Ensuring Cassini's End-of-Mission Propellant Margins

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***Abstract*— The Cassini spacecraft is in its final years. On September 15, 2017, Cassini will plunge deep into Saturn's atmosphere never to reemerge; thus concluding its second extended mission and 13 years in orbit around the ringed planet. As of October 2014, the spacecraft is four years in to its seven-year, second extended mission, the Cassini Solstice Mission (CSM). With three years left and only 2.5% of its loaded bipropellant and 37% of its loaded monopropellant remaining, the Cassini project actively manages the predicted end-of-mission propellant margins to maintain a high confidence in the spacecraft's ability to complete the CSM as designed.**

Accurate spacecraft navigation, rigorous remaining-propellant estimation, and frequent future propellant consumption prediction have resulted in efficient propellant use and a probability of sufficient propellant margin greater than 99%.

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1. INTRODUCTION

The Cassini spacecraft entered Saturn orbit in July 2004. After the completion of its periapsis-raise maneuver in August 2004, the Cassini spacecraft spent the following 6 years completing its prime mission (PM) and first extended mission (EM), including 80 targeted flybys of Saturnian moons across more than 130 orbits, requiring over 180 orbit-trim maneuvers (OTMs) and 600 m/s of ΔV. In October 2010, the Cassini spacecraft began its second and final extended mission, the Cassini Solstice Mission (CSM) [1]. The CSM extends the Cassini mission seven years, to 2017, with more than 150 additional orbits, including 70 targeted flybys. As of October 2014, the Cassini spacecraft had performed more than 280 OTMs and spent roughly 680 m/s of ΔV maintaining orbits and targeting flybys. With three years to go and only a small fraction of the loaded propellants remaining, the Cassini project actively manages the predicted end-of-mission propellant margins through the minimization of navigation ΔV costs, rigorous estimation of the remaining propellants, and meticulous modeling of future propellant consumption. The following sections of this paper will describe each of these efforts in detail, while the remainder of this section will provide foundational information on the propulsion systems of the Cassini spacecraft and the design of the CSM trajectory.

CASSINI PROPULSION SYSTEMS

The Cassini propulsion module subsystem is comprised of two separate propulsion systems: a bipropellant system with the main-engine assembly (MEA) and a monopropellant, reaction-control system (RCS) [2]. The locations of the main engines and RCS thruster pods are shown in Figure 1.

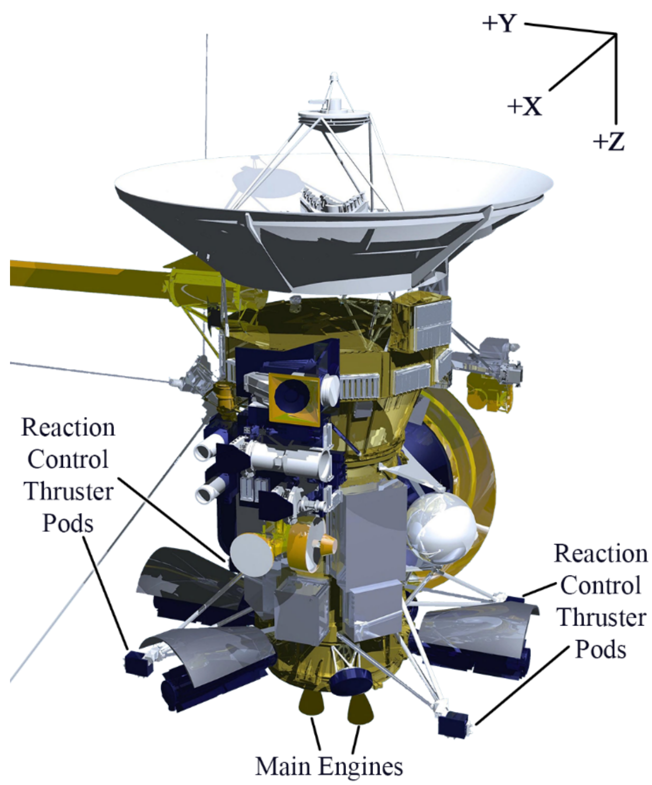

Figure 1 – Cassini Spacecraft Thrusting Components

The Cassini spacecraft has two main engines and four RCS pods, each with four thrusters. Each RCS pod has two thrusters pointed along the +Z-axis and two thrusters pointed along either the +Y-axis or the –Y-axis depending on whether the pod is located on the +Y or –Y side of the X-Z plane. These thrusters are also separated into two branches, A and B, each with four +Z thrusters, two +Y thrusters, and two –Y thrusters.

The bipropellant system uses nitrogen tetroxide (NTO) as its oxidizer and monomethylhydrazine (MMH) as its fuel. The nominal mixture ratio (NTO to MMH) of the bipropellant system has been 1.58 in the CSM and the nominal specific impulse, 301 sec. The monopropellant is hydrazine and has a nominal specific impulse of 217 sec.

The MEA is used solely for translational maneuvers (OTMs) greater than ~0.25 m/s [3]. The RCS is used for small translational maneuvers, attitude control, and spacecraft momentum management. While the RCS could be used for larger translational maneuvers, the MEA cannot be used for attitude control; thus, the monopropellant is a slightly more precious resource than the bipropellant.

Cassini Solstice Mission Trajectory Design

The goal of CSM trajectory design was to maintain science observation opportunities commensurate with those in the PM and EM, while extending the mission to the next Saturn solstice in 2017, seven years away [4]. At the time of the CSM trajectory design, the predicted available ΔV for the CSM was 160 m/s at a 90% confidence level. Stretching this amount of ΔV across seven years yields an average annual ΔV consumption of 23 m/s, an 80% reduction in the average value of the PM and EM, 100 m/s [1].

This reduction was realized by altering the trajectory design strategy to turn the longer duration of the CSM into an advantage. The shorter durations of the PM and EM required the interleaving of science objectives with disparate geometries, which was costly in terms of ΔV. By grouping science objectives with those requiring similar geometry, the CSM trajectory could be segmented into phases and ordered such as to minimize the required ΔV to achieve the science objectives [1].

In addition, the trajectory for the final nine months of the mission was set to the critical orbital inclination, near 63°. This minimizes the rotation of the line-of-apsides caused by Saturn's oblateness, which means these orbits require very little ΔV to maintain [4].

The resulting CSM trajectory requires 158 m/s of ΔV at a 95% confidence level, 119 m/s of which are deterministic [4].

2. Navigation Cost Reduction

In addition to the effort made to minimize required ΔV during the design of CSM trajectory, the Cassini project continues to work to reduce the statistical ΔV cost associated with maintaining the trajectory. While 119 m/s of deterministic ΔV are required in the CSM, the additional 49 m/s are a statistical, 95%-confidence-level value that can vary based on how well the spacecraft's actual trajectory matches the designed trajectory.

The Cassini spacecraft is flown from one satellite flyby to the next, with each flyby serving as a tie-point to the reference trajectory (a point at which the position error between the flown trajectory and the reference trajectory is minimized) [3]. On average there are three maneuvers per flyby: a clean-up maneuver of the previous encounter, a targeting maneuver usually near apoapsis, and an approach maneuver just prior to the next encounter; thus, the encounter ΔV is the sum of the ΔVs performed during each of these maneuvers. A useful metric for determining how closely the spacecraft is flying to the reference trajectory is the navigation ΔV cost, or the difference between the encounter ΔV and the deterministic ΔV in the reference trajectory during the encounter span, the equation for which is shown in Equation 1.

$$\Delta V_{Nav.Cost} = \Delta V_{Encounter} - \Delta V_{Ref.Traj.Det.} \qquad (1)$$

In the PM and EM, the average navigation ΔV cost per flyby was 358 mm/s. Thus far in the CSM, the average navigation ΔV cost has been 118 mm/s, a 67% reduction from the previous average. Several changes in CSM operations have enabled this reduction.

First, by taking advantage of the tracking data and optical navigation images obtained in the previous missions, the orbit accuracy of the Saturnian satellites has improved by more than three orders of magnitude from those in the PM and EM. This has reduced navigational target misses from the ten-kilometer level to the few-hundred-meter level, which requires less ΔV to correct.

Second, fewer OTMs are canceled in the CSM, which may seem like it would increase ΔV consumption; however, maneuver cancelation often results in a downstream ΔV cost as errors between the flown and reference trajectories grow with time [3]. During the PM and EM, the project's risk avoidance strategy focused on minimizing the probability of spacecraft anomalies, and thus, reducing the number of maneuvers. It was not uncommon to pay a ΔV cost of a few hundred millimeters per second downstream in order to cancel a maneuver. In the CSM, the focus has shifted to propellant conservation as there is now a long history of reliable maneuver execution and propellant is a limited resource. Now the project is reluctant to cancel a maneuver even if the resulting downstream ΔV cost is only a few tens of millimeters per second.

Last, maneuvers are executed more accurately. Reconstructions of previous maneuvers have allowed magnitude and pointing biases to be identified, quantified, and reduced [5]. This reduction in biases has meant smaller maneuver execution errors and less ΔV required to correct them.

For further information on the CSM maneuver implementation strategy and performance see [3].

3. REMAINING PROPELLANT ESTIMATION

Significant effort has been put into estimating the amounts of fuel, oxidizer, and hydrazine left in the Cassini spacecraft as well as the amounts of those that are permanently trapped as unusable propellant. This section gives a brief description of the models used and analyses conducted to produce the remaining propellant estimates, their uncertainties, and their unusable amounts for both the bipropellant and monopropellant systems.

REMAINING BIPROPELLANT

The remaining bipropellant is estimated from flow modeling, which is derived from careful reconstruction of main engine burns based on: commanded burn time, feed system pressure drop, flight pressure transducer telemetry, and estimated flow rate (as a function of inlet pressure and propellant temperature). Key features of the flow model are: independent oxidizer and fuel flow rates, thrust adjustments to match flight performance, and specific impulse temperature dependence. As of October 2014, the estimates for the remaining fuel and oxidizer are 24.2 kg and 50.6 kg, respectively.

While the flow model has a high accuracy, it was not designed to be used down to such low estimates of remaining propellant. As such, its uncertainty, which was negligible during the PM and EM, is now a driving factor in the bipropellant margin given the small amounts of remaining fuel and oxidizer. Thus, an analysis was performed to identify and quantify the errors sources in the flow model. By considering errors from loading uncertainty, line pressure drop, tank temperature, tank pressure, burn time uncertainty, mixture ratio uncertainty, and flow model reconstruction, the 1σ uncertainties in the fuel and oxidizer estimates were found to be 7.0 kg and 5.9 kg, respectively.

Fuel and oxidizer is trapped in three places within the propulsion system: as liquid in the lines, as vapor in the tanks, and as liquid in the tanks due to their expulsion efficiencies. All of these quantities can be deterministically calculated, and are found to be 6.3 kg and 15.9 kg for the fuel and oxidizer, respectively.

A summary of the remaining fuel and oxidizer, including uncertainties and trapped propellant is shown in Figure 2.

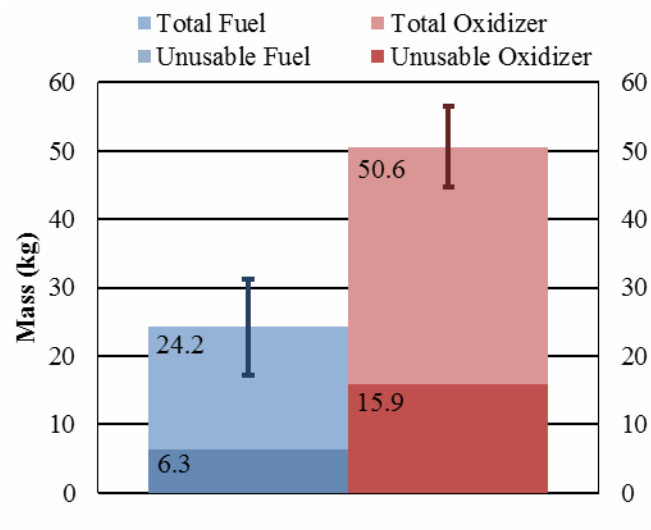

Figure 2 – October 2014 estimates for remaining fuel and oxidizer, with trapped propellant and 1σ error bars

It is worth noting that the current estimates of the remaining bipropellant represent only 2.5% of the total bipropellant loaded at launch, and the uncertainties of the estimates as a fraction of the total bipropellant consumed are less than 1%. The above numbers can also be expressed in terms of remaining bipropellant ΔV as shown in Figure 3.

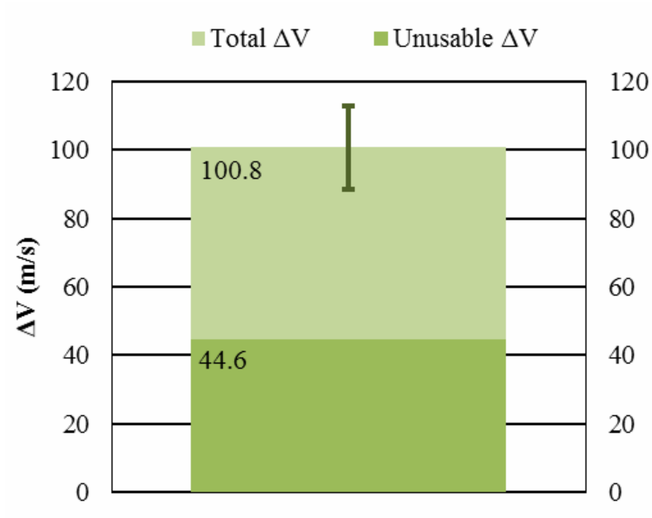

Figure 3 – October 2014 estimates for remaining bipropellant ΔV, with trapped ΔV and 1σ error bars

REMAINING MONOPROPELLANT

The mean remaining monopropellant is estimated using both consumption and tank models. The consumption model is used for the day-to-day tracking of the remaining monopropellant due to its better precision when dealing with individual events of monopropellant usage. The tank model has better accuracy than the consumption model but requires longer timescales between updates and is used to both rein in error propagation in the consumption model and estimate the amount of unusable monopropellant trapped in the system.

As of October 2014, the estimate for the remaining monopropellant is 47.8 kg, from the consumption model.

The amount of unusable monopropellant is estimated with the tank model and has both deterministic and statistical components. The deterministic component is comprised of propellant trapped within the system and various sensor offsets. The sources of the statistical component are loading uncertainty and uncertainties in the tank conditions at depletion. In total, the unusable monopropellant mass is estimated to be 3.6 kg ±6.7 kg, 3σ.

4. PROPELLANT USAGE PREDICTION

Predicting the end-of-mission propellant margins relies on three primary inputs: the remaining usable propellant amount, the future propellant-consuming events, and the performance characteristics of the propulsion systems. In previous sections, remaining propellant estimation and propulsion system performance characteristics were discussed. This section will identify the sources of future propellant consumption, describe the propellant usage predictor (PUP), and the Monte Carlo simulation used to predict the end-of-mission propellant margins at various confidence levels.

SOURCES OF PROPELLANT CONSUMPTION

While OTMs are a large source of remaining propellant consumption, they are not the only one. Science observations and spacecraft operations make a significant contribution to the propellant consumed. The following sections detail each of the sources of propellant consumption identified and implemented in the usage prediction model.

Orbit-Trim Maneuvers—OTMs are the sole consumer of the remaining bipropellant. As of October 2014, about 31 m/s of deterministic ΔV remain in the CSM. This ΔV is split between the bipropellant system and the RCS based on the magnitudes of the individual maneuvers. OTMs of at least 0.25 m/s in magnitude are performed by the MEA, which equates to 12 maneuvers and 30.3 m/s of deterministic ΔV. The RCS performs the maneuvers smaller than 0.25 m/s, of which there are 38 remaining, totaling 0.7 m/s of deterministic ΔV. In addition, the RCS performs two OTM turns for each MEA OTM [6], which point the spacecraft to the necessary attitude for the OTM execution and then back to the original attitude. The average consumption of both turns is 48 g of hydrazine. This value was calculated using hydrazine consumption actuals from the start of the CSM through March 2014.

Reaction Wheel Biases—Reaction wheel biases are used to maintain the health of the reaction wheels by avoiding extreme wheel speeds (both high and low) and limiting revolutions [7]. The RCS thrusters are used to counteract the change in angular momentum created by changing the wheel speeds.

Biases come in two flavors: on-Earth biases, and Y biases. On-Earth biases take place while the spacecraft maintains an Earth-pointed attitude. Y biases are designed to reduce the use of the +Z thrusters and were developed in response to the anomalous degradation of some of the +Z thrusters in the RCS A-branch [8].

On average, biases are performed five times per orbit in the CSM. During the final nine months of the CSM, this number is reduced to three as the average orbital period drops to less than seven days, compared to 20 days during the rest of the CSM. The average on-Earth bias consumes 13.3 g of hydrazine, while the average Y bias consumes 12.6 g. These averages were calculated using hydrazine consumption actuals from the start of the CSM through March 2014.

The PUP assumes the biases are spaced evenly throughout the orbit with one on-Earth bias per OTM in the orbit, to a minimum of one. The remaining biases are modeled as Y biases. In total, biases will consume approximately 4.5 kg between October 2014 and the end of the mission.

Titan Flybys—Titan flybys are a significant source of hydrazine consumption. During low flybys, Titan's thick atmosphere exerts a significant torque on the spacecraft, and the large relative velocity between the two requires high turn rates for tracking science targets. The RCS thrusters are used in such situations to provide the necessary control authority and angular rates.

Of the 21 remaining Titan flybys, 12 will be controlled with the RCS thrusters. Table 1 shows the dates and altitudes of closest approach, as well as the predicted, nominal hydrazine consumption for each of these flybys.

Table 1 – Remaining Titan Flybys using RCS Thrusters

Date	Minimum Altitude (km)	Hydrazine Predict (g)
10/24/14	1013	459
12/10/14	980	300
01/11/15	970	391
02/12/15	1200	431
09/28/15	1036	302
02/16/16	1018	412
04/04/16	990	143
05/06/16	971	415
06/07/16	975	524
07/25/16	976	391
11/14/16	1582	459
04/22/17	979	409

The predicted, nominal hydrazine consumption for all these Titan flybys is just under four kilograms.

Solar Conjunctions—During solar conjunctions the spacecraft is put in RCS thruster control so that the reaction wheels stay in a known, safe state. Only three solar conjunctions remain in the CSM, each lasting on average 5.5 days. The nominal hydrazine required during solar conjunction is 50 g, which is based on historical actuals from past conjunctions.

F-Ring and Proximal Orbits—The F-Ring and Proximal Orbits take place during the last nine months of the CSM. These orbits will bring Cassini closer to Saturn than ever before, yielding unique science observation opportunities [1] [9]. While the exact science observations during this time are still being planned, a healthy hydrazine allocation is included in the PUP. This allocation size is based on input from the science teams as to the number and type of observations they plan to perform during the F-Ring and Proximal Orbits. Past hydrazine consumption for these types of activities was used to estimate the total hydrazine consumption. This value was then doubled, to account for the estimate's coarse nature, to reach the final hydrazine allocation for science activities during the F-Ring and Proximal Orbits, 6.9 kg.

Propellant Usage Predictor

The PUP uses the propulsion systems' performance characteristics, the remaining propellant estimates, and the future propellant expenditures to calculate the propellant remaining before and after each expenditure through the end of the mission.

Given the amounts of remaining propellant, an initial spacecraft wet mass is calculated. From there, the model steps through each expenditure, subtracting the appropriate amounts of fuel, oxidizer, and hydrazine from the remaining propellants at each step given the source of the expenditure.

For OTMs performed by the MEA, the model checks to ensure enough fuel and oxidizer remain to fully execute the maneuver. If either is short, the amount of ΔV that can be executed is calculated and only the associated amounts of fuel and oxidizer subtracted from the remaining amounts, zeroing-out the one that was short and taking a reduced amount from the other. The remaining, unexecuted ΔV is then performed by the RCS and the required amount of hydrazine is subtracted from that remaining. From this point on, all MEA OTMs are performed on the RCS.

Should the RCS system ever not have enough hydrazine remaining to complete the requested expenditure, the total expenditure amount is simply subtracted and the remaining hydrazine amount is allowed to go negative. In these cases, the negative amount of hydrazine at the end of the mission serves to flag the prediction as being short on hydrazine by an amount equal to the negative amount.

The process of stepping through the propellant expenditure events is continued until the end of the mission is reached and the amounts of remaining propellant before and after each expenditure are captured.

Monte Carlo Simulation

The Monte Carlo simulation effectively puts a wrapper around the PUP that applies statistical distributions to the inputs, samples them a specified number of times, runs the PUP for each sample case, and aggregates the results by reporting the remaining propellant at various confidence levels. The inputs to the Monte Carlo simulation are the number of cases to run and the statistical distributions to apply to each of the inputs required by the PUP.

The number of cases is set to 100,000 to ensure a sufficient number of cases are used to define the extreme confidence levels. For example, the 90% confidence level, which the project typically uses for contingency planning, would be set based on the worst 10,000 cases.

Two types of statistical distributions are applied to the different inputs of the PUP by the Monte Carlo simulation: Gaussian and Beta. The Gaussian distribution is used on the propulsion system performance characteristics, all the propellant-consuming events except the OTMs, and the remaining monopropellant. The Beta distribution is used on OTMs and the remaining bipropellants, with separate distributions for the fuel and oxidizer.

Gaussian Distributions—The Gaussian distributions take the nominal values quoted in the previous sections as the mean. The standard deviations are based on actual performance and consumption histories, or in the case of the remaining monopropellant, the error analysis described in Section 3. Table 2 summarizes the parameters used for the Gaussian distributions applied to the propellant-consuming events, propulsion system characteristics, and remaining monopropellant.

Table 2 – The parameters used to define the Gaussian distribution for each of the shown inputs

Input Type	Propellant Consuming Event	Mean Value	Standard Deviation
Propellant Consuming Events	On-Earth Bias	13.3 g	10.4 g
	Y-Bias	12.6 g	6.5 g
	OTM Turns	48.0 g	5.9 g
	Conjunction	50.0 g	0.5 g
Propulsion System Characteristics	Bipropellant Mixture Ratio	1.58	0.25%
	Bipropellant Specific Impulse	301 sec	1.00%
	Monopropellant Specific Impulse	217 sec	1.67%
Remaining Propellant	Monopropellant	47.8 kg	2.2 kg

Beta Distributions—Beta distributions were chosen for the OTM and remaining-propellant distributions over Gaussian for a couple of their unique properties. First, Beta distributions are bounded, meaning their probability density function (PDF) is zero outside of a specified range. This is useful for these particular inputs because it is desired that they never drop below a given lower bound: the OTMs should not be modeled as less than the deterministic ΔV, and the modeled amounts of initial propellant should not be less than the trapped amounts. These lower bounds could have been imposed with other distribution types, log-normal as an example; however, other distributions tend to lack the PDF-shaping parameters that come with a Beta distribution. The two shaping parameters of the Beta distribution allow its PDF to take on drastically different shapes, which affect the distribution's mean, standard deviation, and confidence-level values. Thus, the shaping parameters can be used to match certain statistical characteristics of the inputs to which the distribution is being applied.

The OTM Beta distribution parameters were chosen so as to match the navigation ΔV cost statistics of the CSM to date. Figure 4 shows the cumulative distribution functions (CDFs) of the Beta distribution used in the Monte Carlo simulation and the navigation ΔV cost actuals.

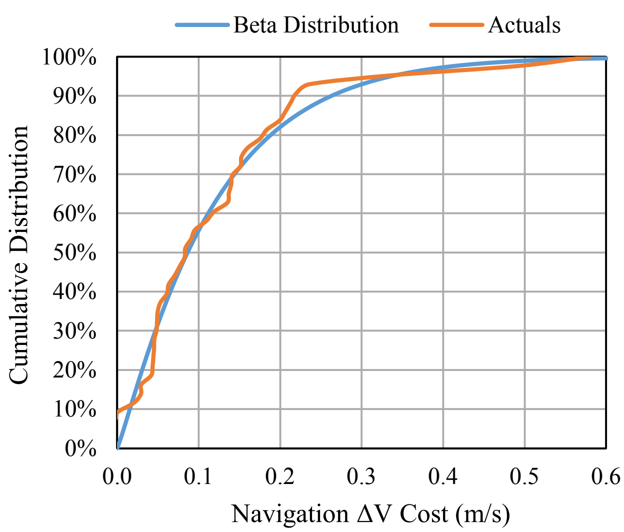

Figure 4 – Cumulative distributions of the actual CSM navigation ΔV costs and their Beta distribution approximation in the Monte Carlo simulation

The lower bound of the Beta distribution was set at zero to ensure that at minimum the deterministic ΔV would be required, while the upper bound was set to the maximum navigation ΔV cost ever paid, 5.7 m/s back in the EM, an extreme outlier whose nearest neighbor is found in the PM at 1.7 m/s. The maximum navigation ΔV cost to date in the CSM is 0.58 m/s, which corresponds to a CDF value of 99.5% in the Beta distribution.

The Beta distribution parameters for the remaining bipropellants (fuel and oxidizer) were chosen to align with the values described in Section 3 and summarized in Figure 2. Specifically, the Beta distribution means were set to the flow model estimates, their standard deviations were set to the 1σ error bar magnitudes, their lower bounds were set at the unusable propellant estimates, and their upper-bounds were set at the 3σ best cases.

PROPELLANT USAGE PREDICTOR VALIDATION

The PUP is continuously validated against the actuals of the CSM. The validation is done by running the simulation from a point in the past to the present, without any mid-simulation corrections for actual propellant consumption, and comparing the results to the actuals. The date at which to start the validation is chosen to be at least as far into the past as the mission end is into the future, as the results should then be indicative of the model's accuracy at the conclusion of the CSM. Currently, the validation interval is set at three years into the past given that the end of the CSM is just under three years away. Figure 5 shows the results of the validation for the bipropellant ΔV consumption, and Figure 6 shows the monopropellant consumption.

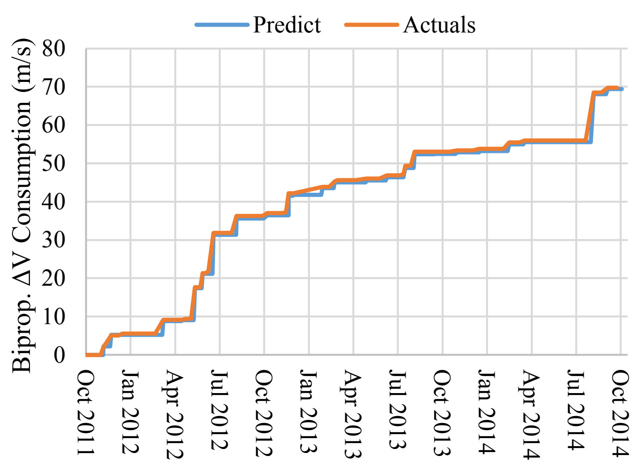

Figure 5 –Predicted and actual bipropellant ΔV consumption from October 2011 to October 2014

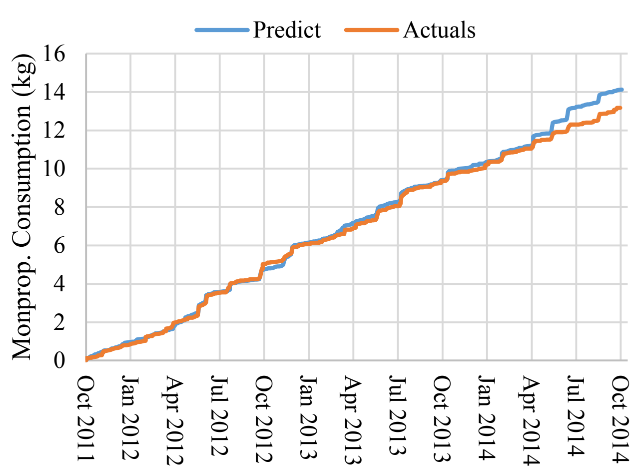

Figure 6 – Predicted and actual monopropellant consumption from October 2011 to October 2014

At the end of the three-year simulation period, the predicted bipropellant consumption was within 0.4 m/s of the actual value, and the predicted monopropellant consumption was within 1.0 kg. The comparison of these numbers to the uncertainties in remaining bipropellant ΔV and monopropellant mass, given in Section 3, indicates that the uncertainty in the predicted end-of-mission propellant levels will be driven by the initial, remaining-propellant uncertainties and not by the inaccuracies of the PUP.

5. PREDICTED PROPELLANT MARGINS

The propellant margins are taken as the usable propellant levels predicted to be remaining in the Cassini spacecraft at the end of the CSM by the Monte Carlo simulation described in the previous section. The bipropellant margin is reported in units of ΔV, as the sole source of bipropellant use is OTMs, which are defined in terms of ΔV. The monopropellant margin is reported both in units of mass (as the majority of monopropellant consuming events are quantified by consumed mass) and units of ΔV, which is combined with the bipropellant ΔV margin to give an estimate of total propellant margin. The following subsection reports the results of the latest prediction, from October 2014.

OCTOBER 2014 PROPELLANT MARGIN PREDICTION

Figure 7 plots the bipropellant margin versus confidence level, which shows a median margin of about 27 m/s.

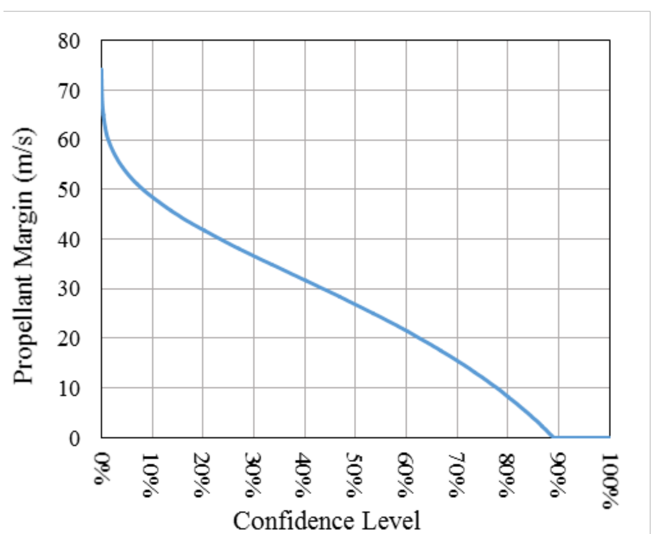

Figure 7 – Bipropellant ΔV margin versus confidence level

Figure 7 also shows that about 11% of cases have no bipropellant left at the end of the CSM; however, this alone does not mean the mission was not completed in these cases. The RCS can be used to complete the OTMs originally planned for the MEA as long as there is sufficient monopropellant margin. Figure 8 plots the monopropellant margin versus confidence level. Only 0.2% of cases have no monopropellant margin.

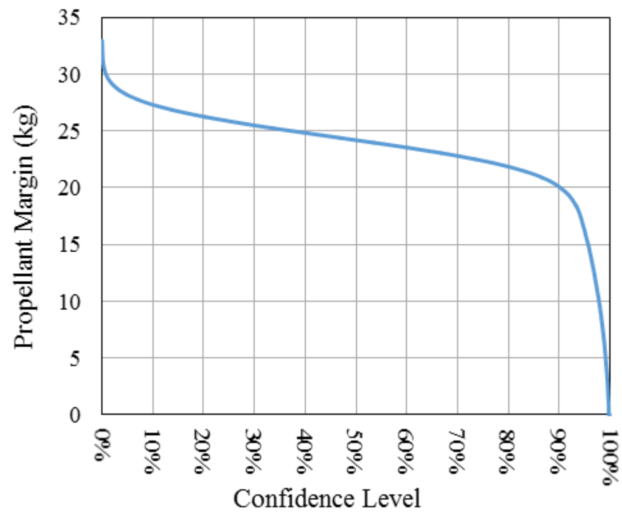

Figure 8 – Monopropellant mass margin versus confidence level

This means that only a small fraction of the cases with depleted bipropellant did not have enough supplemental monopropellant. Combining the two margins, as shown in Figure 9, gives the total propellant margin making it more clear as to the percentage of cases that cannot complete the mission.

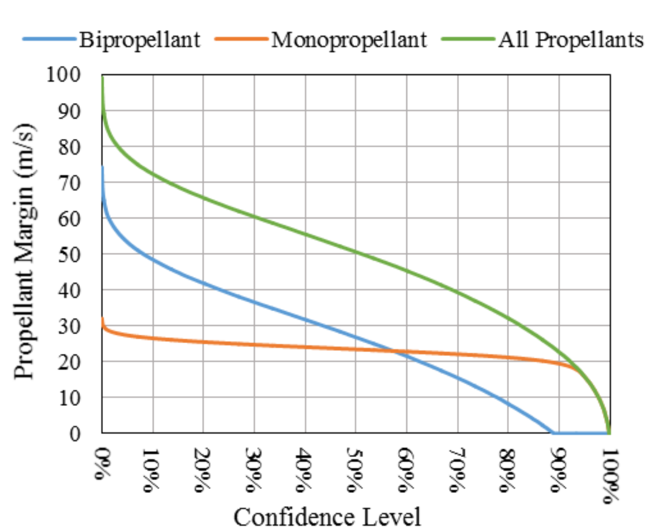

Figure 9 – Bipropellant, monopropellant, and total propellant ΔV margins versus confidence level

In the October 2014 Monte Carlo simulation, 99.8% of cases had enough propellant to complete the CSM.

PROPELLANT MARGIN MANAGEMENT

The propellant margins are updated every ten weeks at the completion of each spacecraft sequence. As part of the update, propellant consumption actuals are compared to the prediction from the start of the sequence; in addition, the statistics of the actuals are analyzed and compared to the distributions used in the Monte Carlo simulation. Any significant deviations between the actuals and the prediction, or their statistics and the distributions, are tracked to see if they persist in subsequent sequences. The remaining propellant estimates are also revised based on the actuals. The Monte Carlo simulation runs the PUP with the new remaining propellant estimates. The results are used to generate the median and 90% propellant margins for the bipropellant and monopropellant, as well as a single, total-propellant margin, all of which are tracked at the project-level.

The Cassini project maintains contingency plans that seek to minimize impacts to future science activities and mission requirements in the event of bipropellant depletion. The contingency response are dependent on the date of bipropellant depletion. Using the results from the October 2014 prediction, of the 11% of cases that depleted the bipropellant, more than 95% of them would have little to no impact on future science activities or mission requirements.

6. CONCLUSION

With the minimization of navigation ΔV costs, the rigorous estimation of remaining propellants, and the meticulous modeling of future propellant consumption, the Cassini project maintains a very high confidence that the spacecraft will have enough propellant to finish the CSM as envisioned.

Propellant margins are updated and reviewed every ten weeks. Deviations from predicted propellant consumption profiles are identified and tracked at the project level. The current probability of having adequate propellant to complete the CSM as planned is over 99%.

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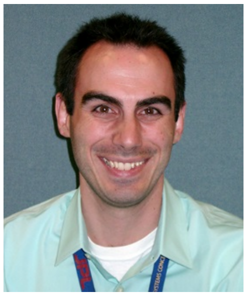
BIOGRAPHY



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