AIAA-2010-8712

Fuel Estimation for Stardust-NExT Mission

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The success of the Stardust-NExT (New Exploration of Tempel 1) mission, which is a follow-on to the Stardust primary mission, depends upon an accurate knowledge of its remaining fuel. Measurements indicate that delaying the arrival of Stardust at Tempel 1 by at least 8 hours will maximize the probability of reaching the objective. Several techniques are used to measure the amount of remaining propellant in spacecraft. Bookkeeping, PVT (Pressure, Volume, and Temperature) and thermal Propellant Gauging System (PGS) are the most popular methods. The PGS method uses the temperature response of the tank to heating in order to infer the propellant load of the tank. Implementation of the PGS method for the Stardust spacecraft is discussed in the current paper. Along with the propellant estimation, an uncertainty analysis was conducted. The current paper compares fuel estimates made for Stardust by several techniques, including bookkeeping, PVT, and thermal PGS. These methods are described in detail, and their results and uncertainties for Stardust are compared. Based on these fuel estimates, project scientists have made their recommendations for the time-of-arrival adjustment. This paper shows how the PGS method can be useful for existing and future NASA/JPL missions. The accuracy of the fuel estimation by the thermal PGS method increases as the fuel load decreases due to the increased sensitivity of the temperature rise as the tank load decreases. The method can be used for mono- or bi-propellant propulsion systems with one-tank or multiple-tank configurations. Execution of the PGS method does not require model calibration during spacecraft Thermo-Vacuum Test.

Nomenclature

F = mismatch function
T = flight temperature data
U = simulation temperature data
m = fuel mass
t_i = time of the i^{th} data point
i = data time sequence index

I. Introduction

A. Stardust

Stardust was the fourth mission in NASA's Discovery program and was launched on February 7, 1999. During its seven-year prime mission, Stardust performed an Earth Gravity Assist in January 2001, flew by the asteroid

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Annefrank in October 2002, collected dust particles from the comet Wild 2 in January 2004, and successful returned those particles to Earth in January 2006. Stardust was selected for an extended mission in April 2007 and was renamed Stardust-NExT (New Exploration of Tempel 1). Stardust-NExT will encounter the comet Tempel 1 on February 14, 2011.

Stardust is a three-axis-stabilized spacecraft using thrusters for attitude control and to perform Trajectory Control Maneuvers (TCM)s. This system consists of four primary and four secondary Reaction Control System (RCS) thrusters of about 1N thrust and likewise four primary and four secondary TCM thrusters of about 5N thrust. The thrusters act mainly along the –Z axis of the spacecraft with cant angles into the other axes to afford full three-axis control. The thrusters are divided into primary and redundant systems. A single-tank mono-propellant blowdown system was chosen for simplicity and reliability. This tank features a four-channel-type Propellant Management Device (PMD) designed to provide gas-free expulsion under acceleration on all axes. It was not designed to locate propellant or position it preferentially. The Stardust mission operations has worked around issues associated with the free-floating propellant and the uncoupled thrusters used.

After the primary mission was completed, about one quarter of the loaded propellant remained. This quantity was estimated from the tank pressure and temperature telemetry (knowing the tank pressure and temperature plus the tank volume, the remaining propellant volume and thus mass can be estimated – this is known as the PVT method). At the time of the start of the extended mission, the remaining propellant was estimated to be sufficient. As the mission has progressed, the remaining propellant has become the primary vehicle expendable. There were more potential demands for the remaining propellant than the resource could support, so an independent means of estimating the remaining propellant was sought so that the mission operations crew could confidently allocate the remaining propellant in such a manner as to maximize the chances of completing the mission.

B. Propellant Gauging Method

The Propellant Gauging Method (PGS) method is based on the idea of measuring the thermal capacity of a tank containing liquid fuel and pressurant gas by measuring its thermal response to heating and comparing the observed temperature rise to simulation results[4]. Described in Refs. 1-4, the PGS method employs a sophisticated thermal model of the propellant tank which takes into account temperature gradients within the tank. The method uses a spacecraft thermal model to determine the thermal environment of the tank. Current implementations of the PGS method are superior in numerous ways to the initial published work in Ref. 2.

The non-uniform heater power distribution and uneven propellant distribution inside the tank cause strong temperature gradients on the tank surface, which propagate into the interior. The non-uniformity of the heater power distribution stems from the fact that heater strips typically cover only a fraction of the tank surface. If the propellant position in the tank is controlled by a vane-type Propellant Management Device (PMD) in microgravity (this is the case with Stardust), then at End-Of-Mission (EOM) the propellant is located in the sump and in the corners formed by PMD vanes and the tank wall. A significant portion of the internal tank wall is not in contact with propellant and therefore dry. This gives it a very small heat capacity in contrast to the wet portions of the wall. All these factors lead to the formation of the temperature gradients on the tank wall. Thus the temperature, which is measured by the temperature sensors on the external side of the tank wall, depends on the sensor locations. The temperature distribution on the tank surface must be determined accurately to successfully compare the test flight data with the simulated temperature data.

Regardless of the spacecraft type, the PGS method employs the same steps:

- Develop thermal models of the propellant tank(s) and of the spacecraft
- Combine the thermal models of the spacecraft and propellant tank(s) into an integrated spacecraft thermal model
- Prepare and conduct the PGS operation
- Simulate the PGS operation for different propellant loads
- Compare flight and simulation data
- Determine the tank propellant loads and uncertainties statistically

Development of the tank thermal model is guided by the tank design and how the heater locations and fuel distribution can be

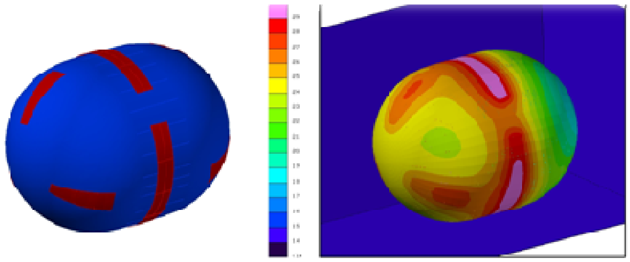
a) FEM Model
b) Temperature Distribution

Figure 1. Tank Model.

expected to influence temperature gradients. A high-fidelity tank model must capture temperature gradients and accurately sample the tank wall temperature at the temperature sensor location. The required fidelity of the spacecraft thermal model depends on the thermal connection between the tank(s) and the spacecraft environment. The spacecraft model can be of low fidelity if the connection is weak, as it is in Stardust. A strong thermal connection implies that the environment will affect temperature distribution in the tank, and thus requires development of a high-fidelity spacecraft model.

C. Tank and Spacecraft Model Development

Development of the tank and spacecraft models relied upon drawings and flight data from the spacecraft during nominal operations. The tank FE model was generated using a combination of programs including Surface Evolver, which was used to determine the position and shape of the liquid in micro-gravity for each tank load given the tank PMD. Also, a suite of tools was developed to complement standard tools and to fulfill the specialized requirements of the integrated model. Fig. 1 shows the tank model and temperature distribution on tank surface.

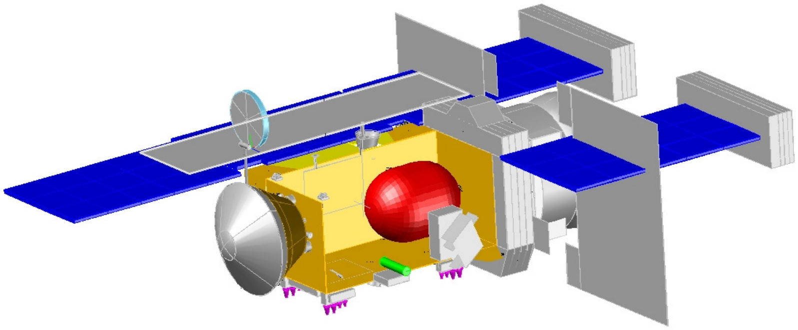

Figure 2. Diagram of Stardust, tank in center.

Figure 2 illustrates the spacecraft and shows the position of the tank. Some external panels are removed for clarity. Because the spacecraft was quite stable thermally and temperatures were available around the box containing the tank, the thermal model for the spacecraft could be reduced to just that box plus the heat paths from the tank to the structural elements inside the box. The fuel tank model and spacecraft model were integrated within the Thermal Desktop tool into an integrated spacecraft model. The integrated model was solved with SINDA (Systems Improved Numerical Differencing Analyzer).

D. PGS Operation

The PGS operation consisted of two steps: PGS operation procedure preparation and a flight operation. The thermal model was used in the development of the flight PGS operation procedure. Two PGS operations were conducted, in Oct. 2008 and May 2009. The flight data along with simulation results for May 2009 are shown in Fig.3

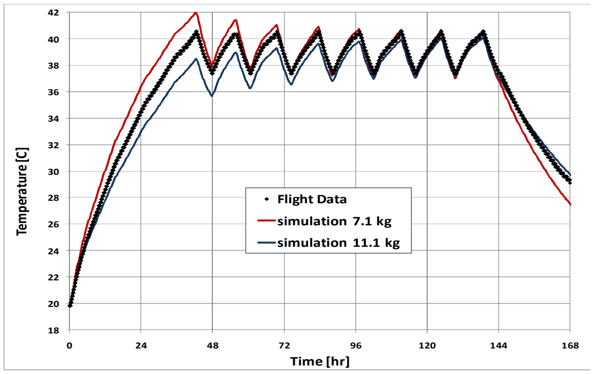

Figure 3. PGS flight operation, May 2009.

The PGS flight operation consisted of three phases: heating, equilibrium and cooling. Each phase has a different function. The slope of the heating curve is greatly affected by tank load. The equilibrium tank temperature characterizes the thermal connection between the tank and its environment. The cooling portion depends on both and serves as a check on both. As can be seen from Figure 3, the thermal model simulates all phases well, even reproducing some variations due to bus voltage fluctuations. This means that the model adequately describes the spacecraft environment relevant for fuel estimation.

E. Model Calibration

The tank and spacecraft models were calibrated using flight data. The goal of calibration was to make sure that thermal environment of the tanks is modeled correctly and corresponds to the current spacecraft conditions. It is well known that thermal conditions on a spacecraft change significantly through a mission due to aging and environmental effects. Therefore the integrated spacecraft thermal model must be calibrated to the current conditions in order to achieve the best possible accuracy. Readings of temperature sensors– located in various parts of the spacecraft – were used to calibrate the integrated spacecraft model.

F. Fuel Estimation

The fuel load was estimated using the calibrated thermal model and the flight data from the PGS flight operation. Figure 3 shows the results for two simulated tank loads (thin lines) with the flight data (thick line). Several simulations were run with varying propellant loads for the fuel tank.

The tank load is determined by comparing flight data with simulation results using a Least Squares Fit (LSF). The goal of an LSF approach is to minimize the sum of the squares of the differences between given data points and the corresponding model points. In theoretical terms, one minimizes the mismatch function F:

$$F = \sum_{i} \left[T_i - U\left(t_i ; m\right)\right]^2$$

In our case, *U* is known only for certain values of *m*, and the behavior of *F* must be inferred from what is known from a limited number of simulations. We approximate the mismatch function F versus tank load. Figure 4 shows the rough behavior of the mismatch function. Our analysis shows that the fuel tank had loads of 10.8 kg and of 9.0 kg in October 2008 and May 2009 respectively. These estimates agree well with the bookkeeping estimate of fuel usage between those dates.

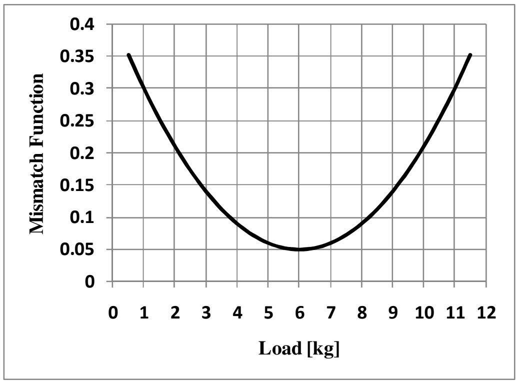

Figure 4. Abstract mismatch versus propellant mass.

The uncertainty in the estimates was 1 kg (one sigma). The primary source of uncertainty was the heater power. (Accurate knowledge of the heater power would have reduced the uncertainty to 0.44.)

G. Comparison with Other Propellant Gauging Methods

During both the primary and extended mission, two propellant-tracking methods were employed: the PVT method mentioned earlier and a Bookkeeping method that takes advantage of thruster performance knowledge and on-board thruster usage telemetry to count thruster pulses and estimate propellant consumed. The methods were used in a complementary fashion in that the bookkeeping method is applicable to short-term propellant estimation (days to weeks) and PVT is better across the long term (months to years). In fact PVT was used to correct or calibrate the bookkeeping results.

PVT is subject to many corrections, including the volume of the tank changing with pressure, potential pressure transducer drift, and helium gas dissolving into the hydrazine fuel and being expelled with it. These corrections were made as best as possible.

A measurement is rarely of use without some estimate of its accuracy. A review of existing methods, including bookkeeping and PVT, can be found elsewhere[5]. An error of estimation of the consumed propellant obtained by the bookkeeping method typically is in the range of 2.5 % - 3.5 % of initial load according to Ref. 5, 6, 7, although heroic efforts can reduce this to less than two percent. Assuming an error of 3%, the bookkeeping method uncertainty would be 3.5 kg of propellant at End of Mission based on the Stardust fuel tank volume.

The accuracy of the PVT method has been the subject of several studies. The reported error of propellant estimation by the PVT method various significantly. The error of propellant estimation has been reported as high as 35% [8] and as low as 0.22% [9] at EOM. The uncertainty is influenced primarily by the accuracy of the pressure transducer and the accuracy of the pressurant gas load. Estimates claiming the highest accuracy for PVT assume that the pressure transducers do not drift during the years of flight.

The best PVT estimate for Stardust was 11.6 kg of fuel on end of 2009. No formal uncertainty analysis was done.

H. Uncertainty Analysis for the PGS Method for Stardust

The PGS uncertainty analysis is a standard sum-of-variances analysis. It considers two categories of uncertainty, namely an uncertainty of the curve fit associated with propellant load estimation (assuming that all distributions are close to gaussian[12]), and uncertainties of specific model parameters which affect the accuracy. The curve fit measures how well the model fits the data, and is also used in assessing whether the model is adequate or whether some unexpected event interfered with the test.

An example of the second category of uncertainty would be the uncertainty in the heater power. These uncertainties are usually statistically independent, although we have sometimes needed to consider correlations in combining them.

Simulation tests have shown again and again that the distribution of the propellant within the tank is a large contributor to the uncertainty and can never be ignored.

II. Discussion

Three methods of propellant gauging, namely Bookkeeping, PVT and thermal propellant gauging, including our PGS method, are typically employed in the spacecraft industry to estimate the propellant remaining in flight. Each method has its advantages and disadvantages. The bookkeeping method is based on calculation of propellant consumed either by using the Rocket Equation, if the spacecraft's impulse change can be measured with high precision, or by using calibrated flow equations for the thrusters. The method is quite accurate at the beginning of mission life but the accuracy decreases over time due to the accumulation of errors. Also, the bookkeeping method requires firing thrusters under specific calibrated conditions in order to satisfy requirements of the flow model which is used to calculate propellant flow through thrusters. If thrusters are used in an uncalibrated mode, the results of the flow model are not accurate.

The PVT method is based on the Ideal Gas Law. The volume of propellant is deduced from the calculated volume of a known amount of pressurant gas. The PVT method accuracy declines as well with time because the volume is inversely proportional to the pressure, meaning that the sensitivity is inversely proportional to the square of the pressure. As the amount of propellant decreases, a decrease of one kg of propellant leads to smaller and smaller decreases in pressure. The PVT method also requires accurate initialization, meaning that the amount of pressurant gas must me known very accurately, and its dissolution into the propellant and expulsion in solution must be accurately calculated. Thermal gauging is free from all the above drawbacks, which makes the method attractive. The effort required for a thermal PGS estimate might seem larger than the effort required for bookkeeping or PVT, but this is primarily because those efforts are spread over years while a PGS estimate is performed entirely over only a few months or even weeks.

The PGS method uses the thermal response of the propellant tank to heating in order to infer the propellant load of the tank. The sensitivity of the PGS method increases with decreasing propellant load. This is because the rate of the temperature rise is inversely proportional to the propellant remaining rather than to the gas or the initial propellant load.

Fig.5 shows the general trend for the uncertainty in the propellant remaining for the bookkeeping, PVT, and PGS methods over time. This shows that the bookkeeping and PVT methods have better accuracy than the PGS method at the beginning of a mission. The accuracies of all methods become comparable in the middle of life. The PGS method becomes superior to the other methods near the end of life, which is when the propellant load is often of most interest.

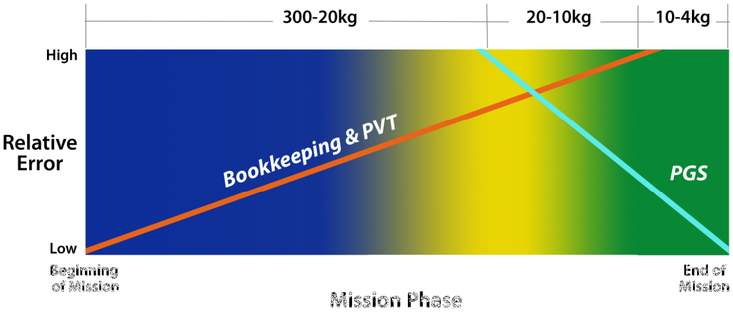

Figure 5. Error of Book-keeping and PGS gauging methods

Even when bookkeeping and PVT are used together, their reduced accuracy near end of life often causes the two methods to disagree, leaving the spacecraft operator to wonder which number to choose. Such a situation calls for an independent method better suited to End Of Mission life. The PGS method serves this purpose well and is being used more and more for many different spacecraft platforms including BSS 601 and 376, LM A2100, LM 3000 and 5000, SS/L FS 1300, Spacebus 2000, and EuroStar 2000 (slightly modified[1]). The method has been used not only at EOM, but in situations where the bookkeeping or PVT methods could not be used, for example when a pressure transducer is not working.

III. Conclusion

The thermal PGS method for propellant estimation was successfully applied to the Stardust spacecraft, showing that the mission was achievable only with some added fuel economy. Following the usual approach for the PGS method, an integrated tank and spacecraft thermal model was developed. This model was used for the PGS procedure development with a preliminary calibration. Based on the resulting flight data, the thermal model was calibrated to the conditions of Stardust spacecraft during the test. The calibrated model was then used to estimate the fuel remaining and its associated uncertainty. Measurements indicate that delaying the arrival of Stardust at Tempel 1 by at least 8 hours will maximize the probability of reaching the objective. Based on these fuel estimates, project scientists have made their recommendations for the time-of-arrival adjustment.

This estimation shows that the PGS method is applicable to the Stardust probe and to similar busses and can be useful for existing and future NASA/JPL missions. This platform joins a growing list of spacecraft platforms to which the PGS method has been successfully applied, including: Boeing 601 and 376; Loral FS 1300; Alcatel Spacebus 2000; Lockheed A2100, 3000, and 5000; and a modified Astrium Eurostar 2000.

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