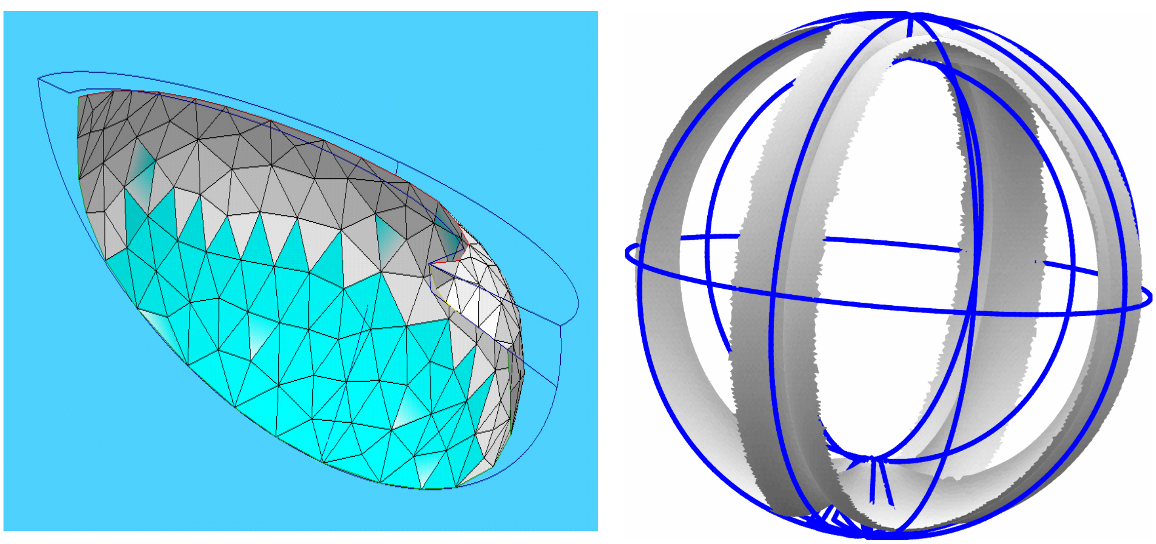
Depending on how much detailed information about the tank is available and used in the model development, the thermal tank model can range from a high fidelity to a simplified model. The high fidelity model typically consists of about 10,000 nodes or more. It provides very detailed propellant and temperature distribution in the tank including the tank surface where temperature sensors are located.

“Surface Evolver “software package that finds a position of gas-liquid interface in microgravity determines the propellant distribution in the tank. The static equilibrium position of the propellant in weightlessness is determined by geometry. Magnitudes of material properties such as density and surface tension are not relevant to the static equilibrium distribution of the propellant as the solution is determined by PMD and tank shapes plus contact angle of the liquid on the solids.

The *Surface Evolver* [SC1, SC2] code solves the 3-D static equilibrium capillary interface problem with excellent fidelity in the important contact angle boundary condition. The solution is obtained through an energy minimization algorithm and user-specified energies.

Surface Evolver produces a grid of triangular facets representing the complex-curvature capillary interface. From this surface grid and knowledge of the tank and PMD geometry, volumetric grids of the propellant, pressurant, and tank wall are created. The volume grids provide the spatial information needed for creating of FE the thermal model, which includes material properties such as densities, conductivities, capacitances, etc. for the propellant, pressurant, and tank design details. The tank wall grid is then used to identify wall nodes that lie under the heater strips.

Some iterative effort is generally required for two items in this process. The *Surface Evolver* grid is manipulated to align certain wall nodes of the thermal model with thermistor locations on the tank. Second, the ratio of the maximum to minimum conductance of links between nodes in the thermal model must be kept sufficiently small to avoid mathematical stiffness problems in the thermal modeling. Interactive efforts to identify and rectify, for example, *Surface Evolver* facets that produce a very thin region of propellant with negligible mass but extremely small or large conductances, assist in reducing the range of conductances.



2 a 2 b

Figure 2. Results of Surface Evolver simulation.

2a Interface between He and Hydrazine in ¼ of Anik E fuel tank. (Cyan color indicates dry wall. Blue lines show tank wall and PMD)

2b. Propellant distribution inside of Anik E fuel tank. Blue semi-circle is major vane. The surface between fuel and gas is gray

Results of Surface Evolver simulation of fuel position in Anik E fuel tank are shown in Fig.2. Due to an axial symmetry of the fuel tank, the Surface Evolver was used to model one quarter of the tank. In Fig. 2a, Cyan color indicates area where He is interfacing with the tank wall. Wall is dry in this area. The heaters situated in such dry area create hot spots during heating. The blue line shows contours of tank wall and PMD major vane. The fuel is located between gray colored area, tank wall and the major vane. The distribution of the fuel inside of the entire fuel tank is shown in Fig. 2b.

The purpose of the High Fidelity Thermal Model is to obtain a detailed picture of fuel and temperature distribution in a single tank. This model is complex, and it is designed to use off-line a single run PGS analysis. The high fidelity model requires a significant processing time and the computational resources to generate results making it unsuitable for real-time or multiple runs computation. To support multiple runs, a Simplified Thermal Model based on the High Fidelity Thermal Model has been developed.

The Simplified Thermal Model is using the detailed High Fidelity Thermal Model as a benchmark in order to accurately simulate the major features of the tank with less complexity. The Simplified Thermal Model has significantly less 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 considerable computation time. It is also could be useful to support real-time PGS operations.

<u>**Uncertainty Sources**</u>

There are three groups of uncertainty which contribute to the error in the fuel load estimated by PGS:

I. Physical phenomena
    - Marangoni convection
    - Emissivity
    - Temperature of fuel tank environment
    - Heater power

II. On-orbit temperature measurement and its interpretation
    - Thermistor resistance variations

- Errors in the current that the RIU generates to measure resistance
- Telemetry errors, which include: error of signal digitization and error of polynomial approximation.

III. Numerical

- Fluid distribution model
- Thermal model meshing (grid)
- Interpolation/Extrapolation

The first group comprises of the uncertainty in physical phenomena, (besides the energy conservation), that play a significant role during PGS and that therefore should be considered. One example is Marangoni convection, which is generated in the liquid by a surface tension gradient. Such a gradient can exist at the gas-liquid interface due to, for instance, a temperature gradient. Marangoni convection is negligibly small in terrestrial conditions, when natural convection is dominant, but it can play a significant role in microgravity. This group also includes uncertainties of temperatures of surrounding tank structures, such as intercostals panels, and of an emissivity of Multi Layer Insulation (MLI). Radiation heat exchange between the tank and environment, which depends on a sink temperature and tank emissivity, affects the overall heat balance at the tank. Temperatures of surrounding tank structures are needed to determine the sink temperature for the thermal model. The effective emissivity, which includes emissivity of MLI, is determined from the flight data. According to the developed technique, on-board data for heater duty cycle and tank temperature are used to infer the coefficient of effective emissivity and a sink temperature. For example, if heater duty cycle is negligibly small, then the sink temperature is very close to the tank temperature. Using obtained sink temperature and tank temperature rise and fall during and after PGS, effective emissivity of MLI and fuel load can be determined

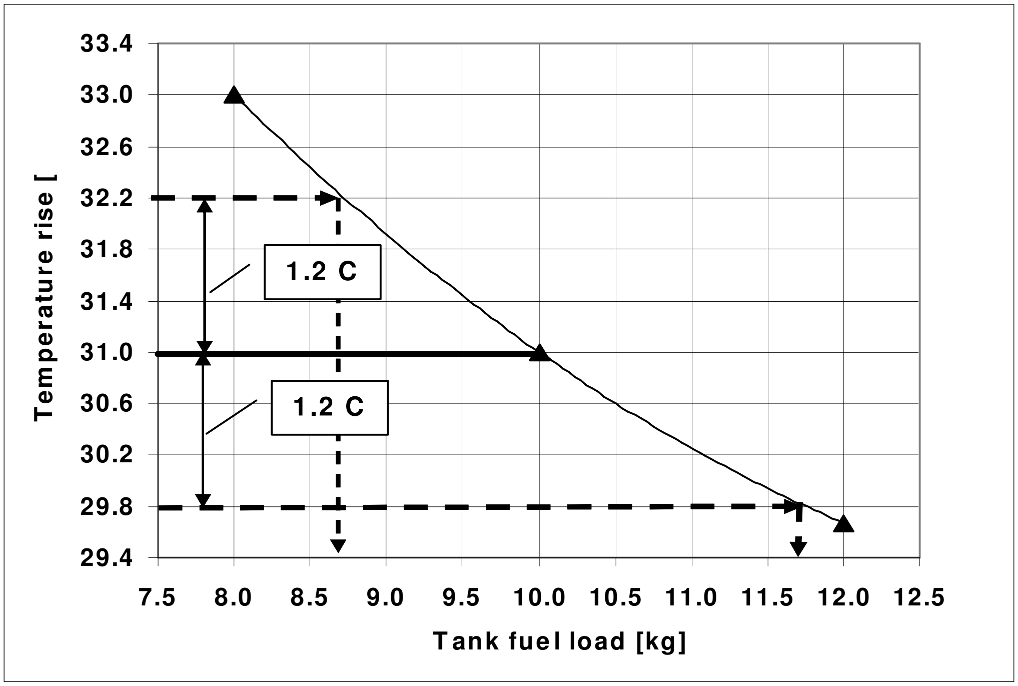


Figure 3. Computation of the PGS method accuracy. Dash lines show calculation of fuel uncertainty.

The second group includes errors associated with temperature measurement on-orbit and its interpretation. An estimation of temperature measurement uncertainty of 0.83 °C was obtained for a different program. The temperature measurement systems for this program and for Anik E are similar. Therefore, temperature measurement uncertainty of 0.83 °C is used to determine the error of fuel remaining estimation.

The last group comprises of errors pertaining to modeling and computations, inherent in all numerical models. This includes error in determination of liquid-gas surface position, meshing errors, such as an error of tank volume discretization during meshing. The resulting mesh is used then to produce a finite element (FE) thermal model, which is solved by thermal analyzer software SINDA. Errors are also introduced when calculating the temperature at temperature sensor locations via interpolation or extrapolation.

Studies have shown that the total temperature error, which takes into account the major uncertainties, is of ±1.2 °C. For example, if FE tank model predicts a temperature rise of 31.0 °C for a 10 kg total fuel load, then an observed true temperature of 30.0 °C ±1.2 °C indicates that the fuel load is indeed 10 kg. Therefore, for 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 3 shows qualitatively a computation of the uncertainty band for this case. In the case presented in Fig.3, the accuracy of PGS estimation is 3 kg (11.7kg -8.7 kg) or ±1.5 kg at 10 kg level.

Fuel load balancing

As initial tests indicated, fuel was distributed non – uniformly between the tanks, which created several problems. Firstly, non-uniformity can lead to an early depletion of one of the tanks while the other tank(s) can still contain a significant amount of fuel. That fuel in that instance would effectively become unusable. Secondly, un-balanced fuel tanks exhibit non-uniform temperature rises during PGS tests, namely, temperature rise on a tank with larger fuel load would be less then the rise on the tank with less fuel. Temperature difference between tanks during PGS can lead to thermal pumping when fuel from tank with higher temperature will be pushed into the tank with larger fuel load that in turn can lead to a depletion of the tank with less fuel load during PGS.

Using the results of the PGS testing, and estimation of the temperature differential required to balance the tank was made. The concept being that the tank pressure will respond to higher temperatures. This response is per Boyles law, most commonly exhibited in the perfect gas equation of state that states that tank pressure and temperature are directly proportional. A simple spreadsheet model of the propellant tank was made which predicted the final tank pressure given parameters such as the initial pressure, initial and final temperatures, initial and final propellant masses, and other items such as tank volume, propellant, and pressurant fluid properties. This model was based on a very detailed model that accounts for pressurant solubility, tank stretch with pressure, and using real fluid properties for the propellant and pressurant, but a simpler model would have worked fairly well for this case. The tool drew control volumes around each tank, thus each tank was modeled separately to predict a final pressure for each tank. The models were then coupled in that the fluid that would outflow from one tank would flow into the other tank(s). The amount of fluid outflow would be iterated on until the tank pressures converged. Of course this was much more difficult on these spacecraft since all four tanks were interconnected, thus all four tank models had to converge at once (see Fig.4)

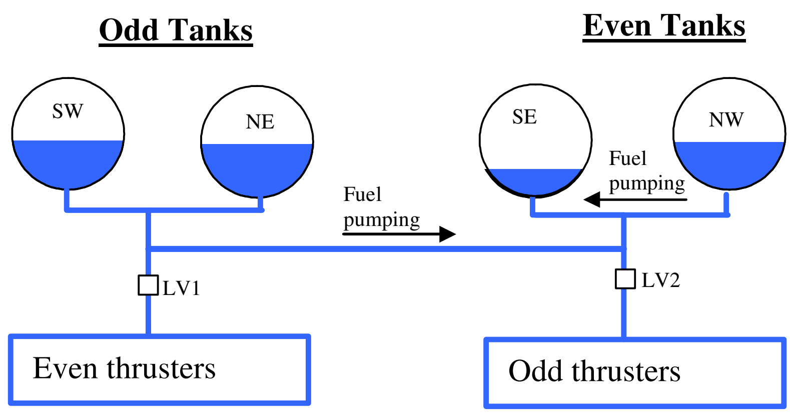


Figure 4. Anik s/c propulsion system

The model derived tank temperature differentials between tanks were then induced in order balance the fuel load of the tanks. This was accomplished by changing the set points of the tank heaters in order 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 more than 1.5 years, with the result of effectively balancing the tank fuel loads. AS time progressed and new PGS results were obtained, the differential heating requirements were adjusted to maintain the propellant balance.

The control of the tank back-up heaters to re-balance the fuel is performed by ground software as there is no on-board processor patch capability. The algorithm used temperature telemetry and heater status telemetry to send heater commands to the satellites. This created the appropriate temperature differentials to re-balance the fuel

In order to prevent thermal pumping during the PGS tests, during both heating and cooling periods, the temperature rise and drop of the four tanks should have the equal rates. With such an intention, the tank heaters were turned ON and OFF according to a special developed algorithm that used temperature telemetry and heater status telemetry to send heater commands to the satellites, thereby matching the thermal profile of the tank with the largest thermal lag (usually the tank with the largest propellant load).

Figure 5 and Figure 6 show PGS test conducted without and with such an algorithm to control the rate of the temperature change. As can be seen, the improved algorithm for controlling the temperature rise was very effective, resulting in little fluid movement during the PGS. This allowed for a much more accurate PGS measurement to be made.

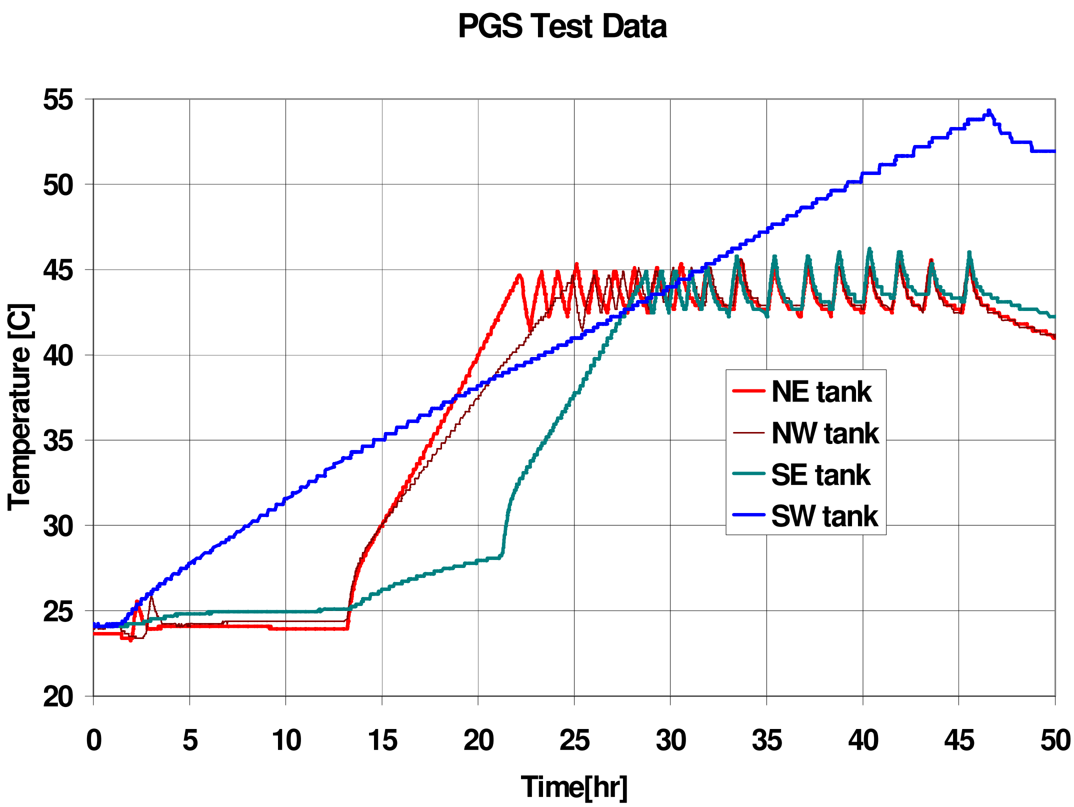


Figure 5. PGS test conducted without control of temperature change.

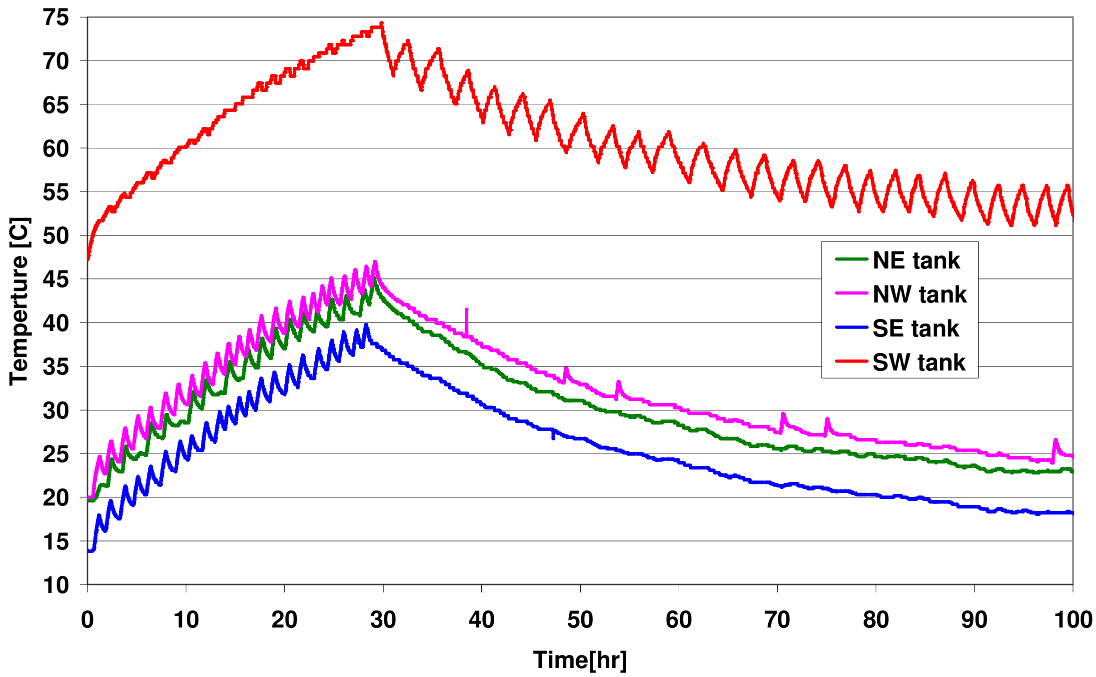


Figure 6. PGS test conducted on Anik E with temperature change control

Fuel remaining estimation

Monitoring of fuel load in each tank is mandatory for a successful tank balancing. It dictated the frequency of PGS tests. The tests were typically conducted one or two months apart for each s/c. The total of 20 PGS tests has been conducted between Anik E1 and E2 s/c (9 tests for Anik E1 and 11 tests for Anik E2). First 4 PGS tests on Anik E1 and first 5 PGS tests on Anik E2 were conducted without control of the temperature change (rise and drop).

Amount of fuel remaining was determined by comparison simulation and PGS test data. A typical comparison is shown in Fig. 7.

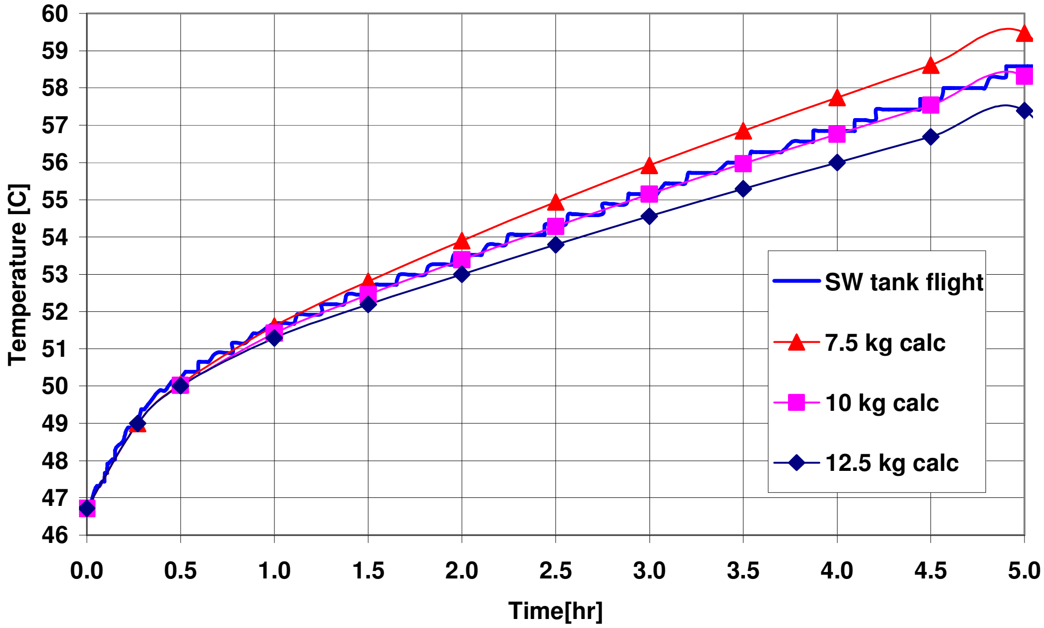


Figure 7. Representative results – calculated vs. flight data

Comparison fuel estimation done by book-keeping and PGS method is given in Table 1 for Anik E1 and E2

Table 1 Book keeping vs. PGS fuel estimation for Anik E1 and E2

PGS test #	Date	Book keeping	PGS	Delta
		Anik E1		
4	Dec 14/01	73.4kg	75.5kg	+2.1kg
5	May 8/02	58.0kg	59.5kg	+1.5kg
6	Aug 22/02	43.5kg	48.0kg	+4.5kg
7	Oct 23/02	38.7kg	39.0kg	+0.3kg
8	Feb 20/03	24.9kg	23.5kg	-1.4kg
9	Apr 24/03	23.3kg	21.5kg	-1.8kg
The average result for Anik E1 PGS is 0.9kg above bookkeeping.				
		Anik E2		
7	May 16/02	47.6kg	52.2kg	+4.4kg
8	Aug 21/02	37.0kg	44.0kg	+7.0kg
9	Oct 17/02	34.9kg	41.0kg	+6.1kg
10	Feb 24/03	22.5kg	27.5kg	+5.0kg
11	Apr 14/03	22.1kg	27.5kg	+5.4kg
The average result for Anik E2 PGS is 5.6 kg above bookkeeping.				

Data in Table 1 indicates that the book keeping and PGS methods predict very close results. The PGS method estimations are above the book keeping ones for the most cases.
Analysis has shown that at 10 kg of fuel level, the PGS provides about fuel uncertainty of ± 0.56 kg., which constitutes ±5% of fuel remaining.

Anik E Operations

Both the Anik Es have had major anomalies that hamper operations. Anik E1 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 augmented mode. This mode sources power through the batteries to augmentation heaters in the thrusters to increase Isp. Anik E2 has lost the use of its' momentum wheels and is a truly zero momentum satellite. Attitude control was performed using the magnetic torquers and thrusters. This method is extremely sensitive to helium bubbles in the propellant lines.

Propellant Tank System:

The Anik E propellant tank system uses four inter-connected tanks with no isolating latch valves. There are three heater sets that provide thermal control of the propellant tanks. There is a primary and back-up Differential Heater Control (DHC) system and a thermostatic heater control system. The DHC system maintains all four tank temperatures to within 2℃ of each other, as well as providing thermostatic control to maintain a minimum tank temperature of 13℃. The thermostatic system maintains minimum tank temperatures but does not provide differential control. There is no ground control over these two systems aside from enabling them. There is ground override command capability on the back-up heater patches for each tank. There are two temperature sensors per tank. The Anik Es up until the implementation of the control method described in this paper operated using the primary DHCs.

On the Anik E's propellant usage was tracked by book-keeping method, basically inputting maneuvers times into a thruster model to determine fuel used for that maneuver and doing so for every maneuver. As EOL approached, Telesat looked for alternative methods to verify bookkeeping results. Lockheed-Martin recommended a thermal propellant gauging technique described elsewhere in this paper.

The thermal gauging test results correlated well with the book-keeping fuel masses. However, the fuel was not equally distributed between the four fuel tanks, with at least one relatively empty tank on each satellite. If left in such a state, a tank would prematurely empty and introduce large amounts of helium into the propellant lines. This would make maneuvers, especially on Anik E2, very difficult to control with large attitude transients. The result would have an unacceptably earlier end of life and satellite de-orbiting.

Differential Heating Set-up

A short series of tests were performed on both Anik E satellites to determine the health of the back-up heaters, which had been unused for almost 10 years. All the thermal components were healthy; however, the pressure sensors were not, so a pressure crosscheck with thermal gauging was not possible. Nevertheless, the basic components for thermal propellant gauging and differential temperature fuel balancing were available, namely, commandable tank heater patches and functioning tank temperature sensors.

The series 5000 bus has very limited on-board processing capabilities as compared to the current generation spacecraft. The on-board processor's functions are for attitude and station-keeping maneuver control. Therefore, thermal gauging and differential heating algorithms were developed to run on ground computers using temperature and heater status as inputs and heater commands as outputs.

Three of the four tanks maintain a temperature differential to the fourth tank (reference tank) for reasons described earlier. The fourth tank was originally hard coded to be the South-East tank as all measurements for both E1 and E2 pointed to that tank being 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 different to accommodate mass differences for each tank, as well as to account for seasonal variations.

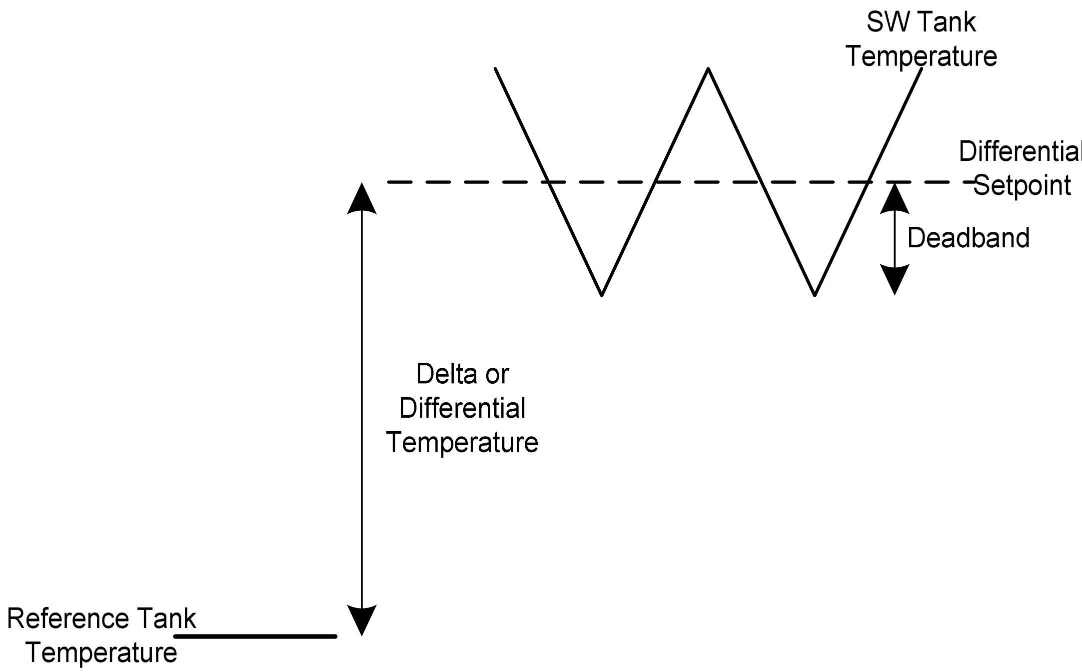


Figure 8. Temperature differential operation

There is as well a thermostatic routine to ensure that individual tank temperatures are maintained above a designated user selectable minimum temperature. As data in Fig. 8 indicates, the thermostatic routine operates on the reference tank, since it is by definition the coldest tank. This control was for E1 as E2 is a much warmer satellite with warmer tanks

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 test. As described earlier, this minimizes fuel movement during the gauging test.

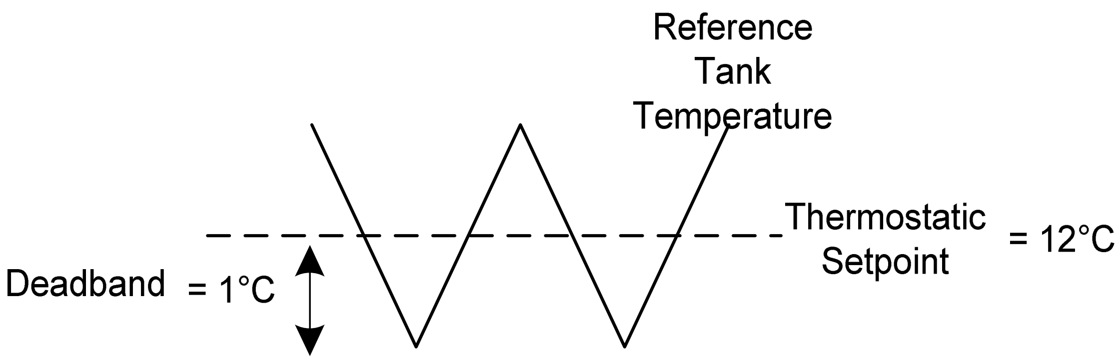


Figure 9. Temperature deadband control

The user can control program on/off, commanding on/off, choice of reference tank, setpoints and deadbands via a GUI as illustrated in the Figure 9.

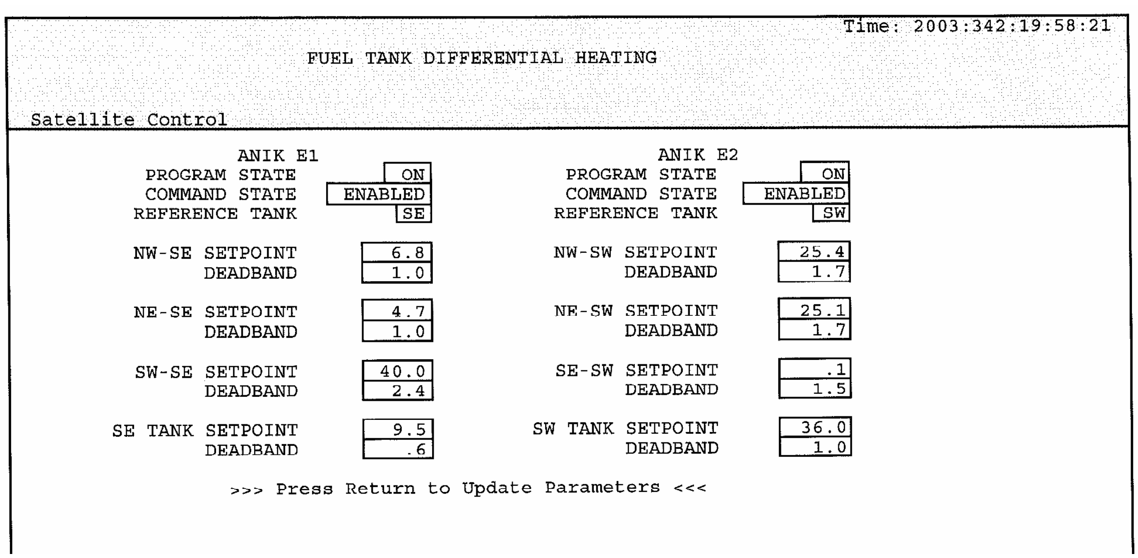


Figure 10. Display for tank differential heating

Another display shows all tank temperatures, differential temperatures and heater status.

Time: 2003:342:19:58:38

220 - FUEL TANK DIFF HEATING
Satellite Control

SAT/RTM/ASP/MODE	E1/1/1/00/C	E1/2/1/00/C	E2/1/1/00/C	E2/2/1/00/C
DAY/TIME (2003)	342:19:58:26	342:19:58:28	342:19:58:28	342:19:58:30
DIFF HEATING STATE	ON	ON	ON	ON
DIFF HEATING CMD	ENABLED	ENABLED	ENABLED	ENABLED
TANK TEMPERATURES				
NORTH WEST	39.0	38.6	60.1	60.9
NORTH EAST	37.0	37.0	60.2	59.5
SOUTH WEST	74.9	75.9	35.2	35.2
SOUTH EAST	32.7	32.7	43.1	43.5
DELTA TEMPERATURES				
NW-SE (NW-SE)	6.2	5.8	24.9	25.7
NE-SE (NE-SE)	4.3	4.3	25.0	24.3
SW-SE (SW-SE)	42.1	43.2	7.9	8.4
TANK HEATER ON/OFF STATUS				
NORTH WEST	OFF	OFF	ON	ON
NORTH EAST	OFF	OFF	OFF	OFF
SOUTH WEST	ON	ON	OFF	OFF
SOUTH EAST	OFF	OFF	OFF	OFF

Figure 11. Operational Display

Operational Constraints

The number of times the heater relays are cycled was tracked and counted . The relays are mechanical relays and thus have a qualification limit for on/off cycles. Due to the way maneuvers are handled in our operating system, the differential heating software is partially disabled (no automated commanding) during all maneuvers. Requests for heater commands appear on a screen and controllers need to action them manually. Fortunately, heater duty cycles are low; therefore few heater commands are required during a typical maneuver.

Life Extension

Our estimate is that we delayed inclined service operations approximately 6 months by implementing differential heating of the propellant tanks. It also took about 6 months from the start of initial thermal propellant gauging activities to operational implementation of the differential heating software. This achievement was the result of significant effort and corroboration between Telesat and Lockheed-Martin.

Conclusion

Thermal Propellant Gauging System is a powerful tool helping to operate a spacecraft, extend the spacecraft mission and bring the mission to a successful end. PGS is capable of determining a fuel load distribution between connected tanks. Thermal pumping along with developed software were able to balance the tank loads and to conduct propellant gauging with a significant safety margin without depletion of a tank during PGS test.

The two satellites completed their nominal mission life and entered inclined service July 2003. That they were able to do so is a testament to Telesat operations personnel and Lockheed-Martin customer support group

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