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On-Orbit Propellant Estimation, Management, and Conditioning for the THEMIS Spacecraft Constellation

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Proper propellant usage is vital to ensure successful completion of initial spacecraft mission goals and to create viable mission extension options. Opportunities exist for spacecraft operators to contribute in this area through the methods that they use to estimate fuel mass, manage its distribution throughout the propellant tanks, and thermally condition it for desired ΔV performance. In this paper, on-orbit propellant estimation, management, and conditioning are described for the THEMIS spacecraft constellation, which investigates magnetospheric phenomena leading to the aurora borealis. THEMIS is a NASA Medium-class Explorer mission comprised of five spacecraft currently making use of fuel reserves left over from its primary mission to execute an ambitious two part mission extension—THEMIS-Low and ARTEMIS. THEMIS-Low comprises the continuation of the original THEMIS mission with the inner three spacecraft flying in a closer formation, while ARTEMIS includes low energy transfers of two of the spacecraft into lunar orbit via two Earth-Moon libration points. Current results are provided from an ongoing nonlinear regression analysis to estimate the fuel mass through the fuel's thermal response to tank heaters. Additionally, propellant management operations for all spacecraft are summarized and the authors evaluate the potential for improved ΔV performance through propellant thermal conditioning. Finally, lessons learned from nominal and extended THEMIS mission operations are highlighted with an emphasis on improving on-orbit propellant estimation, management, and conditioning in future spacecraft operations.

Nomenclature

α = angle between the sun and horizontal spacecraft body plane
β = scaling parameter for heat loss from fuel tank during a fuel tank heater cycle
σ = standard deviation
Δx = change in variable x
ϕ = phasing parameter for the solar energy input
A = scaling parameter for heat input from tank heaters
B = scaling parameter for solar energy input
C = scaling parameter for energy input from earth
c_v = fuel specific heat capacity at a constant volume
D = scaling parameter for heat transfer from fuel tank wall to fuel while heater is off
I_{SP} = specific impulse
kg = kilograms
kPa = kilopascals
m_f = fuel mass
Q_x = fuel tank heat input or loss from source x
T = temperature
t = time
V = Velocity

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I. Introduction

THE effective use of propellant on spacecraft is a driving force in mission success and the realization of mission extension accomplishments. To use propellant effectively, it is beneficial to have accurate knowledge of the mass of remaining propellant, to maintain a balance in the distribution of propellant throughout the spacecraft, and to thermally condition the propellant to prevent freezing and increase ΔV performance. Throughout the history of spaceflight, operators have helped to achieve many desirable primary and extended mission outcomes in part through their efforts in propellant mass estimation, management, and conditioning. However, as exemplified by the conclusion to NASA's Polar Mission—after a decade of extended mission operations, the spacecraft experienced an uncommanded shutdown of the reaction control system during a maneuver due to uncertainties in the instantaneous fuel load[*]—opportunities exist for improvement in this area.

In this paper, the authors describe on-orbit propellant estimation, management, and conditioning for the THEMIS (Time History of Events and Macroscale Interactions during Substorms) spacecraft constellation and highlight lessons learned for the benefit of future spacecraft missions. Propellant mass estimation techniques are described and current results are provided from an ongoing nonlinear regression analysis to estimate the fuel mass through the fuel's thermal response to tank heaters. Additionally, the details of propellant management operations, such as fuel tank repressurization and mass balancing, for all spacecraft are summarized. Next, fuel tank heater operations are discussed and evaluated for the potential for improved ΔV performance through greater operator control over propellant thermal conditioning.

The THEMIS Spacecraft Constellation

The five-spacecraft THEMIS constellation was launched in February 2007 and is operated from a highly automated multi-mission control center at the University of California, Berkeley.[1-3] Its primary mission—funded and managed by the NASA Medium-Class Explorer Program at the Goddard Spaceflight Center—was to study magnetospheric phenomena leading to the aurora borealis.[4] During the primary mission phase, which was completed in the summer of 2009, all five spacecraft collected science data in synchronized, highly elliptical Earth orbits.[5] The primary mission was completed with fuel reserves ranging from an estimated 14.5 kg—out of an initial load of 48.8 kg—on the outermost spacecraft (THEMIS B) to 27.5 kg on one of the innermost spacecraft (THEMIS E), thus creating the possibility for an ambitious mission extension where the constellation could be split into two parts in order to execute two extended mission campaigns—THEMIS-Low and ARTEMIS (Acceleration, Reconnection, Turbulence, and Electrodynamics of Moon's Interaction with the Sun).

THEMIS-Low includes the three spacecraft on the innermost orbits (i.e., THEMIS A, THEMIS D, and THEMIS E), continuing their study of the magnetosphere in a tighter formation. ARTEMIS involves transferring the outer two spacecraft, THEMIS B and THEMIS C, from their Earth orbits with four and two-day periods, respectively, to lunar orbits where these two spacecraft will conduct measurements of the interaction of the Moon with the solar wind and its crustal magnetic fields. To accomplish this transfer to lunar orbit on the leftover fuel reserves, the spacecraft were sent on complex trajectories—primarily designed by engineers at NASA's Jet Propulsion Laboratory—that include sequences of apogee raising maneuvers and lunar flybys.[6,7] Also included in the trajectories are the first ever attempts to position spacecraft in orbit around two of the three collinear earth-moon libration points[8], which have been identified as potential hubs for future space exploration activities[9].

Maneuvers for ARTEMIS began in July 2009 and maneuvers for THEMIS-Low began in January 2010. As of this writing, the three innermost spacecraft have been repositioned for THEMIS-Low science data collection and both ARTEMIS spacecraft are well on their way to libration point orbit insertion. THEMIS B has completed its apogee raising maneuver sequence and three lunar flybys while THEMIS C has finished its apogee raising maneuver sequence and is approaching its first lunar flyby.

The THEMIS Reaction Control System

The design of the monopropellant reaction control systems onboard each spin-stabilized THEMIS spacecraft is depicted in Fig. 1. The fuel, hydrazine (N_2H_4), is stored in two tanks linked upstream of the fuel flow through a valve-less ullage line and downstream of the fuel flow through a valved fuel line. The fuel pressurant, gaseous helium (GHe), is stored in one Composite Over-wrapped Pressure Vessel (COPV) linked to the ullage line between the fuel tanks through a one-shot, pyro-actuated valve and pair of solenoid isolation valves. During a thrust

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[*] Layton, L., "'Broken Heart' Image the Last for NASA's Long-Lived Polar Mission," URL: http://www.nasa.gov/topics/earth/features/polar_heart.html [cited 1 February 2010].

operation, fuel from the two tanks combines downstream of two latch valves near each tank exit—if they are both open—and passes through an orifice on its way out of the thrusters in use. The body-mounted thrusters—two are pointed to thrust along the spin axis (i.e., axial thrusters, A1 and A2) and the other two are pointed to thrust transverse to the spin axis (i.e., side thrusters, T1 and T2)—each have valves and catalyst beds to control the flow of fuel and induce an energy release from it.

To keep the propellant from freezing, electrical heaters are located on the fuel tanks, fuel lines, and thruster catalyst beds. The fuel tank and fuel line heaters are primarily controlled by thermostats on the spacecraft—they cannot be turned on by operators, but operators can shut them off through a workaround in which they temporarily disable one of the heater service buses. The catalyst bed heaters are controlled through operator commanding.

Two pressure transducers, one on the pressurant side of the pyro and isolation valves and one on the fuel side, measure the pressurant and fuel tank pressures, respectively. The temperature for each fuel tank is measured by the thermostat that controls the fuel tank heaters and temperature sensors on the helium (i.e., gas) and hydrazine (i.e., liquid) sides of the tanks. Data from the gas and liquid temperature sensors are included in the telemetry whereas data from the thermostat that controls the fuel tank heaters is neither recorded nor downlinked to earth.

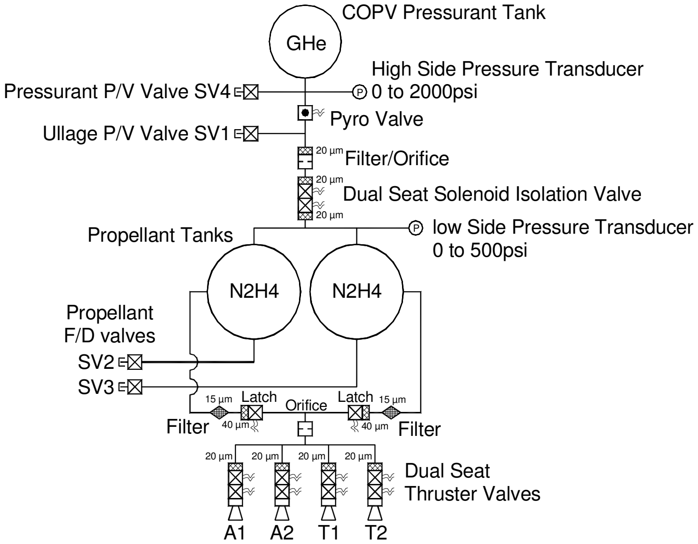

Figure 1. THEMIS Reaction Control System Schematic[10].

For further information on the THEMIS spacecraft reaction control system, see Ref. 10.

II. Propellant Estimation

Propellant estimation affects planning for primary and extended missions. If on-orbit estimates of the remaining fuel reserves are overly conservative, primary and extended mission goals may be scaled back or they may not be attempted at all. Conversely, if on-orbit fuel reserves are overly optimistic, operators may be tempted to engage in wasteful fuel management practices and the spacecraft may run out of fuel before operators can properly dispose of it. Furthermore, poor estimates of the total remaining propellant mass can introduce errors in maneuver analysis and long term propagation of the spacecraft orbits.

The amount of propellant remaining on board a spacecraft is typically estimated through some combination of three methods: propellant bookkeeping, pressure-volume-temperature (PVT) analysis, and thermal gauging.[11,12] All three of these methods are being used to varying extents in the operation of the THEMIS spacecraft constellation and are described in this section.

A. Propellant Bookkeeping

Propellant bookkeeping methods keep track of propellant mass by estimating propellant usage during each maneuver and subtracting that estimate from the estimated pre-maneuver propellant reserves. This type of propellant estimation method has been the leading method used throughout the primary mission and early mission extension phase of the THEMIS mission. Estimates for the mass usage during maneuvers are generated through the General Maneuver (GMAN) software package[13] developed by the Computer Sciences Corporation for the NASA Goddard Spaceflight Center. After each maneuver, telemetry data on the fuel tank temperature and pressure along with thruster ignition times are fed into GMAN so that it can reconstruct the maneuver conditions and generate a propellant mass usage estimate.

The largest drawbacks to propellant bookkeeping methods are errors in both the initial propellant mass estimate and mass usage estimates for each maneuver. In the best of situations, the mass usage estimate errors would not be systematic and would cancel out over time. However, systematic errors do occur and can lead to a decrease in the accuracy of the estimates over time. For example, fuel usage models may require a calibration process that does not mature until many thrust operations have occurred and by that time, the calibration results themselves may have been affected by the accumulated mass estimate errors.

As the primary mission of the THEMIS constellation came to a close, the accuracy of the bookkeeping method used for the THEMIS constellation was brought into question due to several issues. First, GMAN uses a polynomial fit for the relationship between pressure and I_{SP}, rather than the actual function for this relationship that was provided by the thruster manufacturers. Second, it was determined through an intensive thruster efficiency calibration effort[14] that the thrust scale factor input into GMAN for almost all maneuvers conducted in the primary mission phase was too large. This factor affects GMAN's mass usage estimates and the fact that it was consistently higher than it should have been most likely biased fuel usage estimates to larger values than they should have been. Finally, operators discovered that nearly all maneuver reconstructions in the primary mission phase used fuel tank temperature telemetry—instead of fuel tank pressure telemetry—to determine fuel tank pressure through a PVT relationship. These issues inspired operators to investigate the alternative approaches for fuel mass estimation described in the next two subsections.

B. Pressure-Volume-Temperature Analysis

A second method commonly used to estimate propellant mass on board a spacecraft involves using on-orbit propellant tank temperature and pressure measurements along with knowledge of the total propellant storage volume to produce the estimate. For the THEMIS spacecraft constellation, software utilizing Redlich-Kwong equations to characterize propellant PVT and mass relationships was developed and used throughout the early stages of the mission to predict propellant pressure at given temperatures for maneuver planning. However, it was not until the end of primary mission phase that this software—and some newly written data mining software—were first used to estimate the on-orbit propellant mass in response to concerns over the long-term accuracy of the GMAN (i.e., bookkeeping) estimates.

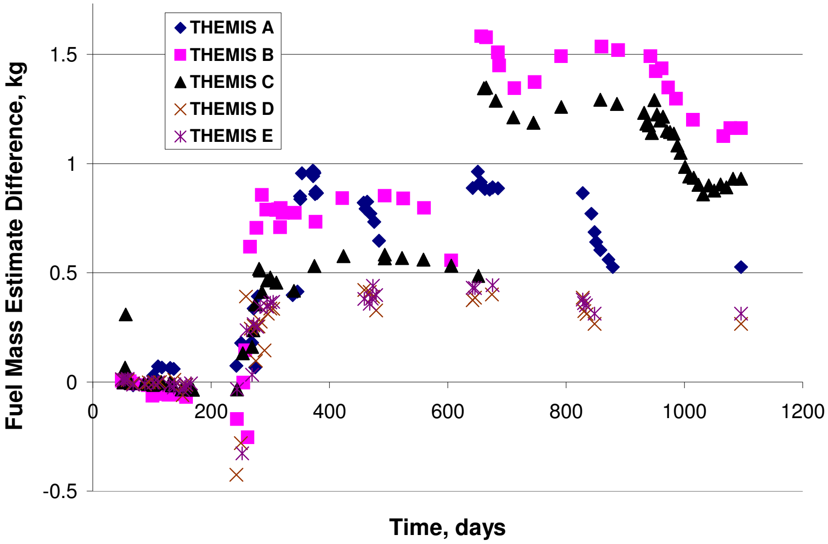

Figure 2. The difference between GMAN and PVT fuel mass estimates prior to Jan. 1, 2010.

As shown in Fig. 2, the bookkeeping approach suggests that the fuel mass remaining on all spacecraft is less than what the PVT analysis would suggest. Moreover, the discrepancy between the estimates tended to grow as fuel usage increased; for the spacecraft that had consumed the most fuel, the difference was larger than one kilogram. In other words, the PVT analysis suggests that GMAN is systematically overestimating fuel usage, probably due to discrepancies in the pressure-I_{SP} relationship and the way that it is approximated in GMAN and to the fact that the thrust scale factors used in almost all of the maneuver reconstructions during the primary mission were too large.

C. Thermal Gauging

A third approach to estimating the propellant mass involves using on-orbit propellant tank temperature measurements during tank heater operations to determine the thermal inertia of the propellant tank, which is related to the mass of propellant in the tank. As stated in Ref. 11 and Ref. 12, thermal gauging offers two main advantages over bookkeeping and PVT estimation near the end of spacecraft's operational life:

1) The accuracy of thermal gauging increases as the propellant reserves deplete whereas the accuracy of bookkeeping and PVT estimation decreases as propellant reserves deplete. This difference is due to the accumulation of bookkeeping errors over time and the decrease in tank pressure over time—conversely, the thermal response of the propellant tank increases as fuel reserves deplete.
2) Thermal gauging allows estimation of propellant mass in individual tanks whereas bookkeeping and PVT analyses only provide estimates for all of the tanks (unless the tanks are isolated from each other).

Attempts to estimate propellant mass in this manner began in the final months of the primary mission phase in order to conduct an independent validation of bookkeeping and PVT estimates. The specific approach used differs from others described in the literature[11,12,15,16] and is the most "homegrown" of the propellant estimation techniques used for the THEMIS spacecraft constellation. Thus, it is described below in more detail than the other propellant estimation approaches.

1. *Thermal Gauging Data Collection and Processing*

Because the electrical heaters on the fuel tanks cannot be turned on manually by spacecraft operators, it was not possible to conduct controlled fuel tank heating experiments. However, over 1,100 full tank heater cycles[†] occurred in the ten propellant tanks in the spacecraft constellation between the launch date and January 1, 2010. Each of these cycles provided an opportunity to observe the change in fuel tank temperature resulting from a given heat input and were thus investigated for inclusion in the thermal gauging data set. A custom MATLAB user interface was created for manually identifying thermal cycle start and stop times, the tank temperatures at the start and stop times, and the total heater on time during each cycle. After the cycles were identified through the interface, the spacecraft and sun position coordinates at the beginning of the heater cycle were then extracted from data archives to determine sun-spacecraft and earth-spacecraft distances and the angle between the sun and spacecraft as observed from earth. Then, each thermal cycle was examined using the Berkeley Trending Analysis and Plotting System (BTAPS)[2,3,17] to determine if spacecraft events that could affect the propellant tank temperature had occurred during the cycle. Data from thermal cycles that coincided with maneuvers, eclipses, and the heating of both fuel tanks at the same time were removed from the data set.

2. *Formulation of the Thermal Gauging Function*

Formulation of the thermal gauging function used for mass estimation began with a simple energy balance for a closed, constant volume fuel system in which no work is being conducted on the fuel.

$$Q_{heater} + Q_{Sun} + Q_{Earth} - Q_{loss} = m_f c_v \Delta T \tag{1}$$

Where the heat inputs from the heater, Sun, and Earth, respectively were assumed to be: constant, a function of normalized sun-spacecraft distance (ℓ) and sun angle (α), and a function of normalized spacecraft altitude over the earth at the beginning of the heater cycle (h).

$$Q_{heater} = A\Delta t \tag{2}$$

$$Q_{Sun} = \frac{B}{\ell^2}\sin(\alpha + \phi)\Delta t \tag{3}$$

$$Q_{Earth} = \frac{C}{h^2}\Delta t \tag{4}$$

Similarly, the heat loss was assumed to be constant.

$$Q_{loss} = \beta\Delta t \tag{5}$$

Dividing both sides of Eq. (1) by Δt, m_f, and c_v; absorbing c_v into parameters A, B, C, and β; and then absorbing β into A yielded Eq. (6).

[†] By convention, a fuel tank heater cycle starts when a tank heater first perturbs a relative thermal equilibrium between the fuel tank walls and the fuel and ends at the last instant that the heater is on before the fuel tank walls and fuel return a relative thermal equilibrium state.

$$\frac{A + \frac{B}{\ell^2}\sin(\alpha + \phi) + \frac{C}{h^2}}{m_f} = \frac{\Delta T}{\Delta t} \tag{6}$$

The right-hand side of Eq. (6) defines the fuel warm up slope for a heater cycle in which the heater remains on for time, Δt. However, as explained in section 4, the fuel tank heaters used on the THEMIS constellation were often turned off and allowed to turn back on repeatedly during heater cycles to prevent localized heating of the dry side of the fuel tank walls. Thus, it is beneficial to define a warm up slope (S_W) as characterized by Eq. (7) where t_{off} is the total time that the heaters were turned off during a cycle.

$$S_W = \frac{\Delta T}{\left(\Delta t - t_{off}\right)} \tag{7}$$

Additionally, it was necessary to include heat transferred into and out of the fuel when the heaters are off into Eq. (2).

$$Q_{heater} = A(\Delta t - t_{off}) + Dt_{off} \tag{8}$$

Plugging Eq. (8) into the process that led to Eq. (6) then yielded the thermal gauging function, Eq. (9).

$$S_W = \frac{A + \frac{B}{\ell^2}\sin(\alpha + \phi) + \frac{C}{h^2}}{m_f} + \frac{\left(D + \frac{B}{\ell^2}\sin(\alpha + \phi) + \frac{C}{h^2}\right)t_{off}}{m_f\left(\Delta t - t_{off}\right)} \tag{9}$$

With parameter estimates and measured values of S_W, α, ℓ, h, t_{off}, and Δt one can multiple both sides of Eq. (9) by m_f and divide both sides by S_W to solve for m_f.

3. Parameter Estimation for the Thermal Gauging Function

In order to estimate the parameters of Eq. (9), a custom Monte Carlo fitting routine is used. The user inputs measurements for all measured variables in Eq. (9), mass estimates at each measurement time, and a range of possible parameter values, and the routine then conducts 100,000 random iterations on the parameter values. The routine then reports the best parameter values corresponding to each of the following curve fitting statistics: the mean squared error and its three components (i.e., bias, unequal variation, and unequal covariation)[18-20]. The user then selects a set of parameters or repeats the routine with a new set of ranges for the parameter values. Figures 3 and 4, respectively, show an example S_W curve fit for one tank in the constellation and the point-by-point difference in the input mass and estimated mass.

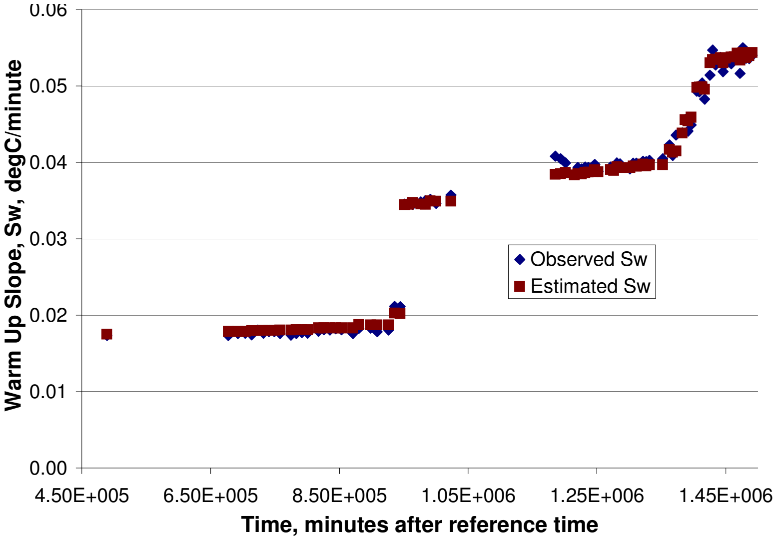

Figure 3. The measured and estimated S_W for THEMIS B Tank 1 using PVT mass inputs.

4. Using Thermal Gauging for Validation of Other Propellant Estimation Techniques

Because the thermal gauging technique used requires an a priori mass estimate, one use for it is in the validation of the other propellant estimation techniques. When the mass estimates from bookkeeping or PVT analysis are used in the parameter estimation routine, the resulting curve fits provide an indication of the relative accuracy of the estimation techniques. For instance, if a point-by-point comparison of thermal gauging mass estimates and bookkeeping mass estimates yields worse results than a point-by-point comparison of thermal gauging and PVT mass estimates, then one would have reason to place more confidence in the PVT mass estimates.

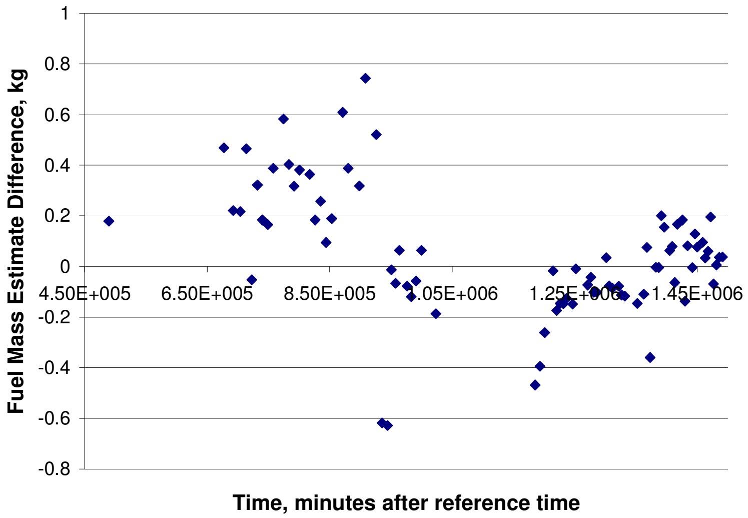

Figure 4. The difference between the PVT and Thermal Gauging Fuel Mass estimate for THEMIS B Tank 1.

Tables 1 and 2 contain summaries of thermal gauging function parameter values and fit statistics for the constellation using GMAN (i.e., bookkeeping) and PVT mass inputs, respectively. The data set summarized in these tables includes 75, 95, 63, 87, and 80 data points for THEMIS A through THEMIS E, respectively. Overall, the bias and unequal variation—the error components most often associated with systematic errors—of the fits for the spacecraft comprise a small fraction of the mean squared error[‡]. The best fits in terms of standard deviation of the mass differences occur on THEMIS B and THEMIS C, probably due to the fact that they are the spacecraft that have consumed the most fuel in the constellation. Moreover, the fits for these spacecraft using the PVT mass estimates are better than those using the GMAN mass estimates, suggesting that the PVT mass estimates are better than the GMAN mass estimates for these spacecraft. The same cannot be said for the fits for the other spacecraft, but it should be noted that the standard deviation of the fitted estimates for those spacecraft is larger than or very close to the average magnitude of the difference between the GMAN and PVT estimates—by comparison, the average magnitudes of the difference between the GMAN and PVT estimates for THEMIS B and THEMIS C are nearly as large of three standard deviations of the fitted estimates for THEMIS B and THEMIS C. Thus, a low degree of confidence should be assigned to inferences based on the relative quality of the fits for those spacecraft. However, if these spacecraft behave like THEMIS B and THEMIS C as they deplete more of their fuel mass, then the standard deviation should decrease and make inferences based on comparison of the fits more convincing.

Thus as of this writing, the available data allows for validation of the discrepancy between GMAN and PVT estimates for THEMIS B and THEMIS C through thermal gauging. As the mission extension progresses, results for these and the other spacecraft should improve due to convergence of the parameter estimation process as more data becomes available and long-term divergence of the GMAN and PVT estimates as more fuel is used.

[‡] Though the bias (U^M) of the curve fit for THEMIS C is significantly higher than that of the others, it is expected to converge to a near-zero value as more data is collected. The bias is believed to be due to the significant fuel usage (and as a result, the significant increase in S_W) that recently occurred during its apogee raising maneuver sequence, which was much more extensive than the apogee raising maneuver sequence for THEMIS B. As of this writing, the data set is heavily weighted towards data prior to the apogee raising maneuver sequence and thus, the THEMIS C curve fit currently does not account for behavior throughout all of its flight regimes as well as the curve fits for the other spacecraft do for their applicable flight regimes.

Table 1. Summary of Fuel Tank 1 Thermal Gauging Parameters and Fit Statistics using GMAN Mass Input.

THEMIS SPACECRAFT	**A**	**B**	**C**	**D**	**E**
A	0.2594	0.2839	0.2853	0.2629	0.2918
B	0.0158	0.0199	0.0136	0.1813	0.0254
C	0.0406	0.1279	0.0155	0.0146	0.0598
D	0.0415	0.0297	0.0274	0.0283	0.0525
ϕ	-38.5677	-83.9239	-51.2340	-92.9626	-82.3285
Mean Squared Error (ºC/Minute)^2	2.47x10^{-7}	9.82x10^{-7}	3.69x10^{-7}	2.55x10^{-7}	3.03x10^{-7}
Mean Absolute Error/Average Observed S_W	0.0177	0.0206	0.0140	0.0209	0.0221
Bias (U^M)	0.0015	0.0218	0.0065	0.0102	0.0031
Unequal Variation (U^S)	3.0x10^{-5}	0.0115	0.0870	0.0098	0.0024
Unequal Covariation (U^C)	0.9985	0.9666	0.9064	0.9780	0.9945
Average Fuel Mass Estimate Difference (kg)	-0.0406	0.0461	-0.0064	-0.0346	-0.0254
σ Fuel Mass Estimate Difference (kg)	0.5163	0.2810	0.2730	0.3950	0.4181
Average Magnitude of GMAN-PVT Estimate Difference (kg)	0.5500	0.7496	0.6470	0.2101	0.2039

Table 2. Summary of Fuel Tank 1 Thermal Gauging Parameters and Fit Statistics using PVT Mass Input.

THEMIS SPACECRAFT	**A**	**B**	**C**	**D**	**E**
A	0.2944	0.2671	0.2938	0.2656	0.2637
B	0.0413	0.0133	0.0168	0.0374	0.0145
C	0.1121	0.2014	0.0418	0.0149	0.0320
D	0.0721	0.0178	0.0422	0.0305	0.0227
ϕ	-76.3535	25.4728	-78.5460	35.0948	28.5796
Mean Square Error (ºC/Minute)^2	3.33x10^{-7}	6.99x10^{-7}	2.64x10^{-7}	2.57x10^{-7}	3.07x10^{-7}
Mean Absolute Error/Average Observed S_W	0.0229	0.0173	0.0124	0.0214	0.0231
U^M	0.0031	3.0x10^{-5}	0.0178	0.0034	0.0006
U^S	0.0122	0.0075	0.0512	0.0068	0.0052
U^C	0.9847	0.9925	0.9310	0.9898	0.9942
Average Fuel Mass Estimate Difference (kg)	-0.0542	0.0490	-0.0583	0.0152	0.0076
σ Fuel Mass Estimate Difference (kg)	0.5406	0.2393	0.2348	0.3920	0.4182
Average Magnitude of GMAN-PVT Estimate Difference (kg)	0.5500	0.7496	0.6470	0.2101	0.2039

5. *Using Thermal Gauging for Propellant Mass Estimation*

Thermal gauging can also be used as a primary means for creating propellant mass estimates once a model of the propellant's thermal response to heater inputs has been validated with flight data. However, it is unclear whether thermal gauging will eventually become the primary means of propellant estimation for the THEMIS spacecraft constellation. The current formulation of the thermal gauging function requires a priori estimates of the fuel mass for parameter estimation and thus, errors in the a priori estimates will carry over into errors in the parameter estimates. Furthermore, due to the lack of operator control over the start of tank heater cycles, it is impossible to conduct controlled experiments for parameter estimation and attempts to validate the parameters by examining long periods in which the fuel mass remained constant have yet to yield enough of a degree of confidence in the parameter estimates to supplant the use of bookkeeping mass estimates for maneuver planning. That said, as suggested in Ref. 11 and the fit statistics in Tables 1 and 2, the accuracy of thermal gauging is improving as fuel mass is being depleted.

Propellant Estimation Lessons Learned

When spacecraft operators and designers look to develop and implement propellant estimation strategies for future missions, they can apply several lessons from the THEMIS/ARTEMIS propellant estimation experience. These lessons are not necessarily mutually exclusive:

1) Multiple approaches to propellant estimation should be implemented from the beginning of the mission and reevaluated periodically and whenever a weakness is discovered in any one of the approaches. While the use of only one approach during the primary mission phase was adequate to complete of the primary mission goals, the goals of the extended mission necessitated additional approaches and the operations team was left to formulate these approaches as they worked through the operations intensive early stage of the mission extension.
2) On/off control of propellant tank heaters would allow operators to conduct controlled experiments on the thermal response of the propellant to given heat loads in order to estimate parameter values for a propellant mass estimation function. Using the thermal gauging function for fuel mass estimates requires a high degree of confidence in the estimation of its parameters, and it is unclear whether it will be possible to build that confidence through review of the flight data alone.
3) If there are factors in the models used for propellant estimation that require extensive amounts of in-flight data for calibration, a plan and, if possible, utilities should be put in place to gradually improve future estimates and revise old estimates as the data becomes available. As mentioned above, the GMAN bookkeeping method used for the THEMIS constellation was affected by thrust scale factor, which needed to be calibrated in flight, and by the time that the calibration had matured, mass estimation errors had accrued to a point where they could have affected the calibration results.

III. Propellant Management

The term propellant management, as used in this paper, refers to the operations conducted to ensure that spacecraft propellant is adequately pressurized and distributed throughout the spacecraft tanks. On the THEMIS spacecraft, the fuel was initially isolated from the pressurant and was allowed to depressurize from 3200 kPa down to as low as 600 kPa. In the autumn of 2007, the fuel tanks were repressurized by permanently opening the one-shot pyro valve and temporarily opening the solenoid isolation valves. Thereafter, the solenoid valves were temporary opened whenever a significant pressure difference accumulated between the pressurant tank and fuel tanks. All of these operations have gone as expected and have provided the operators with an early look at how the fuel system will perform as the fuel pressure drops back down to 600 kPa—as of this writing, the fuel pressures for the spacecraft range from 690 kPa to 1100 kPa.

Fuel balancing is achieved through spacecraft rotation as the absence of a check valve in the ullage line between the propellant tanks and the normally open operating state of the latch valves allows the fuel mass to roughly balance between the two tanks. While differences between the fuel tanks in distance from the center of mass, thermal loading, and surface tension are expected to create both transient and steady-state inequalities in the distribution of fuel mass in the tanks, no balancing actions such as those mentioned in Ref. 11, Ref. 15, and Ref. 16 are currently believed to be required. However, operators will continue to monitor the spacecraft's performance for signs of an imbalance, especially as the thermal gauging process described above matures. In the event that fuel balancing would be required, such an operation would have to be carried out by closing the latch valve on the exit of the tank with the least fuel during a maneuver.

IV. Propellant Conditioning

Thermal conditioning of the propellant on a spacecraft is necessary to prevent propellant freezing and can be used to improve maneuver performance. As mentioned above, the fuel tanks have electrical heaters that are controlled almost entirely by thermostats—operators can turn the heaters off through a workaround in which they temporarily disable one of the heater service buses, but they cannot turn on the heaters. These heaters are meant to keep the fuel from freezing and are triggered when the fuel tanks cool down to roughly 13ºC. In the initial phases of the mission, the heaters operated on a simple on/off duty cycle (i.e., they turned on and remained on until a desired fuel temperature was reached). However, after roughly 40 percent of the fuel mass had been consumed, the heaters were set to a one-third-on/two-thirds-off duty cycle (i.e., the heaters are turned off for twenty minutes after each ten minute interval of heater on-time). This measure was necessary to avoid localized overheating of the fuel tank walls as the amount of fuel present to absorb heat from the walls dwindled.

A. The Effects of Propellant Conditioning on Spacecraft Maneuver Planning

Propellant thermal conditioning affected maneuver planning in several important ways. First, fuel temperature is used in the planning process to predict fuel tank pressure at the maneuver time, and in GMAN, I_{SP} is modeled as a function of fuel pressure. Thus the maneuver ΔV predictions from GMAN, which were used to plan the thruster on-times, were dependent on how well the fuel tank temperature prediction matched the fuel tank temperatures at the time of the maneuver. Unfortunately, because the operators have no control over when the fuel tank heaters turned on and data from the thermostat that controls the heaters is not included in telemetry, accurate fuel tank temperature prediction proved to be problematic. Table 3 contains summary statistics for the fuel tank temperature prediction errors for maneuvers using the side thrusters and the corresponding errors in the planned maneuver ΔV's.

While these ΔV errors—which were typically on the order of cm/s—did not significantly hinder maneuver operations during the primary mission, they forced special precautions to be taken for some of the critical maneuvers of the ARTEMIS extended mission campaign. The ARTEMIS maneuver sequence up to lunar orbit insertion[6,7,8] is chaotic (i.e., successful navigation of it is very sensitive to initial conditions, perturbations, and maneuver errors) and thus errors on certain maneuvers on the order of cm/s were not tolerable. For these maneuvers, multiple maneuver plans, each using different temperature predictions and taking several hours to produce, had be made so that once the maneuver execution time arrived, the plan with the closest fuel temperature prediction could be executed.

Table 3. Temperature error and effect statistics for all pulsed sidethrust maneuvers prior to Feb. 9, 2010.

THEMIS SPACECRAFT	**A**	**B**	**C**	**D**	**E**
Number of Pulsed Sidethrust Maneuvers	31	34	63	22	26
Average Temperature Error (ºC)	0.024	-0.151	-0.357	-0.196	0.183
Average Magnitude of Temperature Error (ºC)	1.356	0.924	0.924	1.372	0.546
Magnitude of Maximum Temperature Error (ºC)	7.493	3.581	6.928	5.299	2.364
Average ΔV Error (m/s)	0.002	-0.003	-0.014	-0.026	0.007
Magnitude of Maximum ΔV Error (m/s)	0.276	0.118	0.635	0.499	0.132
Cumulative ΔV Error (m/s)	0.061	-0.093	-0.882	-0.543	0.163
Cumulative Magnitude of ΔV Error (m/s)	1.313	0.749	1.444	1.981	0.597
Cumulative Magnitude of ΔV Error as a % of Total Magnitude of ΔV Planned	0.452%	0.398%	0.369%	0.636%	0.205%

Another important effect of thermal conditioning on maneuver planning relates to spacecraft survivability as it passes through the shadows of planetary bodies. The ARTEMIS maneuver sequence for THEMIS C involves a long passage through the earth's shadow on March 21, 2010. During detailed design of the trajectory, it was discovered that the length of this passage would be longer than anticipated in the preliminary trajectory design[7] and not survivable for the spacecraft. Thus it was necessary during detailed design of the trajectory to allocate ΔV—from an already tight ΔV budget—for maneuvers to deflect the spacecraft's passage through the shadow. The amount of ΔV allocated for these maneuvers was a function of the amount of shadow time that the spacecraft could survive, and because operators could not control when the fuel tank heaters would turn on, the ΔV had be to allocated based on the assumption that the heaters would turn on at the worst possible time leading up to the eclipse.

B. Propellant Conditioning Lessons Learned

When spacecraft operators and designers look to develop and implement propellant conditioning strategies for future missions, they can apply several lessons from the THEMIS/ARTEMIS propellant conditioning experience. Once again, these lessons are not necessarily mutually exclusive:

1) Better on/off control of propellant tank heaters would help with maintaining safe propellant tank operating temperatures and would allow more accurate planning and execution of thrust maneuvers. Had the THEMIS spacecraft operators been able to control the initiation of tank heater cycles, they could have heated the fuel to a set temperature before each maneuver. Such pre-maneuver fuel conditioning would have improved maneuver performance by increasing the I_{SP}, reducing GMAN ΔV prediction errors, and making fuel temperature a controllable variable in the thruster calibration process. Additionally, operators could have improved spacecraft shadow survivability by heating the fuel prior to lengthy eclipses. Finally, the lack of on/off control of heaters introduced additional operational risks by forcing the operators to establish limited control over the heaters through a workaround in which they repeatedly disabled a subsystem bus that controlled spacecraft functions other than the fuel tank heater cycling.
2) Data from thermostats that control heaters, and other critical control system sensors, should be downlinked to earth whenever possible, especially when the control system is not controllable by operators. Data from the thermostats controlling the fuel tank heaters on the THEMIS spacecraft were neither recorded nor included in the spacecraft's telemetry stream and thus, operators were left to predict fuel tank heater cycles with data from temperature sensors mounted on different locations on the fuel tanks.

V. Conclusion

The THEMIS spacecraft have successfully accomplished their primary mission and are all in good shape for their extended mission campaigns. However, the THEMIS spacecraft constellation's experience with propellant estimation, management, and conditioning thus far leaves several lessons for spacecraft operators and designers to apply on future spaceflight missions. These lessons directly relate to the issues of operator control over spacecraft functionality and the in-flight analysis of spacecraft status and capability. While many of the lessons mentioned in this paper were primarily of concern to the THEMIS extended mission campaigns, they should not be taken lightly in the design and primary mission operation phases of future spacecraft missions. Complex, engineered systems, such as spacecraft, that successfully fulfill their mission are often repurposed for applications beyond those for which they were initially intended. Thus, these lessons, if nothing else, should be considered as examples of responses to the types of issues that can arise when—as is often the case—spacecraft that succeed in their intended mission are thrust into new applications.

Glossary

Propellant Estimation – the act of determining the amount of propellant (i.e., fuel and oxidizer) remaining onboard a spacecraft. The three methods that are generally employed for propellant estimation are propellant bookkeeping (i.e., estimating propellant usage during each maneuver and subtracting that amount from initial propellant mass estimates), pressure-volume-temperature analysis (i.e., using propellant system pressure and temperature telemetry to estimate mass through a pressure-volume-temperature relationship), and thermal gauging (i.e., approximating mass through analysis of propellant system temperature telemetry during given heat inputs).

Propellant Management – operations conducted to ensure that the propellant on a spacecraft is adequately pressurized and distributed throughout the spacecraft tanks. While most of these operations are conducted through use of the propellant system valves, certain propellant management objectives can be achieved through other actions, such as spacecraft rotation and propellant tank heating (i.e., thermal pumping). Consequences of poor propellant management include undesired movement of the spacecraft center of mass and inability to use propellant reserves near the end of the mission due to uneven depletion of the propellant tanks.

Propellant Conditioning – the heating or cooling of propellant to keep it from freezing or to change it to a desired temperature in preparation for a maneuver or other spacecraft event. The benefits of propellant conditioning during maneuver preparation, in particular, are increased maneuver performance and predictability.

Mean Squared Error – a metric for evaluating data curve fits derived from taking the mean of all curve fit errors (i.e., the differences between the observed data points and the corresponding points modeled by the curve) squared. This metric is often superior to the mean of the error because the squaring of each error term ensures that every term will have the same sign before it is averaged with the other terms. Furthermore, this curve fit metric can be broken down into three components identified by economist Henri Theil (i.e., bias, unequal variation, and unequal covariation) for further interpretation of the quality of the curve fit.

Bias (U^M) – the component of the mean squared error—as identified by economist Henri Theil—due to the difference in the mean of the observed data points and the mean of the points on the curve corresponding to the observed data points. The sum of U^M and Theil's other components of mean squared error (i.e., U^S and U^C) is unity, and a relatively high value of U^M often suggests that a systematic error in the curve formulation has offset the curve from the data trend.

Unequal Variation (U^S) – the component of the mean squared error—as identified by economist Henri Theil—due to the difference in the standard deviation of the observed data points and the standard deviation of the points on the curve corresponding to the observed data points. The sum of U^S and Theil's other components of mean squared error (i.e., U^M and U^C) is unity, and a relatively high value of U^S often suggests that a systematic error in the curve formulation prevents the curve from replicating cycles in the data trend or the overall range of data point values.

Unequal Covariation (U^C) – the component of the mean squared error—as identified by economist Henri Theil—due to the difference in the covariance of the observed data points and the points on the curve corresponding to the data points. The sum of U^C and Theil's other components of mean squared error (i.e., U^M and U^C) is unity, and a relatively high value of U^C could suggest a systematic phase offset of the curve from the data trend. However, it is more often due to unsystematic (i.e., random) deviations of the data point values from the curve values and thus it is usually desirable for most of the mean squared error to be due to U^C.

Mean Absolute Error – a metric for evaluating data curve fits derived from taking the average of the magnitudes of all curve fit errors. Like the mean squared error, this metric is often superior to the mean of the error because it ensures that every term will have the same sign before it is averaged with the other terms.

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