Orbit Control Operations for the Cassini-Huygens Mission

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The Cassini-Huygens spacecraft was launched in 1997 as an international and collaborative mission to study Saturn and its many moons. After a seven-year cruise, Cassini began orbiting Saturn for a four-year tour. This paper gives an overview of the maneuver operations component of Cassini navigation. Specifically, this paper reviews the orbit control and staffing strategies developed and executed as a result of these maneuver experiences. Examples of maneuver processing and analysis are also shown.

I. Introduction

The Cassini-Huygens spacecraft was launched in 1997 as an international and collaborative mission to study Saturn and its many moons. After a seven-year cruise, Cassini began orbiting Saturn for a four-year tour. This tour consists of 157 planned maneuvers, and their back-up locations, designed to target 52 encounters, mostly of Saturn's largest moon Titan. One of the mission's first activities was to release the Huygens probe to Titan in December 2004. Currently in its last year of the prime mission, Cassini-Huygens continues to obtain valuable data on Saturn, Titan, and Saturn's other satellites. Return of this information is in large part due to a healthy spacecraft and successful navigation. A two-year extended mission, beginning July 2008, will offer the opportunity to continue science activities. With a demanding navigation schedule that compares with the prime tour, the Cassini Navigation team relies on operations procedures developed during the prime mission to carry-out the extended mission objectives.

Current processes for orbit control operations evolved from the primary navigational requirement of staying close to predetermined targeting conditions according to Cassini science sequence planning. The reference trajectory is comprised of flyby conditions to be accomplished at minimal propellant cost. Control of the planned reference trajectory orbit, and any trajectory updates, is achieved with the execution of Orbit Trim Maneuvers (OTMs). The procedures for designing, processing, and analyzing OTMs during Cassini operations is presented. First, a brief overview of the Cassini-Huygens Mission is given, followed by a general description of navigation. Orbit control and maneuver execution methods are defined, along with an outline of the orbit control staffing and operations philosophy. Finally, an example schedule of orbit control operations is shown.

II. Cassini-Huygens Mission

Cassini-Huygens is the first mission solely dedicated to studying the Saturnian system. While Pioneer 11, Voyager I, and Voyager II orbiters made distant flybys of Saturn in 1979, 1980, and 1981, respectively, the Cassini spacecraft has orbited Saturn since 2004. Sponsored by the National Aeronautics and Space Administration, the European Space Agency, and the Italian Space Agency, the Cassini-Huygens project is the collaboration of approximately 400 scientists and engineers located at JPL, various space centers, research institutes, and universities in the United States and Europe. The spacecraft contains twelve science instruments, each devoted to specific science objectives such as: optical remote sensing of Saturn, its

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rings and moons; microwave remote sensing for moon mapping; and detection of field, particle and waves around Saturn. These instruments aid scientists with their understanding of Saturn and its many moons. Specifically, the prime mission plan includes 40 plus encounters of Saturn's largest moon, Titan, close flybys with Hyperion, Dione, Rhea, Enceladus and Iapetus, and distant flybys with other icy satellites such Mimas. Table 1 lists milestones and recent science results of the Cassini prime tour.[1]

Table 1. Cassini-Huygens Prime Tour Milestones and Science Highlights

Date	*Event*
October 15, 1997	Launch of Cassini-Huygens Spacecraft
December 30, 2004	Jupiter flyby
July 1, 2004	Saturn Orbit Insertion
December 25, 2004	Huygens Probe release
January 14, 2005	Huygens Probe lands on Titan
March 9, 2005	First Enceladus flyby
2005	Identification of Titan's Lakes
2006	Discovery of Enceladus Water Plumes
	Saturn's New Rings
June 16, 2007	100th executed maneuver
2007	Close-up of Iapetus' Ridge
	Saturn's Northern hexagon and Southern hurricane poles
June 30, 2008	End of Prime Tour

II.A. Navigation

Cassini Navigation is responsible for the design of the reference trajectories; and estimation, prediction, and control of the spacecraft. This involves the intricate and immediate collaboration between several subsections. Specifically, Cassini Navigation includes four components: trajectory design, orbit determination, optical navigation, and trajectory control via orbit trim maneuvers, as depicted in Figure 1.

The *reference trajectory* includes all of the prime tour's targeting conditions, negotiated for maximizing science objectives. The reference trajectory is updated at least once a year to reflect changes in target conditions, such as flyby altitudes. The trajectory analyst ensures all science targets are met with minimum propellant usage. Maneuvers generated in the reference trajectory only include deterministic maneuvers, or maneuvers of significant size that shape the trajectory.

To maintain the planned trajectory, velocity changes, known as *maneuvers*, are executed by the spacecraft while minimizing propellant use. Note that maneuvers performed can produce execution-errors which result in deviations from the reference trajectory. Maneuver analysts prepare maneuver designs and present targeting strategy recommendations to Cassini Navigation. More details of maneuver activities are presented later in this paper.

Maneuver designs are based on the constant, usually daily, understanding of the current spacecraft's orbit and satellite ephemeris as given by *orbit determination*. Orbit determination incorporates physical constants, tracking predictions, telemetry, and planetary and satellite ephemeris files to establish spacecraft location.[2,3] An orbit determination analyst monitors a maneuver burn, provides a reconstructed trajectory, and updates modeling parameters.

Spacecraft location obtained via receipt of range and rate data is also validated with satellite images or *optical navigation*. Optical Navigation analysts receive optical images and supply image location error estimates to support orbit determination data.

Interaction between all of these components is constant with the requirement for fast, reliable, and consistent product turn-around. Overall, the three primary objectives for Cassini Navigation are to

1. Estimate and predict the state of the spacecraft, major satellites and the planets;
2. Control the flight path of the spacecraft;
3. Generate the reference trajectories.

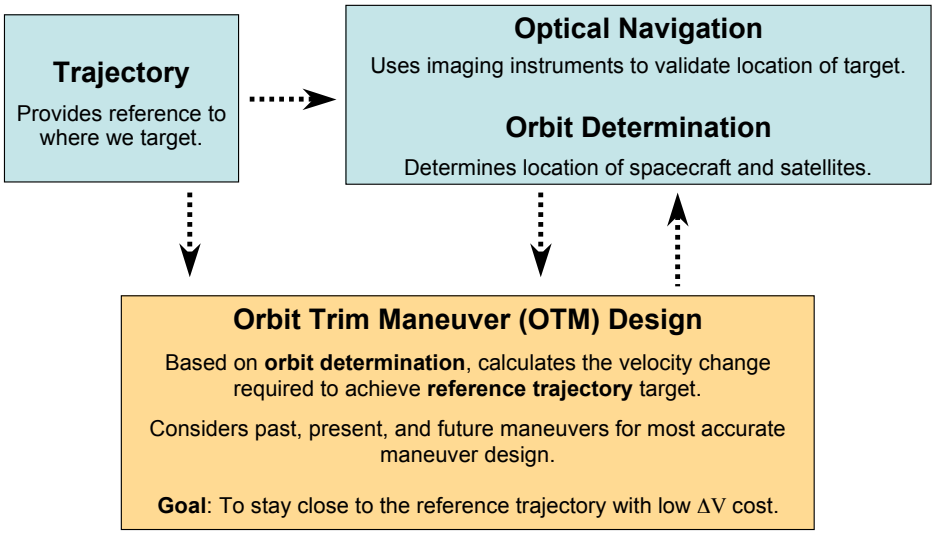

Figure 1. Interaction between Cassini Navigation

These objectives are achieved with efficient analysis of orbit determination and maneuver designs. In addition, Cassini operations entail the interaction of three major teams: the spacecraft office (spacecraft hardware, command uplink, and sequences); science planning (scheduled observations); and navigation. To satisfy compact time schedules, navigation operations and procedures were developed to efficiently produce results required to maintain the tour's objectives.

Navigation of the Cassini-Huygens spacecraft incorporates the execution of Orbit Trim Maneuvers (OTMs). An OTM maintains the spacecraft's proximity to the reference trajectory via targeting components. Previously written papers describe maneuvers planned and performed during interplanetary cruise and the first three years of the Saturn tour.[4–9] The prime tour experiences were utilized for extended tour maneuver planning.

III. Orbit Control Strategy

The navigation strategy since launch has been to target the spacecraft to encounter conditions defined in the reference trajectory. In particular, the navigation strategy during the Saturn tour has been to target to three B-plane parameters;[10] the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$, and the temporal component time-of-flight (TF). In general, the control of the spacecraft trajectory has been accomplished with three propulsive Orbit Trim Maneuvers (OTMs) between each targeted Titan or icy satellite encounter: a flyby cleanup maneuver, an apocrone (Saturn-relative apoapsis) targeting maneuver, and an approach targeting maneuver. Past studies have shown that any additional maneuvers between encounters do not significantly lower the ΔV requirements.[11] Figure 2 illustrates these maneuver locations for an outbound-to-inbound[a] Titan transfer.

The first maneuver targeted to an encounter is normally performed near apocrone (within a few days) to "shape" the trajectory in order to achieve the flyby conditions. During the first year of the extended mission, several of these trajectory shaping maneuvers are near periapsis due to multi-revolutions between targeted encounters. The approach maneuver, the last targeting maneuver, is usually executed three days before an encounter to resolve execution errors from the previous targeting maneuver and to achieve as accurate flyby conditions as possible. The approach maneuver location avoids interference with science measurements during the encounter period and allows enough time to perform a backup maneuver if necessary. Usually performed three days after an encounter, the cleanup maneuver is used to correct trajectory errors from a previous flyby. The cleanup maneuver location depends on the time required to reliably converge the orbit determination (OD) process after an encounter, and the time required for maneuver designing, sequencing,

[a]An outbound flyby occurs after pericrone (Saturn-relative periapsis). Conversely, an inbound encounter occurs before pericrone.

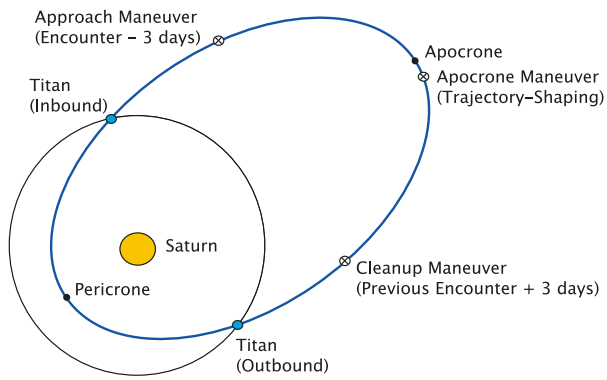

Figure 2. Maneuver Strategy for Saturn Tour

and uplinking.

III.A. Targeting Options

Several maneuver and targeting options exist and are dependent on a given scenario. These options include:

- *Nominal maneuver strategy for the deterministic maneuvers.* As described in the previous section, the most common strategy for the cleanup and trajectory-shaping maneuvers are to chain the two maneuvers to control the three B-plane flyby conditions at the targeted encounters. This strategy is based on a single encounter-to-encounter orbit transfer consisting of three planned maneuvers to achieve target conditions: a cleanup maneuver that occurs three days after the most recent encounter, a trajectory-shaping deterministic maneuver, at most times performed near apocrone, and, if necessary, a fine tuning maneuver is executed three days before the next encounter. The cleanup and trajectory shaping maneuvers which are optimized or "chained" together to achieve the flyby target for a lower ΔV. In addition, this nominal strategy includes additional downstream encounters (beyond the current encounter) and maneuvers are optimized to further reduce ΔV. Besides providing an optimal distribution of the ΔVs over multiple legs, this optimization strategy helps control reference trajectory asymptote errors without actively altering downstream flyby aimpoints after each encounter. Another benefit of this strategy is that the designed cleanup maneuver ΔVs are less sensitive to maneuver time shifts.[12]

- *Maneuver combinations.* Orbit geometry and prior maneuver performance can create opportunities to combine or "lump" two maneuvers together to achieve an encounter target. Comparisons between the nominal and lumped maneuver strategies are made, with consideration of downstream maneuver cost and trajectory deviations.

- *Cancellation.* Cancellation of a maneuver offers additional targeting strategies. In general, when a maneuver design produces a ΔV less than 9 mm/s, analysis for maneuver cancellation and target biasing is conducted. The cancellation of a maneuver is favored because it reduces spacecraft use and ground-system stress at moderate propellant cost, but only takes place if certain conditions are met. Also, consideration is given to maneuver size and whether cancellation of a maneuver is: allowable to stay on tour; acceptable given changes to the trajectory and the next target asymptote; and satisfactory for navigation pointing and science requirements. Also, a review is made on effects to downstream maneuvers and ΔV penalties. During the second year of the Cassini tour, opportunities for maneuver cancellation analysis became more frequent due to the accuracy of maneuvers performed by Cassini. As result, a streamlined procedure was developed to address the above conditions.[8]

- *X,Y,Z Targeting.* There is an option in which the cleanup maneuver can be targeted to the Cartesian state of the apocrone or trajectory shaping maneuver location. This strategy is called "X,Y,Z targeting"

and differs from the nominal strategy because it controls the trajectory between the targeted encounters. The perturbed state location for the apocrone maneuver is constrained and chosen when there is little to no science observations. Conversely, this strategy can be utilized to target a specific location for science. The "X,Y,Z targeting" strategy usually increases the ΔV costs and implementation is contingent on the project level cost and benefit analysis.

- *Target Biasing.* Whether a maneuver is above or below the 9 mm/s minimum, a target biasing can be introduced. Target biasing entails changes in the 'spatial' component of the B-plane ($\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$), when there is a substantial saving in downstream cost. As a result of several prior maneuvers being cancelled, the accumulated asymptote errors produce a sizable negative region in flyby cost contour as in Figure 3. Biasing $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ components can bring the post-flyby trajectory closer to the reference by reducing the accumulated asymptote errors and at the same time provide opportunities to cancel further downstream maneuvers. Note that prospects for target biasing are limited and are dependent on the encounter's science activities. Typically, there is at the most one week to present the alternate aimpoint to the scientists. Then the project meets and reaches a decision based on the science and navigation team's analysis and recommendations.

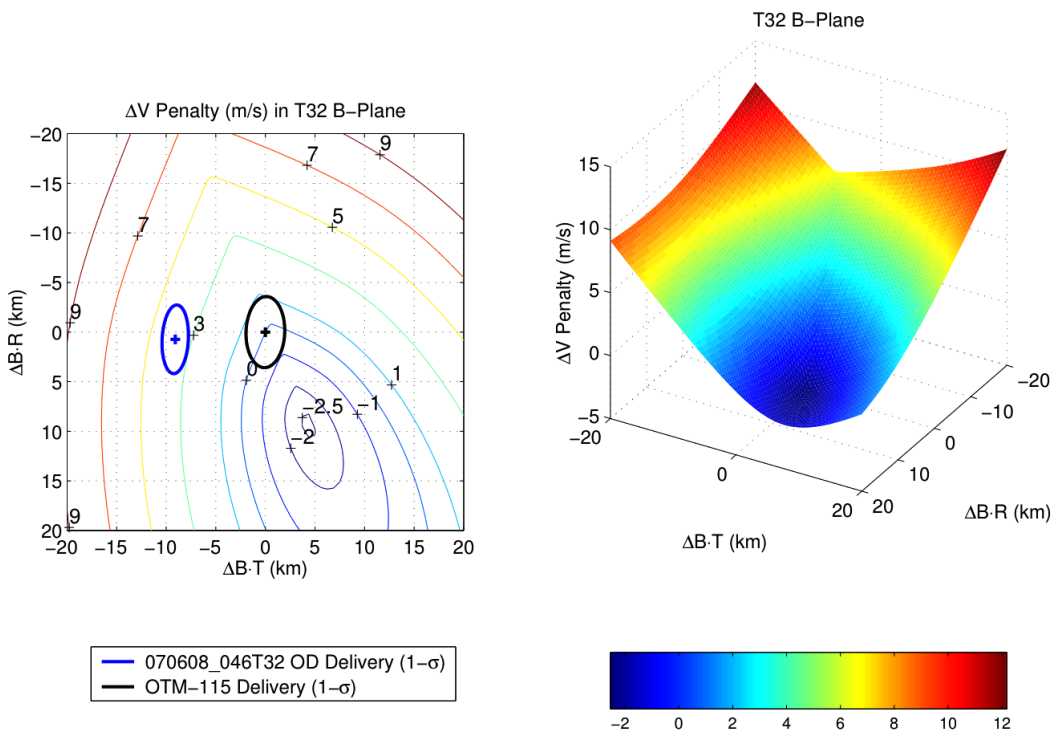

Figure 3. Maneuver Cancellation Package, Contour plot for OTM-115

- *Backup Maneuver Location.* Backup locations for all maneuvers are scheduled and designed. Commonly placed one day after the prime location, this option is considered if the ΔV cost is lower (with acceptable downstream effects) than the prime location and/or satellite tracking is unavailable for command uplink. During the prime tour, two different maneuvers placed at the backup location were executed, OTM-081-BU and OTM-123-BU. As example, for OTM-081, the backup maneuver design was smaller than the prime maneuver location design. This difference could have been due to a singularity between the two maneuver locations. The singularity refers to the observation of the TF gradient being coplanar to $\mathbf{B}\cdot\mathbf{R}$ and $\mathbf{B}\cdot\mathbf{T}$ gradients.

IV. Maneuver Operations and Staffing Strategy

Maneuver analysts for the Cassini Navigation team are comprised of members of JPL's flight path control group. With specialized experience in orbital mechanics, engineering systems, mathematics, and computer programming, maneuver analysts support the navigation team by producing maneuver strategies and performance options. During Cassini operations, a maneuver analyst: obtains an orbit determination (OD) solution; accesses target aimpoints; evaluates need for maneuver with statistical analysis; makes recommendations for maneuver execution or cancellation; transfers maneuver inputs to spacecraft team; generates presentation materials for maneuver approval meetings; and preserves maneuver profile details for navigation archives. When not performing operations duties, maneuver analysts conduct analysis and studies on past, present, and future maneuver locations. Other activities include maneuver/orbital mechanics studies and software/scripting development.

Within the Navigation Team, there are six maneuver analysts who are paired for OTM operations with one maneuver analyst as the prime and the second analyst as the back-up. The staffing strategy was developed to include a pair of maneuver analysts who are scheduled to work together on three OTMs, starting with the approach maneuver, the cleanup maneuver, and the trajectory-shaping apocrone/preicrone maneuver. This system is effective for maneuver staffing because approach maneuver cancellation or implementation analysis has a great bearing on the cleanup maneuver. This system is also most efficient since the prime maneuver analyst who sets-up the design of the encounter cleanup maneuver is indirectly preparing the design for the trajectory-shaping maneuver. In addition, the complicated set-up of the cleanup maneuver in the Maneuver Automation Software[13] can be checked out by perturbing a pre-encounter OD solution at a given time. Furthermore, interactive scripts developed and used for maneuver file delivery and notification allow for additional time savings.

Overall, maneuver analyst staffing must meet the aforementioned requirements due to hiring and training time delays. Additionally, all maneuver analysts should be proficient in all aspects of operations to allow for staff vacations, rescheduling, or emergencies.

V. Maneuver Execution

The Cassini tour of Saturn was designed to take advantage of the substantial gravity assists provided by each Titan flyby, with closer flybys imparting larger velocity changes, or ΔVs, to the spacecraft. For instance, a Titan flyby at an altitude of 950 km and a $\mathbf{V}_\infty$ of 6 km/s supplies an equivalent ΔV of about 800 m/s to Cassini. During the tour, propulsive maneuvers are necessary not only to correct the spacecraft's trajectory due to flyby dispersions, but also to change the trajectory when Titan gravity assists are not sufficient.

Maneuvers are accomplished through the use of two independent propulsion systems. The bi-propellant main engine assembly (MEA), with two main engines MEA-A and MEA-B, performs large maneuvers, while the Reaction Control System (RCS) thrusters handle small trajectory corrections.[14]

As a general rule, all maneuvers > 0.3 m/s (engine "cut-off" boundary) are performed on MEA and all maneuvers ≤ 0.3 m/s are performed on RCS. Main engine MEA-A has been used for every main engine burn since launch. The coordinate system for the spacecraft is presented in Figure 4: $X_{S/C}$, $Y_{S/C}$, and $Z_{S/C}$. The $Z_{S/C}$ axis points from the high gain antenna to the MEA, the $X_{S/C}$ axis points away from where the Huygens probe was attached, and the $Y_{S/C}$ axis completes the right-handed system.

Several activities associated with a maneuver contribute to the total ΔV imparted to the spacecraft. These include, but are not limited to, dead-band tightening and limit cycling, roll and yaw turns, pointing-bias-fix turns, the burn itself, and Reaction Wheel Assembly (RWA). Generally, only the RWA bias ΔVs are not considered in the total ΔV, with other ΔV events added when analyzing execution errors (except for RCS burns, where dead-band tightening and limit cycling are also considered in the total ΔV).

Maneuver execution errors are modeled to understand propulsion system performance and to help improve fuel usage prediction. Specifically, the Gates model incorporates the magnitude and pointing errors for MEA and RCS. Updates to the execution-error model have been made and implemented throughout the course of the mission.[15]

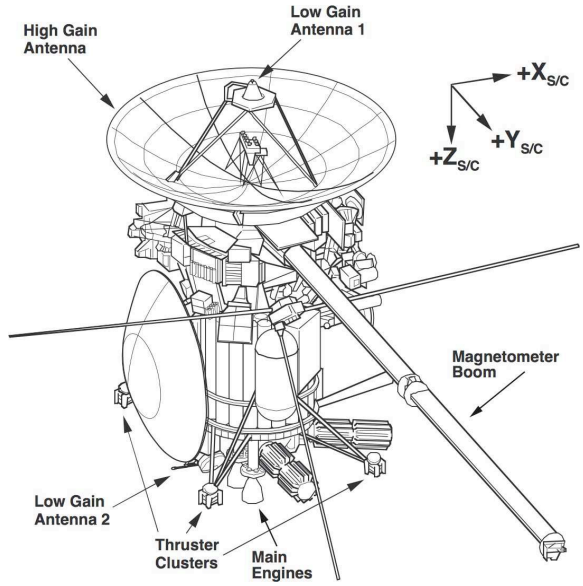

Figure 4. Cassini-Huygens Spacecraft

V.A. Prime Tour Objectives and Maneuver Experience

The prime tour consists of 160 planned maneuvers and their backup locations, with encounters to Titan, Hyperion, Dione, Rhea, Enceladus, and Iapetus. Navigation activities included delivering of the Huygens probe, staying on the planned trajectory, and producing quick orbit determination and maneuver design and analysis during several repeated 16-day orbits during the last two years of the tour. Maneuver execution and performance were also essential in placing Cassini in an inclined Saturn orbit for a pi-transfer, a sequence preferred for Saturnian science observations.[16,17] The success of the prime tour navigation can be attributed to careful delivery of maneuver design and assessment of maneuver execution.

As of March 2008, over 120 maneuvers have been successfully executed since launch in 1997. Table 2 shows the number of maneuvers and encounters performed since Saturn Orbit Insertion (July 1, 2004). For maneuver analysis and review, the prime tour was divided into four sections.

Note that although the number of encounters and maneuvers increased towards the end of the tour, not all maneuvers were executed. This is due to the cancellation and deletion of maneuvers. Maneuver analysis showed the deletion of apocrone maneuvers between 20-day outbound-to-inbound encounters not only simplified operations, but improved reconstruction of the preceding cleanup maneuvers, improved OD convergence for encounter approach maneuvers, and reduced workload. Furthermore, cost of maneuver deletion is within in an acceptable range in the mean of predicted ΔV statistics.

Table 2. Planned and performed maneuvers during the prime tour.

Tour Section[a]	*Date Range*	*Encounters*	*Maneuvers Planned*	*Maneuvers Executed (as of 3/08)*
First	Jul-04 to Aug-05	8	26	21
Second	Aug-05 to Jul-06	13	39	23
Third	Jul-06 to Jul-07	18	54	39
Fourth	Jul-07 to Jul-08	13	41	24

[a]As determined by papers written by the maneuver team

V.B. Extended Tour Objectives and Maneuver Planning

The two-year extended mission begins July 1, 2008 and ends July 1, 2010. The mission and science plan is just as active as the last two years of the prime tour. The extended mission encompasses 36 close flybys

of Saturn's moons Titan, Enceladus, Rhea, and Dione, along with 95 planned maneuvers and their backup locations. The extended mission features three "double" flybys, or back-to-back flybys of Titan and another satellite using no maneuvers in between the two encounters. Of the 33 targeted flybys in the extended mission, 18 encounters will be performed when Cassini has a 16-day orbit period, thus approximately one maneuver per week is planned. As with the prime tour, there is a pi-transfer that takes place during March 2009.

In Figure 5, the frequency of maneuvers to take place from April 2008 through the end of the extended mission are shown. The majority of the maneuvers take place within 5 days of each other. This schedule requires fast turn around of maneuver products, and motivates the need for Navigation team staffing to remain at prime mission levels.

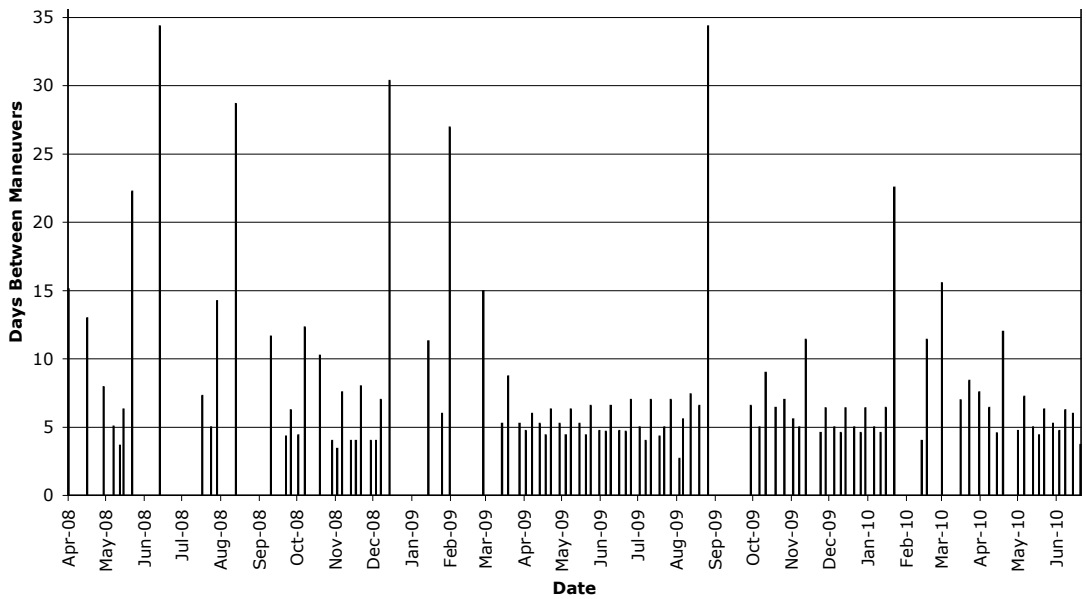

Figure 5. Frequency of maneuvers through the end of the extended mission.

V.C. Maneuver Design Process

The maneuver design process consists of the parameter set-up, target strategy review and statistical analysis for an OTM as defined by JPL-ISO 9000. This process includes the implementation of tools that produce presentation packages and delivery files. Figure 6 shows the flow of activity for designing a maneuver. The steps for the maneuver process by seven major steps:

1. *Derive Maneuver Strategy.* Define maneuver parameters according to reference trajectory. Prepare namelists and input files; anticipate maneuver size (MEA or RCS).

2. *Prepare Prospective Targeting Strategies.* Set-up nominal strategy according to maneuver orbit location (cleanup, shaping, or approach). Prepare other targeting strategy inputs (e.g., cancellation, biasing, etc.) if necessary.

3. *Access Orbit Determination Solution.* Obtain current orbit determination information. A minimum of three orbit determination solutions are scheduled per maneuver design. Determine current and downstream maneuver sizes.

4. *Evaluate Result.* Review maneuver solution and compare with statistical predictions. Conduct additional analysis and studies if necessary.

5. *Present Maneuver Design.* Prepare presentation packages and supporting design documents for Navigation team and Project Approval.

6. *Deliver Approved Maneuver Design.* Transfer maneuver parameters to Spacecraft Operations Team for maneuver command and uplink.

7. *Document.* Produce maneuver details for archives.

The tools used to produce relevant files and presentation packages are Search Path Vary (SEPV); Maneuver Operations Software-Maneuver Automation Software (MOPS-MAS); Linear Analysis of Maneuvers with Bounds and Inequality Constraints (LAMBIC); and a suite delivery scripts. SEPV performs trajectory searches on finite burn parameters for maneuvers with deterministic, or trajectory-shaping components. LAMBIC produces predicted ΔV mean, 1-σ and ΔV95 statistics for all deterministic and statistical maneuvers. LAMBIC also incorporates execution errors and orbit determination models. Delivery scripts automate the transfer of maneuver files for internal Navigation team reviews and official file deliveries for command uplink.

V.D. Maneuver Automation Software

After the Huygens probe release, the frequency of orbit trim maneuvers increased. During the first year of the four-year prime mission, maneuvers took place several weeks or months at a time. The planned trajectory for the latter part of the tour required the execution of maneuvers at least once a week. Given this anticipated schedule, the Navigation and Spacecraft office made an unified effort to develop a tool to support the processing of subsystem inputs and file transfer for a maneuver design. Development for the Maneuver Automation Software (MAS) began before the prime tour and was available for implementation after launch. MAS is composed of two major components, spacecraft office software (SCO-MAS), and Maneuver Operations Software (MOPS-MAS). The scope of this discussion includes MOPS-MAS details, while a general MAS description can be found in Reference 13.

In general, the Maneuver Operations Software (MOPS-MAS) automates the design, file transfer, and retrieval of a maneuver design. The role of the maneuver analyst is to prepare the MOPS-MAS configuration input file for a maneuver. Using MOPS-MAS to process inputs using the most recent orbit determination solution through several programs (such as SEPV and TWIST, a parameter post-processor) reduces human error, provides parameter file name consistency, and allows opportunities for other targeting strategies, scenarios, and contingencies. Another major component of MOPS-MAS is the generation of presentation and geometry packages used for maneuver design review meetings. The automation of these packages enables the maneuver analysts time to consider the maneuver design and logic. In addition, MOPS-MAS can be used to set-up and design a maneuver in the backup location. Finally, MOPS-MAS allows for rapid turn-around of maneuver designs during times of short orbits, and maintains consistency between the Navigation, Spacecraft office, and Sequence teams.

V.E. Maneuver Products and Presentation

Since maneuver results need to be coordinated among several subsystems, numerous reviews of a maneuver design are made. Orbit control products are based on the navigation required to achieve the targets in the reference trajectory. The schedule of products is driven by the maneuver locations in the tour. As example, when a target and its associated maneuver locations are known, the following nominal chain of activity occurs:

- Project-wide **encounter strategy meeting**. The objective of the encounter strategy meeting is to provide an overview of the upcoming encounter flyby, navigation parameters, science objectives, and its associated maneuvers. A representative from each subsystem teams are present, and report subsystem status as related to the upcoming flyby. Review of spacecraft and instrument health, as well as past flybys details are also reported. This meeting occurs at least one week before the first maneuver associated with the targeted flyby. Figure 7 shows the maneuver performance history and is an example data presented by the maneuver team during the encounter strategy meeting. This package also includes reconstructions of past maneuvers and predicted statistics for upcoming maneuvers. Any empty spaces in Figure 7 denote unavailable data.

- Project-wide OTM specific **preparation meeting**. The purpose of an OTM preparation meeting is to review spacecraft input parameters for an upcoming maneuver. This meeting is lead by a Spacecraft Office team member with navigation analysts in attendance. Presentation relates to the maneuver size, background activities, health of spacecraft, science planning, and DSN availability.

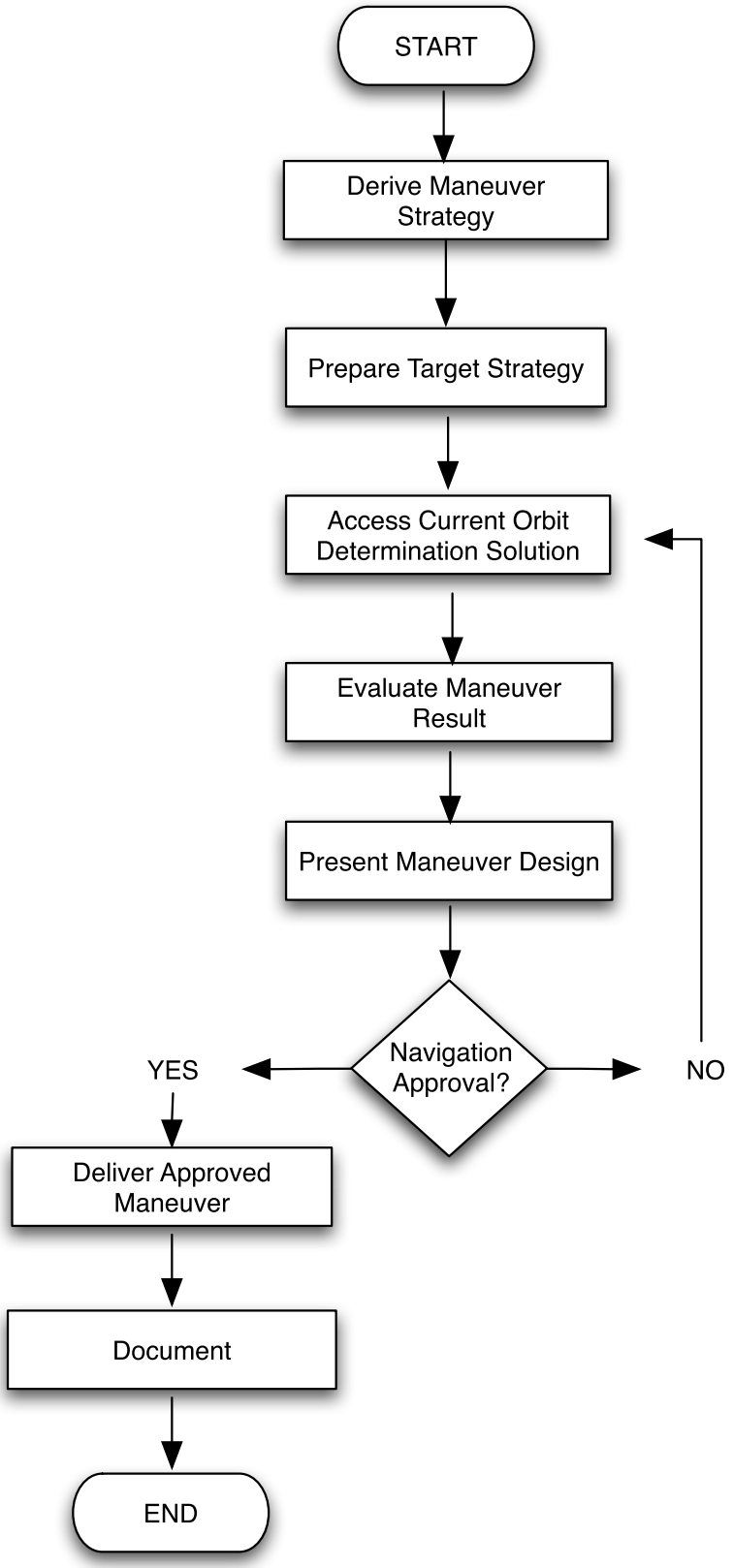

Figure 6. Overview of Maneuver Design Procedures

Maneuver Performance History

Maneuver	Maneuver Location	Predicted ΔV Statistics Mean (m/s)	1-σ (m/s)	95% (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Pred. Error* (σ)	Burn Type
OTM-134	T37+3d	1.172	0.745	2.501	1.172	1.173	0.000	MEA
OTM-135	T37∼apo	15.842	0.139	16.057	15.764	15.762	0.572	MEA
OTM-136	T38-3d	0.083	0.054	0.189	0.018	0.014	1.280	RCS
OTM-137	T38+3d	0.897	0.720	2.283	0.680	0.681	0.300	MEA
OTM-138	T38∼apo	9.577	0.157	9.767	9.643	9.636	0.374	MEA
OTM-139	T39-3d	0.049	0.032	0.110	0.014	0.014	1.132	RCS
OTM-140	T39+3d	0.867	0.807	2.440	- - - - - - *CANCELLED* - - - - - -			
OTM-141	T39∼apo	1.920	0.238	2.225	2.052	2.046	0.533	MEA
OTM-142	T40-3d	0.028	0.016	0.058	- - - - - - *CANCELLED* - - - - - -			
OTM-143	T40∼per	2.888	0.200	3.240	2.881	2.879	0.049	MEA
OTM-144	T40∼apo	37.615	0.343	38.188	37.397	37.406	0.608	MEA
OTM-145	T41-3d	0.239	0.178	0.578	0.299	0.291	0.294	MEA
OTM-146	T41∼per	6.602	0.303	7.241	7.028	7.021	1.379	MEA
OTM-147	T41∼apo	0.630	0.521	1.611	1.121	1.120	0.941	MEA
OTM-148-BU	E3-2d	0.048	0.029	0.104	- - - - - - *CANCELLED* - - - - - -			
OTM-149	E3+1d	2.840	0.112	3.030	2.760		*0.718*	MEA
OTM-150	E3∼apo	0.104	0.061	0.220	0.054		*0.813*	RCS
OTM-151	T42-3d	0.011	0.006	0.023				
OTM-152	T42∼per	3.387	0.395	3.851				
OTM-153	T42∼apo	1.303	1.621	4.653				
OTM-154	T43-3d	0.032	0.024	0.079				

*Predicted ΔV error = [recon. ΔV (*design ΔV*) - predicted mean ΔV] / predicted 1-σ ΔV

Figure 7. Encounter Strategy Package, Maneuver Performance History

- OTM specific **preliminary navigation review**. The preliminary navigation review is made after the first orbit determination data is available. This meeting serves as an initial set-up for OD and maneuver design and processing. The maneuver design is presented, along with prime and backup maneuver analysis, potential contingency issues, and a schedule of upcoming navigation activities. This meeting is primarily attended by the Navigation team, although this review is open to the project.

- OTM specific **navigation and cancellation review**. A comparison review of the converged OD solution and maneuver design is made. If applicable, cancellation products, downstream propellant cost effects, trajectory deviations, and science planning analysis is presented. Navigation, Spacecraft Office, and Science Planning team members are in attendance. Figure 8 shows a page from the cancellation package prepared by maneuver team members. This table compares the nominal execution and cancellation of a maneuver. The downstream cost of the maneuver was acceptable to the project, in this case actually saving ΔV, with no impact on downstream maneuvers and science activities; therefore, this maneuver was cancelled.

- OTM specific **final navigation review**. Final OD solution and maneuver design review for formal file delivery, along with backup maneuver design. Maneuver monitoring schedule discussed. Review of the backup maneuver design is also presented.

- Project-wide OTM specific **approval meeting**. Final review of products to be uplinked to spacecraft for maneuver execution. A confirmation of current orbit determination, spacecraft health, monitoring plan and commands is made. Official delivery of the maneuver design files are transferred to the Deep Space Network for spacecraft command uplink.

Each of these meetings require different products and presentations, reflecting the most current maneuver design. Note that each OTM planned for the tour requires all six meetings and reviews, and can take place within just a few days. Therefore, a proficient maneuver design processing strategy and analysis must satisfy the given OTM schedule.

Strategy: Cancel OTM-151

Downstream ΔV Comparison (Deterministic)

Encounter Span	Maneuver	Cancel OTM-151	Nominal Strategy	Difference from Nom. Strategy
		ΔV (m/s)	ΔV (m/s)	ΔV Cost (m/s)
E3-T42	OTM-151	0.0E+00	0.0037	-0.0037
T42-T43	OTM-152	3.5667	3.5336	0.0331
	OTM-153	0.0001	0.0001	-3.9E-06
T43-T44	OTM-155	0.9995	0.9794	0.0201
	OTM-156	0.1796	0.2537	-0.0742
T44-T45	OTM-158	0.5880	0.6319	-0.0439
	OTM-159	11.6915	11.6636	0.0279
T42-T45	**Subtotal**	**17.0254**	**17.0623**	**-0.0369**
E3-T45	**Total**	**17.0254**	**17.0660**	**-0.0406**

T43 Asymptote Difference from 070918 Ref. Traj.

	Cancel OTM-151	Nominal Strategy	LAMBIC 1-σ
Right Ascension (mrad)	-0.3595	-0.3875	0.1390
Declination (mrad)	0.1767	0.2027	0.1166

Based on **080320_062T42** OD

Figure 8. Maneuver Cancellation Package, Cancellation Comparison

OTM-152 Maneuver Design

Maneuver Location: T43 - 31d, 11-APR-2008 01:04:08 UTC (19:15:45 PDT ERT, Thursday)
True Anomaly: -82.3°
Central Angle: 1316.2°
Distance to Saturn: 6.7 R_S
Maneuver Strategy: Optimization Chain (070918 ref) ('B.R','B.T','TF')
Engine Type: MEA
Turn Type: RWA Roll (0.14 °/sec), RCS Yaw (0.06 °/sec)
Total-ΔV Magnitude: 3.3306 m/sec
MPF Total-ΔV Mag.: 3.3249 m/sec (*offset*: 5.77 mm/sec)
Turn-ΔV Magnitude: 7.86e-03 m/sec
Burn Duration: 20.3 sec (0 m 20.3 s) Max 5.0%
Turn Angles: 58.89° (Roll), -33.09° (Yaw)

Figure 9. Maneuver Approval Slide

VI. Example of an Orbit Control Activity Schedule

As the prime and extended tour descriptions indicate, there are several back-to-back 16-day Titan orbits used to achieve trajectory geometries preferred for science observation. Using the nominal three maneuvers per encounter strategy, project-wide and navigation team meetings, along with OTM design and analysis, occur daily. As a result, the prior discussed orbit control-staffing strategies were developed to handle these activities. This schedule is common during the prime and extended missions.

To illustrate a typical 16-day orbit schedule, Figure 10 outlines the activities that occurred during December 2007. Titan encounters are noted by circles and maneuvers by diamonds. The propulsion system to be utilized for maneuver execution is noted by RCS or MEA.

With a Titan encounter taking place every two weeks, each maneuver and their associated meetings are listed. Note that the daily processing of OD and maneuver design updates are not shown. Consider that while December contained several holidays for the normal workforce, continuous activity is planned during these times. Therefore, it is necessary to have a number of trained staff members available to produce the required products.

This schedule reiterates the critical need for capable Navigation team members and efficient maneuver design processing. A strict timeline requires strong communication and collaboration between all Cassini subsystems, and a strong coordinated effort is necessary for successful navigation.

VII. Lessons Learned and Conclusions

The Cassini Navigation team developed processing and staffing procedures to accommodate demanding OTM design activities. As the Cassini prime tour progressed, maneuver frequency increased to achieve short orbit geometry. Therefore, time was spent to develop the Maneuver Operations Software (MOPS-MAS) to automate presentation and delivery activities. Automation tools enabled flight path control members to have the time to analyze maneuvers and consider various orbit control strategies.

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
25	26 - OTM-134 Wrap-up - OTM-135 Approval	27 **OTM-135 MEA**	28 - T38-T39 Encounter Strategy Meeting - OTM-135 Wrap-up - OTM-136 Prep	29 - OTM-136 Preliminary Navigation Review	30 - OTM-136 Final Navigation Review - OTM-136 Approval	1
2 **OTM-136 RCS**	3 - OTM-136 Wrap-up	4	5 **Titan-38 Flyby** - OTM-137 Prep	6 - OTM-137 Navigation & Cancellation Review	7 - OTM-137 Approval - OTM-138 Prep	8 **OTM-137 MEA**
9	10 - OTM-137 Wrap-up - OTM-138 Preliminary Navigation Review	11 - OTM-138 Final Navigation Review	12 - OTM-138 Approval	13 **OTM-138 MEA** - T39-T40 Encounter Strategy Meeting	14 - OTM-138 Wrap-up - OTM-139 Prep	15
16	17 - OTM-139 Final Navigation Review - OTM-139 Approval	18 **OTM-139 RCS**	19 - OTM-139 Wrap-up - OTM-140 Prep	20 **Titan-39 Flyby**	21	22
23	24 **OTM-140 CANCELLED**	25	26 - OTM-141 Prep	27 - T40-T41 Encounter Strategy Meeting	28	29 **OTM-141 MEA**
30 - OTM-141 Wrap-up - OTM-142 Prep	31	1	2 - OTM-142 Final Navigation & Cancellation Review	3 **OTM-142 CANCELLED**	4	5

Figure 10. OTM Events for December 2007

In addition, the current maneuver design process evolved to consider several maneuver design and targeting scenarios. Procedures were extended to consider single maneuvers, multiple maneuvers, special targeting, maneuver biasing and cancellation strategies.

Finally, the current orbit control staffing schedule was employed to meet time constraints of maneuver processing during the prime tour. The orbit control staffing strategy was defined as assigning two maneuver analysts per encounter. While one maneuver analysts is engaged with encounter strategy and cleanup maneuver activities, the second analysts prepares approach and shaping maneuver designs.

Overall, the development, evolution, and implementation of current procedures allowed for accurate Cassini navigation and proximity to the reference trajectory. As a result, these strategies can be applied to the navigation of the Cassini spacecraft during the extended mission.

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