CASSINI'S MANEUVER AUTOMATION SOFTWARE (MAS) PROCESS: How to Successfully Command 200 Navigation Maneuvers

Genevie Velarde Yang, David Mohr, and Charles E. Kirby*
Jet Propulsion Laboratory, California Institute of Technology

Abstract

By the end of the prime mission on July 1, 2008, the Cassini spacecraft had completed 74 orbits of Saturn resulting in over 2000GB of science data and hundreds of science publications. Cassini is scheduled to complete an additional 76 orbits over the next 28 months during its extended mission. These orbits, all predetermined years in advance to maximize science return, include a wide range of targeted flybys (Titan and numerous other Saturnian satellites), orbital periods (from 8 to 80 days), and orbital inclinations (from near equatorial to near polar). The sequencing of spacecraft pointing and science commands is absolutely dependent on the delivery of the spacecraft to the correct location at the correct time.

To keep Cassini on its complex trajectory, more than 200 orbit trim maneuvers (OTMs) have been planned from July 2004 to July 2010. With only a few days between many of these OTMs, the operations process of planning and executing the necessary commands had to be automated. The resulting Maneuver Automation Software (MAS) process minimizes the workforce required for, and maximizes the efficiency of, the maneuver design and uplink activities.

The MAS process is a well-organized and logically constructed interface between Cassini's Navigation (NAV), Spacecraft Operations (SCO), and Ground Software teams. Upon delivery of an orbit determination (OD) from NAV, the MAS process can generate a maneuver design and all related uplink and verification products within 30 minutes. To date, all 112 OTMs executed by the Cassini spacecraft have been successful. MAS was even used to successfully design and execute a maneuver while the spacecraft was in safe mode.

Acronyms

AACS = Attitude and Articulation Control Subsystem
ACC = Accelerometer
CDS = Command Data System
c.m. = Center of Mass
CMT = Constraint Monitor Table
DOY = Day of Year
DV = Change in Velocity, Delta V
ECR = Engineering Change Request
eCRF = Electronic Command Request Form
ITL = Integrated Test Laboratory
KPT = Kinematic Predictor Tool
MAS = Maneuver Automation Software
MDT = Maneuver Design Tool
MEA = Main Engine Assembly
MIF = Maneuver Implementation File
MOPS = Maneuver Operations Program Set
MPF = Maneuver Profile File
MSS = Mission Sequencing Subsystem (Ground Software Team)
NAV = Navigation
OD = Orbit Determination

*Authors are members of the Cassini Flight System Engineers-Spacecraft Operations Team. Mail Stop 230-104, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109-8099, USA.

OS = Operating System
OTM = Orbit Trim Maneuver
Prop = Propulsion
RCS = Reaction Control System
RTC = Real Time Commanding
RWA = Reaction Wheel Assembly
SASF = Spacecraft Activity Sequence File
S/C = Spacecraft
SCO = Spacecraft Operations
SEQGEN = Sequence Generator
SEQTRAN = Sequence Translator
SID = Star Identification Algorithm
SOI = Saturn Orbit Insertion
SSR = Solid State Recorder
SSPS = Solid State Power Switch
TCM = Trajectory Correction Maneuver
TWTA = Traveling Wave Tube Amplifier

I. Introduction

The Cassini spacecraft has reached the end of its prime mission on July 1st 2008, and has successfully completed 74 orbits of Saturn. The Huygens probe, developed by the European Space Agency, was successfully released on December 24, 2004.[1] Cassini is currently in its 2 year extended mission, dubbed "Equinox". This paper will pertain mostly to Cassini's Prime Mission.

Cassini's prime mission included plans for 162 propulsive orbit trim maneuvers between May 2004 and July 2008. Trajectory control requires 3 OTMs per targeted encounter of Titan (typically one per orbit of Saturn) or an icy satellite. Figure 1 shows an example of outbound targeted Titan encounter.

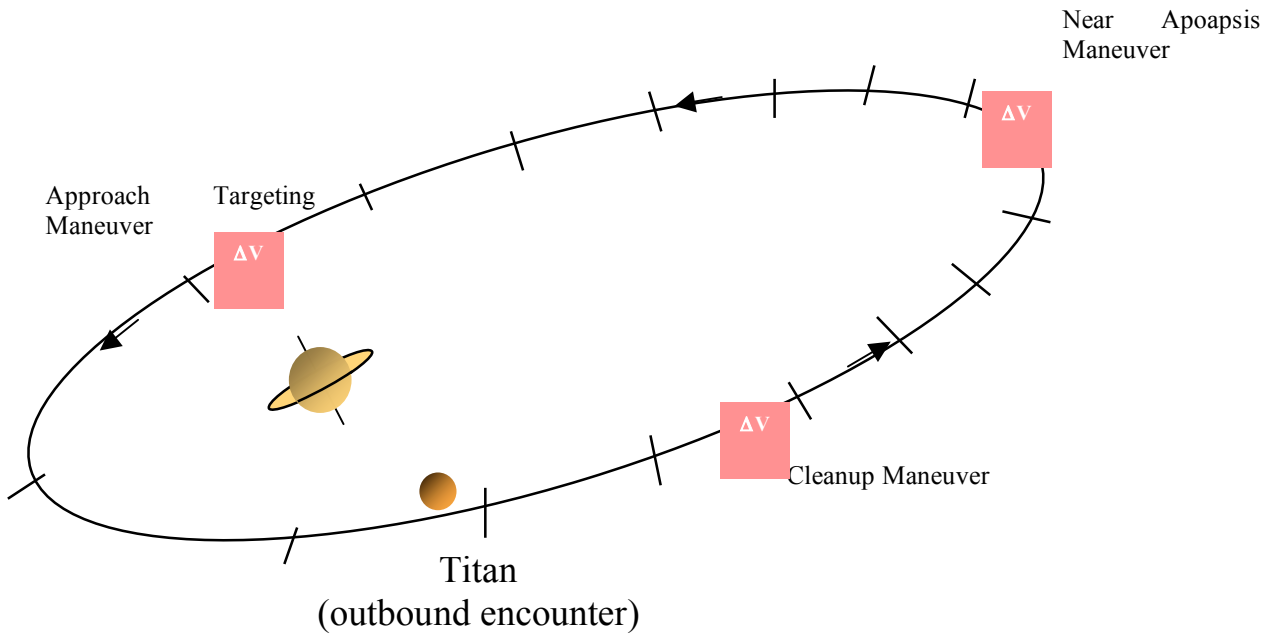

Figure 1. Three Maneuver per encounter strategy

The prime mission included a significant number of 16 day orbits, meaning as little as 5 days on average between maneuvers. Cassini's Equinox extended mission will similarly contain many 16 day orbits, and we will likely execute more than 200 OTMs by time of its completion. In order to accomplish this large number and frequency of maneuvers, a maneuver design process that uses a unique ground software tool named Maneuver Automation Software (MAS) is employed. [2]

II. Why MAS was created

From the beginning of the prime mission (July 2004) to the end of the Equinox extended mission (Sept 2010), the Cassini spacecraft will complete 140 orbits of Saturn. These orbits were predetermined years in advance to optimize science return and include a wide range of targeted flybys (Titan and icy satellites), orbital periods (from 8 to 80 days), and orbital inclinations (from equatorial to near polar). The sequencing of spacecraft pointing and instrument commanding is absolutely dependant on successful maneuvers that deliver the spacecraft to the correct location at the correct time.

During Cassini's cruise phase, propulsive maneuvers were few and far between; the Navigation (NAV) and Spacecraft Office (SCO) teams could take a month to develop the necessary maneuver commands. Developing maneuver command products involves finalizing the orbit-determination, creating the maneuver design, and then preparing and analyzing the more than 100 propulsion, attitude control, and other subsystem commands required to execute the maneuver. [3]

Now that Cassini is in orbit around Saturn, the time between these maneuvers can be as short as 3 days. The high frequency of these OTMs was strong incentive to develop the MAS process. For each OTM, the MAS process executes within 30 minutes from beginning to end. In these 30 minutes, MAS takes an Orbit Determination (OD) file, designs the maneuver, and outputs the OTM mini-sequence in both human and spacecraft-readable forms. It also outputs files that describe properties of the OTM, and reports that cross-check the numerous output products. MAS provides the capability to merge a separate spacecraft activity sequence file (SASF) and analyze the interactions of the OTM mini-sequence with the background sequence currently executing on the spacecraft. Not only has MAS reduced the development time of an OTM mini-sequence, it has also reduced the required number of people, cost, and potential for "pilot" error in developing an OTM.

III. The MAS Process

A simplified, high-level view of the MAS process is shown in Figure 2. MAS consists of Java classes, Perl, and c-shell scripts that link together the multiple software programs shown. MAS is thought of as a *process* as well as a software program because it links several sequential activities together, and allows for user intervention, analysis, and modification while it is running with each OD delivery. The user, typically a system engineer, accepts input parameters and files from the Propulsion, Attitude and Articulation Control Subsystem (AACS), NAV, and Systems teams for each OTM. Once these inputs have been verified, a MAS run is initiated with the press of a single button.[4]

The team input files and parameters are fed into NAV's Maneuver Operations Software (MOPS) along with the orbit determination (OD) solution. MOPS creates a Maneuver Profile File (MPF) that provides estimates (needed by the NAV team) for the change in velocity (DV), burn duration, and turn parameters. The MPF is passed to AACS's Maneuver Design Tool (MDT), which uses it and knowledge of the spacecraft capabilities to determine the actual values for the DV, burn duration, and turn parameters and saves this information in a Maneuver Implementation File (MIF). There are 47 parameters that uniquely define each OTM in the MIF. These are passed into the Sequence Generation Software (SEQGEN) in the form of a subroutine call statement. Depending on the size (the required delta V) of the OTM, either a Reaction Control System (RCS - for small maneuvers) or Main Engine Assembly (MEA) algorithm (or 'block' – for large maneuvers) is called. The block will accept these input parameters and implement the approximately 125 commands necessary to successfully execute the OTM. Finally, the resulting command mini-sequence is passed to Sequence Translation Software (SEQTRAN) to create the spacecraft-readable file (and its human readable equivalent) that can be reviewed and uplinked. Both SEQGEN and SEQTRAN are maintained by the Mission Sequence Subsystem (MSS). [5]

Different commands are required depending on whether an MEA or RCS burn is specified, and subsets of commands can be turned on and off in the block via MAS parameter settings, but the same fundamental sets of commands are required for each OTM mini-sequence. These commands are hard-coded in the block algorithm and are written to the OTM mini-sequence for every OTM. The OTM mini-sequence will always include commands to power on the accelerometer (for MEA burns), reset the fault protection log, power heaters on and off, put science instruments to "sleep" and "wake" them back up, set the spacecraft mass and thrust properties, turn the spacecraft to and from the burn attitude, and execute the burn. The parameters that make each OTM unique specify how to turn the spacecraft to the burn attitude (i.e., the roll and yaw turn size and rate), the duration of the burn, and the values of the spacecraft mass and thrust properties.

Figure 2 does not show the output comparisons (automated checks) that occur throughout a MAS run. An MPF-MIF comparison (comparing NAV's desired implementation with the spacecraft capabilities) is produced. Deviations between the two designs that are larger than a user defined tolerance are flagged. There is also a comparison of the SEQTRAN output (the final uplink product) to both the MIF and the MPF. Finally, the turn durations from the spacecraft's initial attitude to the burn attitude (and back again) are compared between MDT and another key piece of AACS ground software, the Kinematic Predictor Tool (KPT). These comparisons, as well as the MAS input values, OD solution, maneuver design, and any special circumstances are discussed in detail at four meetings prior to approval and uplink of the OTM command mini-sequence.

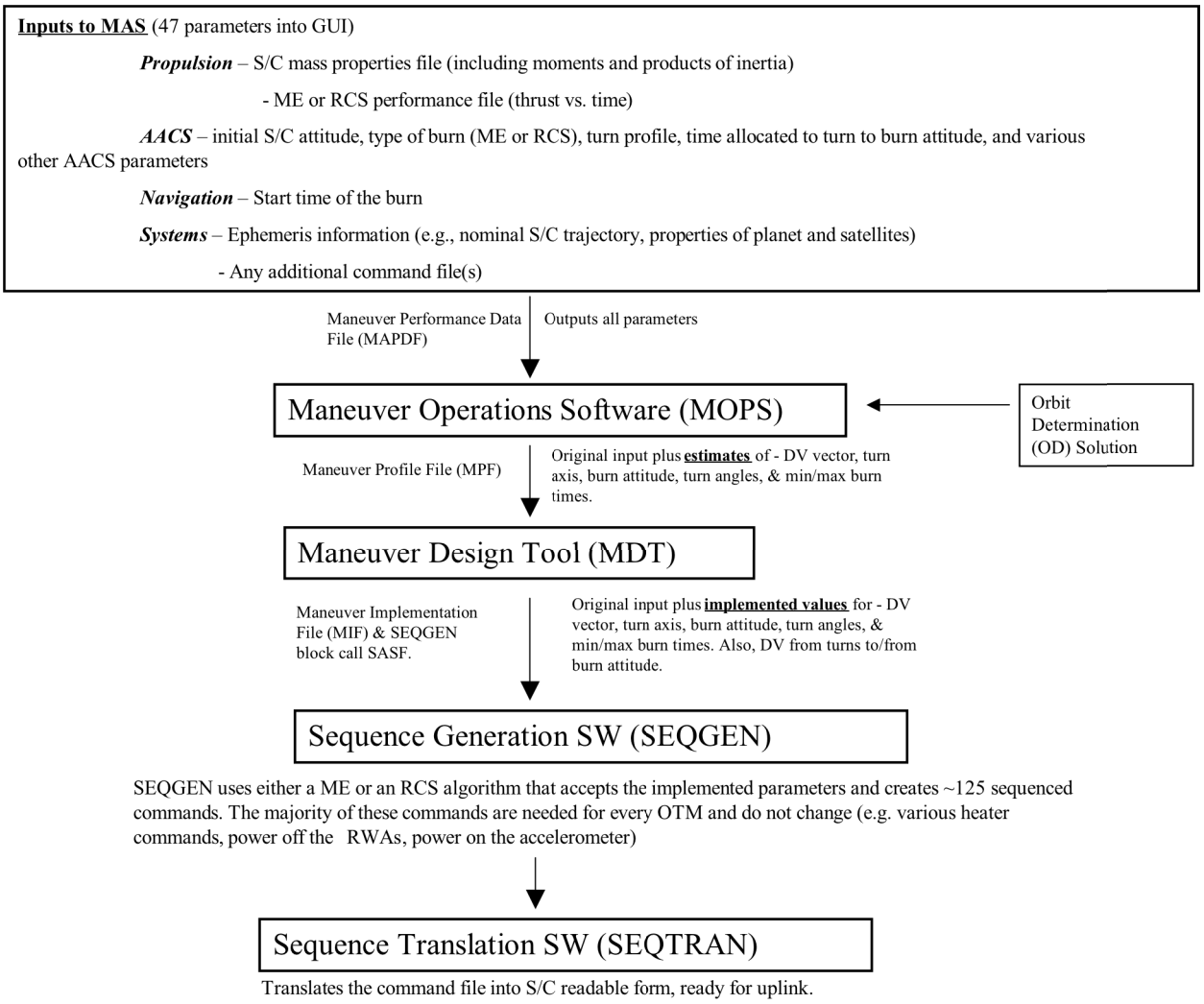

Figure 2. High-level View of MAS Process

IV. The Evolution of MAS

Since the start of the prime mission, there have been many changes to the original MAS design. The overall architectural structure has not changed; team handshaking and file transfer still occurs with a push of a button. Changes have included updating the inner block workings, increasing operational efficiency, adding new capabilities, fixing "bugs", enhancing visibility into errors and abnormalities, and deleting legacy features when no longer required.

Updating MAS for changes to the OTM blocks (including adding commands not part of the original block design) has been fairly common, but should be minimal for the remainder of extended mission. In MAS versions 5 and 6, many of the block inputs were parameterized, making them user settable. Since there has been evolving changes to the spacecraft state since launch, the organization decided to make any field that could possibly vary (e.g., which set of three out of the four reactions wheels are active) parameterized. This parameterization also means that users can avoid making hand edits to the mini-sequence, which, by bypassing internal software checks, could increase the risk of sending bad commands or command values to the spacecraft. The one drawback of having additional parameters is that mini-sequence review complexity is increased by creating more items to check. The latest block changes for MAS, delivered just recently for use in extended mission, will allow us to use the nominal MEA and RCS blocks for contingencies, greatly reducing operational complexity and risk.

Some changes added new capabilities to, and increased the operational efficiency of MAS. The capability to generate an RWA bias (bias the reaction wheels) in the case of maneuver cancellation reduced the amount of work for the AACS subsystem by at least an hour, now that it is done with a push of a button. A feature added to allow additional command files to be merged with the OTM mini-sequence allowed us to bypass going through an entirely separate Real Time Commanding (RTC) process for those files (at the expense of adding more checks up front to make sure that the product that was merged does not interfere with the background sequence and OTM mini-sequence). Another capability was added to send automated email to teams to announce that products from various stages of MAS processing were available for review. While this seems like a trivial capability, it significantly reduces human errors that can occur when generating these e-mails by hand.

Some capabilities took more than one attempt to correctly implement. This has happened when a user wrote a requirement for a new feature and a new "bug" was introduced along with it in the implementation. An example is the capability of merging other files with the maneuver mini-sequence. None of the earlier developers envisioned merging a file that included turn commands with the maneuver and running the merge through MAS. The code for making turn comparison reports expected a certain number of turn commands, and was confused when the merged command file introduced additional turn commands.

Changes were made to improve how reports were displayed to the MAS user, and to understand and clean up obsolete capabilities. Having gone through the development and review of maneuvers a few times, the users started to recognize where it would be useful for the reports to include bold font or other eye-catching cues, especially when running checks in the wee hours of the morning. A MAS run generates a directory with about 86 files in it, many of which are reviewed when evaluating an OTM. The main MAS log itself, which is reviewed after every run, is over 1500 lines long. Requirements to remove features in MAS that are no longer used is also maintained. The System Leads have to make sure that existing features are still needed with the current MAS operational scenarios.

Future challenges entering the Equinox extended mission include upgrades to the existing infrastructure to make sure that the current MAS software continues to work. Many new computer systems have faster processors, newer Operating Systems (OS), and third party software versions that sometimes necessitate reworking home-grown tools to work in the new environment. Figure 3 shows the breakdown of the MAS software has changed over time. The Spacecraft Office Team tracks all of these changes in a Ground Software System (GSS) using Microsoft Access.

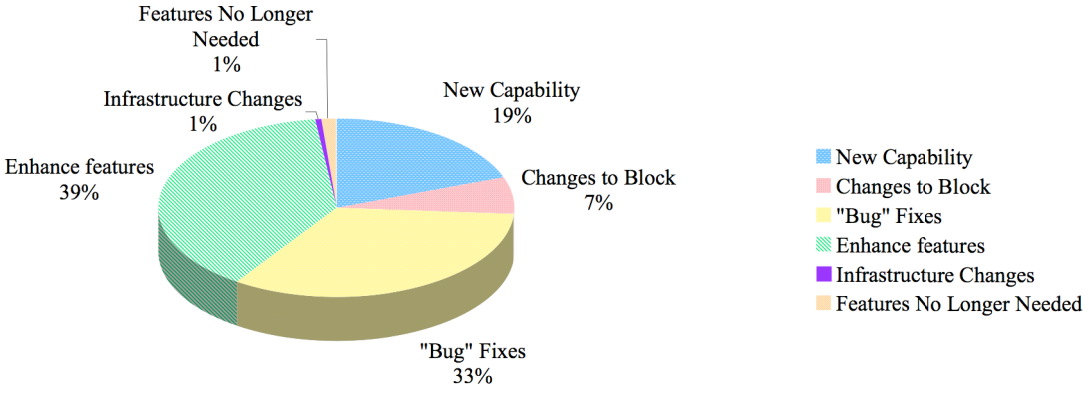

Figure 3. MAS Software Changes Breakdown

V. MAS Track Record

As of July 1, 2008, MAS had a 100% success rate developing orbit trim maneuvers that executed to within an acceptable margin of error during the prime mission. One hundred and sixty two OTMs were defined in advance for the prime mission. Six of these were deleted (i.e., it was determined that they could be removed prior to the start of development for that OTM). Forty-four OTMs were cancelled after going through at least preliminary design, having met specific cancellation criteria. While all of the OTMs have been successful to date there have been several with special circumstances.

Of the one hundred and twelve maneuvers that were executed during the prime mission, seventy two utilized the main engine assembly (MEA), and forty used the reaction control system (RCS) thrusters.[7] The executed maneuvers ranged in magnitude from 9 mm/s to over 393 m/s. RCS thrusters have been used for maneuvers ranging from 9 mm/s to 372 mm/s. These OTMs have ranged in duration from 6.875 seconds to 464.625 seconds. The relationship between duration and magnitude of RCS maneuvers is not monotonically increasing due to the monopropellant tank assembly (MTA) recharge which occurred prior to OTM-058. RCS OTMs following the MTA recharge had better efficiency than those performed before.

MEA OTMs ranged in magnitude from 238 mm/s to 393.450 m/s, and in duration from 1.523 seconds to 3068 seconds. The relationship between duration and magnitude of an MEA maneuver is not monotonically increasing due to a fuel-side repressurization which occurred prior to OTM-033. MEA OTMs following the fuel-side repressurization had better efficiency than those performed before. Figure 4 shows a statistical breakdown of maneuver magnitudes. Figure 5 shows a statistical breakdown of maneuver durations. Table 1 provides a detailed list of all defined maneuvers for the prime mission and some of their defining characteristics.

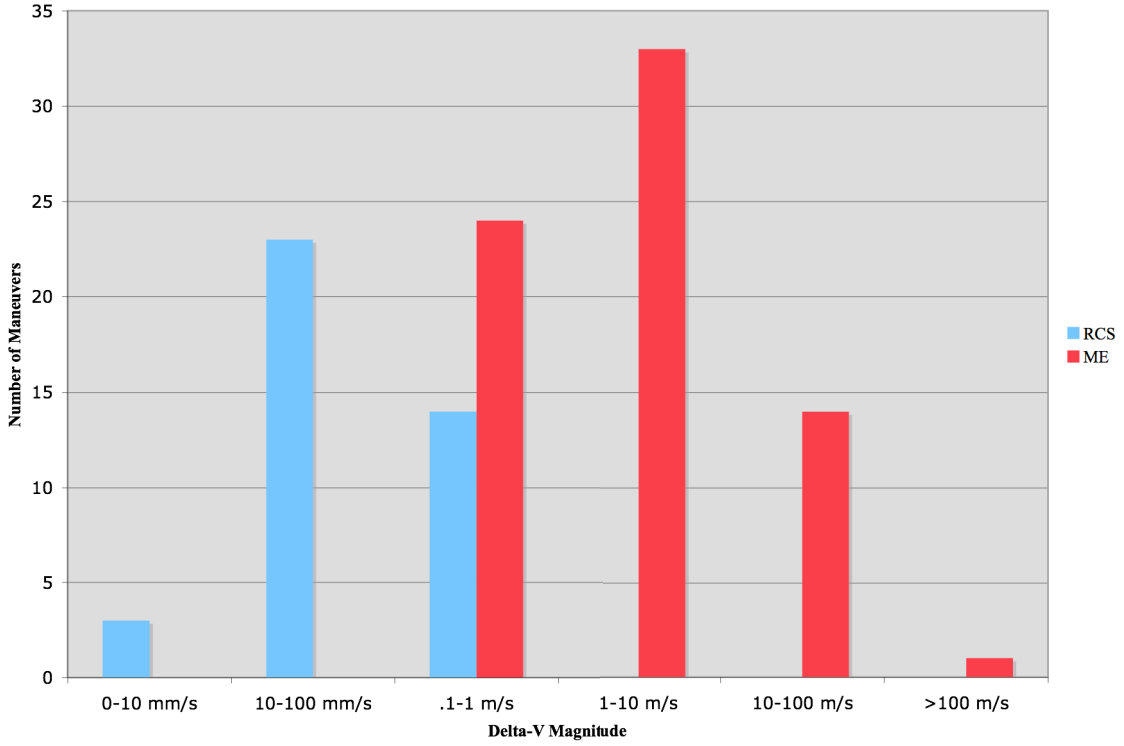

Figure 4. Cassini Prime Mission OTM Magnitude Distribution

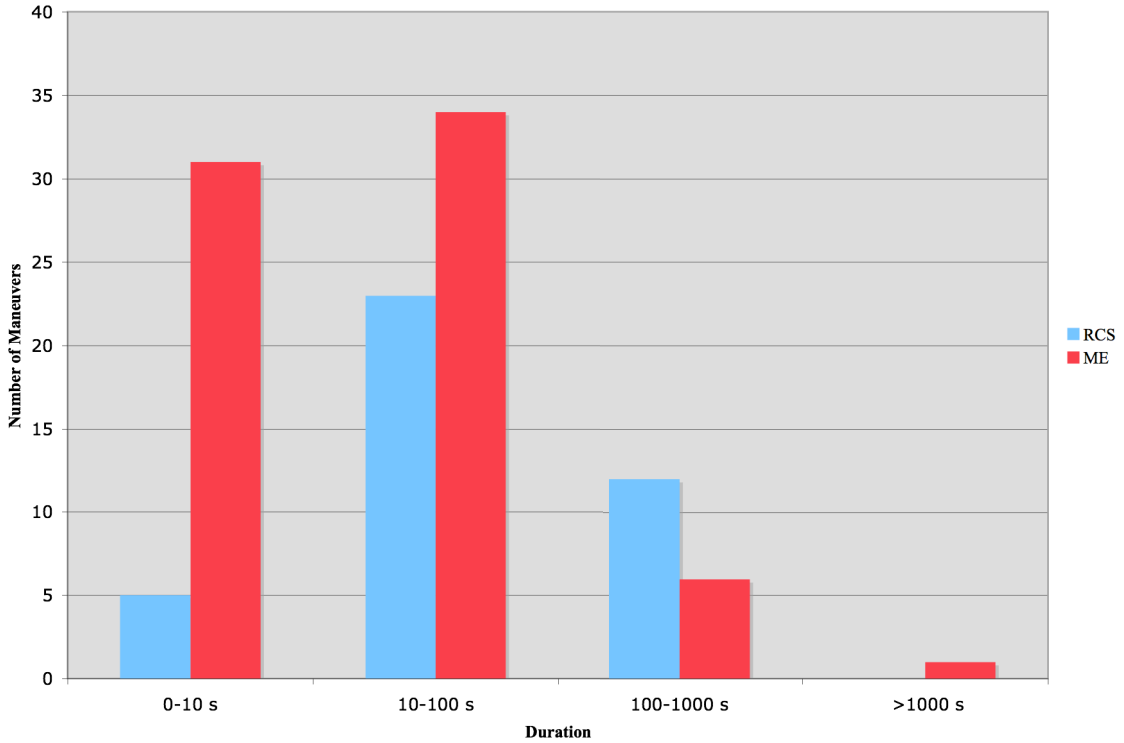

Figure 5. Cassini Prime Mission OTM Duration Distribution

Many maneuvers have had special circumstances during implementation, execution, or both. Saturn Orbit Insertion (SOI) was performed so successfully that the first OTM and its contingency (OTM-001 and OTM-001a) were cancelled. This made the first maneuver during the prime mission OTM-002, the Periapsis Raise Maneuver (PRM). The PRM was designed to ensure that Cassini would not pass too close to Saturn on subsequent orbits. With a magnitude of 393.450 m/s and a duration of 51 minutes 8 seconds, the PRM was the largest and longest maneuver of the prime mission by an order of magnitude. It was the only fully pressure-regulated burn of the tour, requiring a separate spacecraft activity sequence file (SASF, a command file) to open and close a latch valve to perform the pressure regulation. Due to its large size, it also required a special SASF that adjusted the mass properties and performed constraint monitor table (CMT) management immediately following the burn. Both hand-built SASFs were merged with the maneuver mini-sequence by MAS.

OTM-010 was the first maneuver post Huygens Probe release. The main engine is gimballed, allowing x and y translation to maintain pointing the thrust vector through the spacecraft center of mass (c.m.). This c.m. normally migrates some over the course of the mission due to propellant depletion, affecting the direction of the thrust vector. The release of the 350 kg probe significantly changed the c.m. and the resulting thrust vector direction, therefore these properties had to be updated prior to the maneuver. There was also concern that uncertainty in knowledge of the center of mass post-probe release could lead to large pointing transients. Since the star tracker can be confused by large transients, it had to be suspended so that it could not corrupt the spacecraft attitude knowledge. Both requests were implemented by merging hand-built SASFs with the MAS produced maneuver mini-sequence.

In OTM-041 we began experimenting with the MAS "settle after burn" parameter, setting it to 38 minutes to measure its effect on the post burn RWA torque "roughness". After this successful demonstration, one at 19 minutes during OTM-042, and one at 17 minutes during OTM-056, a final value of 15 minutes was eventually incorporated as part of the standard maneuver design procedure.

For OTM-061 had accelerometer (ACC) power on/off and mask commands merged with the maneuver by MAS. This additional SASF allowed the ACC to be powered on one hour before the burn to perform thruster calibration post MTA recharge.

OTM-079 needed an additional Command Data System (CDS) SASF were merged with the maneuver by MAS to zero out global variables created by a second downlink pass block (a set of commands that configure the spacecraft telemetry rate table) in the background sequence. When a second downlink pass block from the background sequence occurs during an OTM window, it can erroneously configure the spacecraft telemetry mode. If the global variables for OTM-079 had not been zeroed out, the spacecraft would have begun transmitting data while off Earth-point. Background sequence checklists for OTMs were updated as a result of this incident.

OTM-106 was the first use of a "time-of-flight" bias. This shifted the arrival time of the spacecraft to the target by a very small amount (less than 0.5s), thereby allowing a small increase in the magnitude of the burn. Increasing the magnitude of the burn is desirable in those cases where a maneuver is too small to implement, but cannot be cancelled due to downstream delta-v costs or science pointing accuracy. The "time-of-flight" bias is introduced into the maneuver design prior to running MAS, and therefore is transparent to the MAS user. This "time-of-flight" bias was also used on OTM-121.

Starting with OTM-111 we began using "hydrazine-efficient" rates for MEA OTMs. By increasing the maximum allowable off-Earth time (thereby restricting the amount of science playback during an OTM track), we were able to reduce the yaw turn rates, thereby reducing hydrazine expenditure. A compromise maximum off-Earth time was chosen such that yaw turns less than 130 degrees would use the "hydrazine-efficient" rates, while those above would use the faster allowable turn rates.

As the reaction wheel assemblies (RWAs) have continued to show degraded performance, more attention has been paid during sequence development to protecting their health and safety. Since OTMs are uplinked in real-time, there is always a risk that a bias needed to protect the RWA health and safety will not make it to the spacecraft. Starting with OTM-133, we began placing these high risk biases in the background sequence. OTM-133 was the first time we placed the bias associated with an RCS OTM in the background sequence. The bias was placed prior to the burn, and the bias option in MAS was turned off. By modifying the biasing strategy so that more biases are included in the background sequence, we've reduced the amount of real-time commanding during the MAS process.

Prior to OTM-128, the spacecraft experienced a solid state power switch (SSPS) trip which had a significant impact to the planning and execution of the maneuver. This SSPS trip was to the active traveling wave tube amplifier (TWTA), and resulted in calling system fault protection, swapping to the backup TWTA, and putting the spacecraft in safing two days before OTM-128. OTM-128 was a 13.461 m/s deterministic maneuver that was mandatory to stay on tour. The background sequence could not be recovered in two days, so OTM-128 had to be planned and executed without one. Before executing the OTM, the spacecraft had to be sufficiently recovered from safing. Special commanding to configure the spacecraft to execute an OTM without a background sequence had to be uplinked.

Analysis of the block structure showed that we could use the nominal MEA OTM block rather than a contingency block designed to execute in the "no background sequence" scenario. There was less risk using the nominal block. The contingency block had never been used in flight, there had been many modifications since the contingency block had been implemented, and it had been at least a year since the contingency block had been tested in the spacecraft simulation testbed (ITL). A block walkthrough and ITL test confirmed that the spacecraft would properly perform the OTM using the nominal block, even though a background sequence was not running. OTM-128 required other unique parameter settings, including changing the secondary pointing from the nominal to the safing secondary vector, the initial RWA rates to zero, the final RWA rates to values that would be safe while operating without a background sequence for an indefinite period, and merging required spacecraft vectors with the maneuver. OTM-128 planning, design, and testing were performed in parallel with spacecraft safing recovery exercises. The OTM executed nominally with a post-execution error of only 1.07 sigma. This was an extremely satisfactory result considering the delta-v models had to be reevaluated to take safing into account using only one tracking pass, and that the MEA was expected to perform with slightly lower efficiency due to its lower temperature.

VI. Conclusion

The successful orbit trim maneuvers that were sent and executed by the Cassini Spacecraft were all generated by the Maneuver Automation Software. This customized software tool made it possible for the Cassini Spacecraft Office Team and Navigation Team to generate maneuver files easily and efficiently. The Maneuver Automation Software and Process allowed Cassini to stay on its trajectory path and minimized the workforce required for designing the maneuver strategy around Saturn.

Table 1. Cassini Prime Mission Orbit Trim Maneuvers

OTM	Type	Burn Duration (s)	Size (m/s)	Executed?	Comments
OTM001	MEA		1.900	Cancelled	SOI cleanup – not required due to excellent SOI.
OTM001a	MEA			Cancelled	Contingency location for OTM001.
OTM002	MEA	3068.000	393.450	Executed	Periapse Raise Maneuver (PRM). Longest and largest MEA and overall burn.
OTM003	MEA	3.600	0.460	Executed	
OTM004	RCS	464.625	0.372	Executed	Largest and longest RCS maneuver.
OTM005	MEA	4.725	0.630	Executed	
OTM006	MEA	3.088	0.391	Executed	
OTM007	RCS	80.800	0.064	Cancelled	
OTM008	MEA	84.940	11.896	Executed	
OTM009	RCS	18.875	0.016	Executed	
OTM010	MEA	153.410	23.755	Executed	First post probe release OTM.
OTM010e	MEA	289.900	44.885	Cancelled	
OTM010a	RCS	147.625	0.135	Executed	
OTM011	MEA	140.330	21.563	Executed	
OTM012	MEA	120.096	18.650	Executed	
OTM013	RCS	220.500	0.203	Executed	
OTM014	MEA	4.583	0.683	Executed	
OTM015	MEA	40.165	6.230	Executed	
OTM016	RCS	10.880	0.009	Cancelled	
OTM017	MEA	2.822	0.395	Executed	
OTM018	MEA	10.262	1.568	Executed	
OTM019	RCS			Cancelled	
OTM020	MEA	5.789	0.884	Executed	
OTM021	MEA	37.350	5.821	Executed	
OTM022	RCS	67.625	0.061	Executed	
OTM023	RCS			Cancelled	
OTM024	MEA	131.534	20.525	Executed	
OTM025	MEA	2.100	0.308	Executed	
OTM026	MEA	16.570	2.589	Executed	
OTM027	MEA	15.386	2.384	Executed	
OTM028	RCS			Cancelled	
OTM029	MEA	9.173	1.317	Executed	
OTM030	MEA	91.350	14.314	Executed	
OTM031	RCS	66.875	0.059	Executed	
OTM032	MEA	2.017	0.305	Cancelled	
OTM033	MEA	176.177	27.879	Executed	
OTM034	RCS	205.950	0.180	Cancelled	
OTM035	RCS	321.250	0.290	Executed	
OTM036	MEA		0.482	Cancelled	
OTM037	RCS	33.265	0.028	Cancelled	
OTM038	MEA	92.275	14.782	Executed	
OTM039	RCS	96.625	0.090	Executed	
OTM040	RCS	297.063	0.260	Cancelled	
OTM041	MEA	77.649	12.370	Executed	Began experimenting with "settle after burn" parameter to see effects on RWA torque roughness. Set to 38 minutes. Success of demo lead to eventual use of 15 min settle after burn value as the default.

Table 1. Cassini Prime Mission Orbit Trim Maneuvers

OTM	Type	Burn Duration (s)	Size (m/s)	Executed?	Comments
OTM042	MEA	13.171	2.068	Executed	"Settle after burn" parameter set to 19 min
OTM043	RCS	63.125	0.056	Executed	
OTM044	RCS	262.265	0.233	Executed	
OTM045	RCS	43.932	0.037	Cancelled	
OTM046	RCS	151.532	0.130	Cancelled	
OTM047	RCS	198.750	0.179	Executed	
OTM048				Deleted	
OTM049	RCS	3.797	0.003	Cancelled	
OTM050	RCS	229.608	0.200	Cancelled	
OTM051	RCS	203.125	0.182	Executed	
OTM052	RCS	5.605	0.005	Cancelled	
OTM053	RCS	291.500	0.261	Executed	
OTM054				Deleted	
OTM055	RCS	4.525	0.004	Cancelled	
OTM056	MEA	2.715	0.404	Executed	"Settle after burn" set to 17 minutes
OTM057	MEA	2.206	0.326	Executed	
OTM058	RCS	53.125	0.072	Executed	
OTM059	MEA	2.973	0.444	Executed	
OTM060				Deleted	
OTM061	RCS	85.125	0.115	Executed	ACC power on/off and mask SASF merged with OTM to perform thruster calibration.
OTM062	RCS	20.185	0.026	Cancelled	
OTM063	MEA	11.975	1.890	Executed	
OTM064	RCS	47.750	0.065	Executed	
OTM065	RCS	96.875	0.132	Executed	
OTM066				Deleted	
OTM067	RCS	1.873	0.002	Cancelled	
OTM068	RCS	31.737	0.042	Cancelled	
OTM069	MEA	33.804	5.382	Executed	
OTM070	RCS	164.125	0.223	Executed	
OTM071	MEA	40.887	6.522	Executed	
OTM072	MEA	50.806	8.124	Executed	
OTM073	RCS	14.899	0.019	Cancelled	
OTM074	MEA	2.344	0.354	Cancelled	
OTM075	MEA	40.250	6.438	Executed	
OTM076	RCS	26.500	0.036	Executed	
OTM077	RCS	104.954	0.138	Cancelled	
OTM078	MEA	5.225	0.821	Executed	
OTM079	RCS	44.250	0.058	Executed	CDS SASF required to zero out global variables from a second downlink pass block.
OTM080	MEA	22.703	3.620	Executed	
OTM081	RCS	160.125	0.215	Executed	First time chose to use backup window for downstream delta-v savings.
OTM082	RCS	1.571	0.002	Cancelled	
OTM083	MEA	4.758	0.748	Executed	
OTM084	MEA	42.275	6.816	Executed	
OTM085	RCS	17.110	0.022	Cancelled	
OTM086	MEA	2.823	0.433	Executed	
OTM087	MEA	10.172	1.608	Executed	
OTM088	RCS	27.625	0.036	Executed	

Table 1. Cassini Prime Mission Orbit Trim Maneuvers

OTM089	RCS	158.500	0.209	Executed	
OTM	**Type**	**Burn Duration (s)**	**Size (m/s)**	**Executed?**	**Comments**
OTM090	MEA	14.694	2.339	Executed	
OTM091	RCS	7.625	0.011	Executed	
OTM092	RCS	1.377	0.001	Cancelled	
OTM093	MEA	1.523	0.238	Executed	Shortest MEA and overall burn.
OTM094	RCS	28.000	0.037	Executed	
OTM095	MEA	1.841	0.280	Cancelled	
OTM096	MEA	4.079	0.640	Executed	
OTM097	RCS	4.277	0.005	Cancelled	
OTM098	MEA	6.639	1.046	Executed	
OTM099	MEA	9.955	1.585	Executed	
OTM100	RCS	49.750	0.064	Executed	
OTM101	MEA	3.221	0.483	Executed	
OTM102	MEA	16.712	2.667	Executed	
OTM103	RCS	24.875	0.033	Executed	
OTM104	MEA	1.853	0.277	Cancelled	
OTM105	MEA	21.888	3.508	Executed	
OTM106	RCS	8.875	0.012	Executed	First time using "time-of-flight" bias (bias of arrival time).
OTM107	MEA	2.894	0.449	Cancelled	
OTM108	MEA	34.508	5.551	Executed	
OTM109	RCS	14.500	0.021	Executed	
OTM110	MEA	0.512	0.069	Cancelled	
OTM111	MEA	34.257	5.515	Executed	First use of hydrazine efficient rates.
OTM112	RCS	11.962	0.014	Cancelled	
OTM113	MEA	4.303	0.678	Executed	
OTM114	MEA	75.567	12.218	Executed	
OTM115	RCS	25.500	0.033	Executed	
OTM116	MEA	4.585	0.731	Executed	
OTM117	MEA	49.037	7.947	Executed	
OTM118	RCS	6.875	0.009	Executed	Smallest RCS and overall maneuver 9.114 mm/s. Shortest RCS maneuver.
OTM119	RCS	13.875	0.019	Executed	
OTM120				Deleted	
OTM121	RCS	7.000	0.009	Executed	
OTM122	RCS	39.611	0.049	Cancelled	
OTM123	MEA	2.598	0.397	Executed	
OTM124	RCS	28.897	0.035	Cancelled	
OTM125	MEA	2.975	0.465	Executed	
OTM126				Deleted	
OTM127	RCS	17.593	0.021	Cancelled	
OTM128	MEA	83.415	13.461	Executed	Spacecraft in safing. SSPS trip swapped us to backup TWTA. Maneuver executed with no background sequence, using the nominal MEA block with special parameter settings. First OTM using RCS roll turn (during tour). Safing recovery and setup files needed on pass prior to OTM.
OTM129	RCS	79.000	0.099	Executed	
OTM130	RCS	14.375	0.020	Executed	
OTM131	MEA	8.168	1.308	Executed	
OTM132	MEA	6.013	0.955	Executed	
OTM133	RCS	50.750	0.063	Executed	
OTM134	MEA	7.207	1.148	Executed	

Table 1. Cassini Prime Mission Orbit Trim Maneuvers

OTM	Type	Burn Duration (s)	Size (m/s)	Executed?	Comments
OTM135	MEA	96.475	15.737	Executed	
OTM136	RCS	10.625	0.014	Executed	
OTM137	MEA	4.178	0.657	Executed	
OTM138	MEA	59.073	9.620	Executed	
OTM139	RCS	7.125	0.009	Executed	
OTM140	RCS	3.817	0.004	Cancelled	
OTM141	MEA	12.551	2.032	Executed	
OTM142	RCS	22.862	0.027	Cancelled	
OTM143	MEA	17.638	2.861	Executed	
OTM144	MEA	227.850	37.383	Executed	
OTM145	MEA	1.725	0.275	Executed	
OTM146	MEA	42.600	7.005	Executed	
OTM147	MEA	6.798	1.098	Executed	
OTM148	RCS	1.166	0.001	Cancelled	
OTM149	MEA	16.673	2.742	Executed	
OTM150	RCS	40.500	0.050	Executed	
OTM151	RCS	2.810	0.003	Cancelled	
OTM152	MEA	20.163	3.299	Executed	
OTM153	MEA	3.062	0.485	Executed	
OTM154	RCS	3.801	0.004	Cancelled	
OTM155	MEA	7.100	1.145	Executed	
OTM156	RCS	155.125	0.192	Executed	
OTM157	RCS	2.135	0.002	Cancelled	
OTM158	RCS	130.127	0.156	Cancelled	
OTM159	MEA	73.547	12.146	Executed	

Acknowledgments

The authors would like to acknowledge the contributions of Michael Pelligrin, MAS software developer; Troy Goodson, Sean Wagner, Shadan Ardalan members of the Cassini Navigation Team; Thomas Burk, Allan Lee, members of the Cassini AACS Team; Todd Barber, Loucas Christodoulou, members of the Cassini Propulsion Team; Andrew Ging, member of the Cassini Power Team; Jerry Millard, member of the Cassini Thermal and Devices Team; David Beach, Susie Adamiak, members of the Cassini CDS Team; Joel Signorelli, Shaun Standley, Jeannette Illsley, Torsten Zorn, Katalin Herman, David Herman, and Arden Acord, members of the Flight System section at JPL; and Julie Webster, Cassini SCO Manger. These people improved the technical accuracy of this paper through their accounts and careful reading. Any remaining errors of fact or interpretation are the authors' responsibility. Several Cassini MAS requirements were mentioned in this paper. In case of conflict between requirements mentioned here and those given in official Cassini documents, requirements given in the official Cassini documents have precedence. The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] A. Lee and G. Hanover, Jet Propulsion Laboratory, Pasadena, CA AIAA-2005-6269
AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, California, Aug. 15-18, 2005 Spacecraft Attitude Control System Flight Performance

[2] NTR 42137, Maneuver Automation Software, July 2007

[3] T. Burk, Jet Propulsion Laboratory, Pasadena, CA AIAA-2005-6270 AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, California, Aug. 15-18, 2005 Attitude Control Performance During Cassini Trajectory Correction Maneuvers

[4] Maneuver Automation Software (MAS) User's Guide. JPL Internal Document D-28416.

[5] Troy Goodson, Amy Attiyah, Brent Buffington, Yungsun Hahn, Joan Pojman, Bob Stavert, Nathan Strange, Paul Stumpf, Sean Wagner, Peter Wolff, and Mau Wong, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA Proceedings of the 16th AAS/AIAA Space Flight Mechanics Conference, AAS 06-219, Jan 2006. Cassini-Huygens Maneuver Automation for Navigation.

[6] G. Carr and A. Ging, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA AIAA-2007-4762 5th International Energy Conversion Engineering Conference and Exhibit (IECEC), St. Louis, Missouri, June 25-27, 2007 The Cassini Power System Performance over the Last Decade

[7] S. V. Wagner, E. M. Gist, T. D. Goodson, Y. Hahn, P. W. Stumpf, and P. N. Williams, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA AIAA-2008-6748 Communicating Navigation Data Inside the Cassini-Huygens Project: Visualizations and Tools