Communicating Navigation Data Inside the Cassini-Huygens Project: Visualizations and Tools

Sean V. Wagner, Emily M. Gist, Troy D. Goodson, Yungsun Hahn, Paul W. Stumpf, and Powtawche N. Williams*

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

The Cassini-Huygens Saturn tour poses an interesting navigation challenge. From July 2004 through June 2008, the Cassini orbiter performed 112 of 161 planned maneuvers. This demanding schedule, where maneuvers are often separated by just a few days, motivated the development of maneuver design/analysis automation software tools. Besides generating maneuver designs and presentations, these tools are the mechanism to producing other types of navigation information; information used to facilitate operational decisions on such issues as maneuver cancellation and alternate maneuver strategies. This paper will discuss the navigation data that are communicated inside the Cassini-Huygens Project, as well as the maneuver software tools behind the processing of the data.

I. Introduction

The science-laden Cassini-Huygens mission to Saturn poses an interesting navigation challenge. From July 2004, beginning with Saturn orbit insertion, through the end of the prime mission in June 2008, the Cassini orbiter performed 112 out of a planned 161 Orbit Trim Maneuvers (OTMs). This demanding schedule, where shortened encounter intervals often require OTMs to be scheduled only a few days apart, motivated the development of the Maneuver Automation Software (MAS). This timeframe was also the impetus for the creation of maneuver analysis software tools by the Cassini Maneuver Team. Besides generating maneuver designs and accompanying presentation materials, these tools are the mechanism to producing other types of navigation information; information used to facilitate operational decisions on such issues as maneuver cancellation and alternate maneuver strategies. This paper will discuss the navigation data that are communicated inside the Cassini-Huygens Project for decision making, as well as the architecture and evolution of the software tools behind the processing of the data. Meetings to review maneuver designs and encounter strategies, and maneuver cancellation discussions are among the forums that the Cassini Navigation Team use to relay information to the project. The emphasis of this paper will be on the maneuver presentations and the related tools developed by the maneuver team.

II. Overview

In almost any given month in the Cassini tour of Saturn, maneuver operations usually span every week, even spilling into weekends and holidays. To accommodate this type of schedule, the Maneuver Automation Software (MAS) was created to expedite the maneuver processing. Post-processing scripts in conjunction with MAS take a maneuver design and produce visualization materials for the maneuver analyst to present at meetings. In this section, overviews of MAS and other maneuver analysis tools are given.

II.A. Maneuver Automation Software

Given the anticipated schedule, the Cassini Project made a concerted effort to develop a tool to support the processing of subsystem inputs and file transfer for a maneuver design. This culminated into the

*Members of Flight Path Control Group and Cassini Navigation Team, 4800 Oak Grove Drive, Pasadena, CA 91109, and AIAA Member Grade.

Maneuver Automation Software (MAS), which is documented in reference 1. Development of MAS began before the prime mission and was first implemented at the end of the interplanetary cruise in 2004. MAS is comprised of two subsystems, the Spacecraft Office Software (SCO-MAS), and the Maneuver Operations Set (MOPS-MAS). The scope of this paper is on the maneuver team-developed tools to support MOPS-MAS. A general MOPS-MAS description can be found in reference 2.

In general, MOPS-MAS automates the design of an OTM, along with maneuver products and presentations. During operations, the maneuver analyst prepares OTM configuration inputs using the most recent orbit determination (OD) solution. MOPS-MAS processes the maneuver inputs and incorporates several programs (such as SEPV and TRNMPF, see below description) to obtain a maneuver solution. Besides reducing the possibilities of human errors and producing a consistent set of parameters and file names, MOPS-MAS facilitates the generation of presentation packages used for maneuver design review/cancellation meetings and maneuver approval meetings. The automation of these packages affords the maneuver analysts time to consider the maneuver design and its effects on the trajectory and downstream maneuvers and encounters. In addition, MOPS-MAS can be used to quickly set-up and design a maneuver at its backup location. Not only does MOPS-MAS allow for rapid turn-around of maneuver designs during times of short orbits, it also helps maintain reliability between the navigation, spacecraft office, and sequence teams.

Navigation software used within the JPL Guidance, Control, and Navigation Section are incorporated into MOPS-MAS and other Cassini maneuver analysis tools. These include several Double Precision Trajectory (DPTRAJ[3]) and Maneuver Operations Set (MOPS) programs listed below:

- *Search Path Vary Program (SEPV).*[3] Performs a high precision non-linear search on a velocity correction at the impulsive burn time, or on finite burn direction and duration. The computed ΔV(s) satisfy the given sets of encounter condition(s), targeting to any event specified by time or body-related conditions and in a variety of coordinate systems.

- *TRNMPF.* Decomposes a ΔV (from SEPV output) into burn and turn vectors. Also writes the Maneuver Profile File (MPF), which is used by MAS to create the maneuver command sequence files.

- *TWIST.*[3] Generates trajectory data from a spacecraft ephemeris file in user-requested coordinate systems (B-plane, conic, etc.) at user-requested epochs and at specified trajectory events.

- *Linear Analysis of Maneuvers with Bounds and Inequality Constraints Program (LAMBIC).*[4] Simulates the execution of a sequence of maneuvers by computing the statistics of ΔV magnitude and delivery accuracy using the Monte Carlo method.

II.B. Maneuver Design/Analysis Processes

Figure 1 gives an overview of MOPS-MAS and how it relates to maneuver team-developed tools, such as the Encounter Strategy Tool, the Maneuver Cancellation Tool, and the MOPS-MAS Delivery Tool. The Encounter Strategy Tool, described in section III, not only generates presentation materials for the encounter strategy meetings, but also provides data for the Maneuver Cancellation Tool and information for other MOPS-MAS post-processing scripts. MOPS-MAS is comprised of many software components and user EXEs, which are pre- and post-processing scripts developed within the maneuver team for maneuver products and presentation materials. A few noteworthy user EXEs are described in section IV, with an emphasis on the Maneuver Cancellation Tool in section V. The MOPS-MAS Delivery Tool takes a maneuver design and related products and delivers them to the appropriate file systems. This and the Encounter Strategy Tool also generate maneuver/encounter information pages, like the ones presented in figure 8, and update related history tables (see section VI).

II.C. I/O Configuration/Database Files

MOPS-MAS and the Encounter Strategy Tool are key-driven, meaning a database file of keys and values is used for both input and output to the software. This I/O configuration/database file serves as the interface with the user and between each component of the tools (see figure 1). Keys are alpha-numeric and uppercase with values that are contained on the same line, such as the following examples:

```
THIS_IS_A_KEY     This is the value # This is a comment
HERE_IS_A_NUMBER  1234.5
```

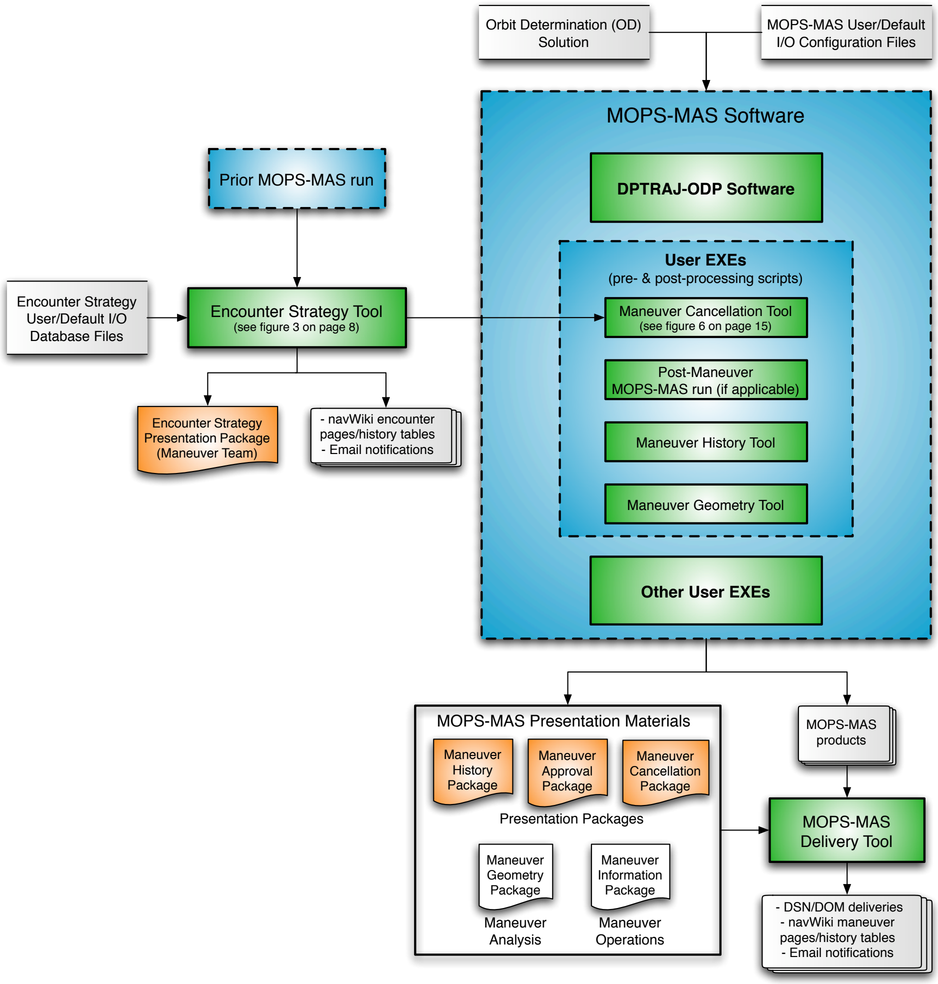

Figure 1. High-Level View of Maneuver Software

II.D. User Templates

Besides passing variables into the tools as an associative array (hash), keys can be used to fill user-definable templates. Templates supply the information and layout of the slides that comprise the various presentation packages, as well as determine the layout of email notifications, logs/summary reports, and maneuver/encounter history/data pages that are uploaded to the JPL navigation wiki website (navWiki). Here is an example template, where a key is preceded by a colon to signify the value to be returned:

```
:THIS_IS_A_KEY for the DV: :HERE_IS_A_NUMBER m/s
```

Filling this template, via the MOPS-MAS script `fill_template`, produces the following output:

```
This is the value for the DV: 1234.5 m/s
```

These templates can be altered at any time by the maneuver analysts, increasing the flexibility of the generated products and presentations. The ease of altering the templates enable the maneuver team to quickly respond to requests originating from the navigation team or inside the project.

II.E. Presentation Materials

The presentation packages (see figure 1) are created from LaTeX templates that are filled and processed via `fill_template` and `pdflatex`, respectively, to create Portable Document Files (PDFs). These PDFs are presented as-is or included as part of larger packages. It is worth mentioning that the presentation packages are produced satisfactorily, meaning they do not require manual editing after they are generated.

Several terms are used throughout each of the presentations that should be clarified up front:

- Maneuvers are accomplished through the use of two independent propulsion systems. The bi-propellant main engine assembly (MEA) performs large maneuvers, while the Reaction Control System (RCS) thrusters handle small trajectory corrections.[5,6]
- The nominal strategy for targeting encounters is through three maneuvers: a cleanup maneuver that typically occurs three days after an encounter, a trajectory-shaping maneuver that usually occurs near Saturn apoapsis (apocrone), and an approach maneuver that usually occurs three days before the next encounter to fix any flyby errors left by the previous maneuver.
- Maneuver ΔVs are the sum of the burn and turns ΔVs. The turn ΔVs are the roll and yaw turns associated with orienting the spacecraft for the burn. The design ΔVs that are commanded to the spacecraft are computed using SEPV.
- Flyby target conditions are typically three B-plane parameters; the spatial components $\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$; and the temporal component time-of-flight (TF).[7] Specific targeted flybys of a satellite are denoted by the first letter of the body name and a number. For example, Titan-45 is specified as T45 and Enceladus-4 as E4.
- The reference trajectory provides predetermined targeting locations according to science sequence planning and objectives. The navigation strategy has been to target the spacecraft to encounter conditions defined in the reference trajectory.
- Deterministic maneuvers are the trajectory-shaping maneuvers that are necessary to achieve the targeted flybys.
- Statistical maneuvers cleanup the errors left by the deterministic maneuvers in targeting the encounter conditions.

For further explanation of these and other terms, see other papers written by the Cassini Maneuver Team, such as references 8–12.

III. Encounter Strategy Meetings

The Cassini-Huygens Mission requires frequent flybys of Titan, Saturn's largest moon, and Saturn's icy satellites (Enceladus, Iapetus, Dione, etc.) at various altitudes and locations. These encounters define the tour, particularly the Titan flybys which impart much of the ΔV required to fly the mission via gravity assists. The complexity of this flown trajectory has motivated the project to hold encounter strategy meetings to discuss operations leading to each forthcoming flyby. The project-wide encounter strategy meetings provide an overview of the time period between two encounters, and its associated navigation parameters, science objectives, and maneuvers. Navigation reports on the characteristics of maneuvers that have been performed/cancelled and accuracies of encounters that have been accomplished, and provides details of upcoming maneuvers. Besides outlining the epochs, targeting strategies, and backup plans of these maneuvers, other analysis such as how the maneuvers map to the B-planes of the encounters and the resulting impact probabilities are also discussed. This meeting usually occurs at least one week before the maneuver associated with the first of the two targeted flybys.

III.A. Encounter Strategy Presentation Package

The presentation package that was created for the T45-E4 Encounter Strategy Meeting is shown in figure 2. For the Cassini Maneuver Team, the presentation packages for the encounter strategy meetings are generated via the Encounter Strategy Tool, which will be described in the next section. The first two slides in figure 2, the title page (slide 1) and the agenda page (slide 2) are self-explanatory. Slide 10 in figure 2 helps inform the project of the prime and backup maneuver analysts for each upcoming maneuver, along with the corresponding times for the maneuver product file deliveries. The remainder of the presentation package will be discussed in the following subsections. Note, any blank entries in a table denote unavailable data at the time the presentation package was generated.

T45 to E4 Encounter Strategy Meeting

(OTM-162 through OTM-163)

Cassini Maneuver Team

July 17, 2008

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Agenda

- Maneuver Performance Histories
- Upcoming Maneuvers
- E4 Impact Probabilities
- T45-E4 Trajectory
- Targeted Encounter History
- Maneuver Staffing/Delivery Schedule

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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-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	2.753	0.781	MEA
OTM-150	E3~apo	0.104	0.061	0.220	0.054	0.055	0.792	RCS
OTM-151	T42-3d	0.011	0.006	0.023	- - - - - - *CANCELLED* - - - - - -			
OTM-152	T42~per	3.387	0.395	3.851	3.329	3.327	0.150	MEA
OTM-153	T42~apo	1.303	1.621	4.653	0.512	0.515	0.486	MEA
OTM-154	T43-3d	0.032	0.024	0.079	- - - - - - *CANCELLED* - - - - - -			
OTM-155	T43+5d	1.019	0.297	1.398	1.176	1.173	0.518	MEA
OTM-156	T43~apo	0.875	0.821	2.679	0.196		*0.827*	RCS
OTM-157	T44-3d	0.014	0.008	0.029	- - - - - - *CANCELLED* - - - - - -			
OTM-158	T44+4d	0.366	0.422	1.211	- - - - - - *CANCELLED* - - - - - -			
OTM-159	T44~per	12.120	0.233	12.553	12.185		*0.281*	MEA
OTM-160	T45-3d	0.317	0.240	0.784				
OTM-162	T45+4d	2.827	0.440	3.572				
OTM-163	E4-3d	0.135	0.088	0.308				

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

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Maneuver Performance Per Encounter

Encounter Span	Ref. Traj. Det. ΔV (m/s)	Predicted ΔV Statistics Mean (m/s)	1-σ (m/s)	95% (m/s)	Design ΔV (m/s)	Recon. ΔV (m/s)	Navigation ΔV Cost* (m/s)
T28-T29	3.533	4.331	0.589	5.482	3.556	3.550	0.017
T29-T30	5.824	6.706	0.698	8.100	5.610	5.608	-0.215
T30-T31	5.529	7.204	1.270	9.692	5.535	5.534	0.005
T31-T32	12.137	13.265	0.902	15.015	12.974	12.972	0.835
T32-T33	8.215	9.793	1.200	12.142	8.736	8.730	0.514
T33-T34	0.011	0.987	0.648	2.219	0.036	0.038	0.027
T34-T35	0.018	1.506	0.954	3.366	0.431	0.427	0.409
T35-I1	0.003	0.989	0.441	1.831	0.487	0.488	0.485
I1-T36	13.430	13.179	0.255	13.462	13.609	13.597	0.167
T36-T37	2.468	2.753	0.337	3.367	2.380	2.371	-0.097
T37-T38	16.976	17.098	0.611	18.186	16.954	16.954	-0.022
T38-T39	9.761	10.524	0.576	11.648	10.336	10.331	0.569
T39-T40	2.051	2.815	0.614	4.017	2.052	2.046	-0.004
T40-T41	40.528	40.742	0.536	41.692	40.576	40.576	0.048
T41-E3	6.444	7.280	0.760	8.839	8.149	8.141	1.697
E3-T42	1.273	2.955	0.127	3.174	2.814	2.808	1.535
T42-T43	4.006	4.722	1.289	7.256	3.841	3.843	-0.164
T43-T44	1.074	1.908	0.620	3.156	1.372		*0.299*
T44-T45	11.960	12.802	0.596	14.007			
T45-E4	2.667	2.963	0.450	3.708			

*Navigation ΔV cost = total recon. ΔV (*total design ΔV*) - ref. traj. det. ΔV

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Upcoming Maneuvers

	Maneuver Location	Burn Start Epoch (UTC/SCET) Prime	Backup	Maneuver Strategy
OTM-160	T45-3d	27-JUL-2008 14:36:00	28-JUL-2008 23:00:00	T45 B-Plane (B·R, B·T, TF)
OTM-162	T45+4d	03-AUG-2008 22:15:00	05-AUG-2008 14:05:00	E4 B-Plane (B·R, B·T, TF)
OTM-163	E4-3d	08-AUG-2008 21:20:00	09-AUG-2008 21:20:00	E4 B-Plane (B·R, B·T, TF)

- OTM-161 was not assigned.
- IVP update P-file deliveries:

22-JUL-2008 15:00 PDT (prior to OTM-160)

31-JUL-2008 18:00 PDT (prior to OTM-162)

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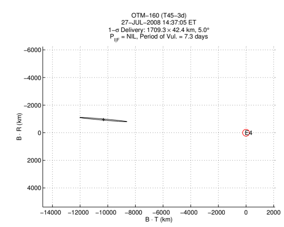
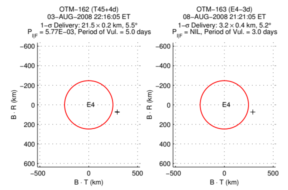
Impact Probabilities at E4 (OTM-160: T45 Flyby / Errors Mapped to E4)



Enceladus encounter (E4) on 11-AUG-2008 21:07:24 ET
Earth Mean Orbital Plane and Equinox of J2000.0

6

Impact Probabilities at E4 (OTMs 162-163)



Enceladus encounter (E4) on 11-AUG-2008 21:07:24 ET
E4 flyby altitude = 53.5 km (spherical model), atmos. altitude = 0.0 km
Earth Mean Orbital Plane and Equinox of J2000.0

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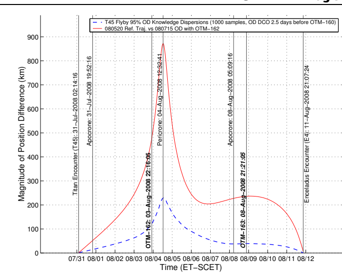
T45-E4 Trajectory



T45 to E4 = 11.8 days, 1.5 revs., 2 mvrs. (1 deterministic, 1 statistical)

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Targeted Encounter History

	Reference Trajectory Target Conditions (EMO2000) B·R (km)	B·T (km)	Time of Closest Approach (ET/SCET)	Alt.* (km)	Flyby Diff. from Ref. Traj. B·R (km)	B·T (km)	TCA (sec)
T29‡	-3690.23	-953.12	26-APR-2007 21:34:03	980	-0.78	-0.18	0.02
T30‡	-3609.69	-1159.26	12-MAY-2007 20:11:03	960	-0.32	3.58	-0.03
T31†	-4805.08	-1806.43	28-MAY-2007 18:53:00	2300	1.53	-1.18	0.21
T32‡	-3487.51	-1524.80	13-JUN-2007 17:47:16	975	9.33	3.92	1E-02
T33	-2655.50	3954.85	29-JUN-2007 17:00:51	1932	0.06	0.28	-4E-03
T34‡	530.95	-4127.55	19-JUL-2007 01:12:25	1332	-0.28	0.21	0.18
T35†	-4075.95	-4619.26	31-AUG-2007 06:33:39	3326	-1.69	4.51	1.80
I1†	799.05	-2245.86	10-SEP-2007 14:16:45	1644	-0.14	-7.38	8.43
T36	3744.17	-652.74	02-OCT-2007 04:43:48	975	-2.14	-0.82	0.06
T37	2533.97	-2866.69	19-NOV-2007 00:48:30	1000	-0.39	0.45	0.01
T38	4040.65	827.48	05-DEC-2007 00:07:55	1300	-1.90	1.00	-0.09
T39	3756.11	531.16	20-DEC-2007 22:59:00	970	-0.45	-0.32	-0.05
T40†	2162.62	-3166.55	05-JAN-2008 21:31:25	1010	-2.97	-6.94	-0.37
T41	3207.07	-2080.45	22-FEB-2008 17:33:12	1000	-2.70	-3.80	-0.08
E3†	88.66	290.09	12-MAR-2008 19:07:17	56	0.64	-2.37	0.02
T42†	2806.42	-2594.81	25-MAR-2008 14:28:53	1000	-1.81	-0.94	-5E-04
T43†	-631.49	-3770.16	12-MAY-2008 10:03:03	1000	-1.96	-1.05	-0.04
T44†	-615.54	-4178.73	28-MAY-2008 08:25:37	1400			
T45	3246.44	-3029.17	31-JUL-2008 02:14:16	1613			
E4	73.39	291.73	11-AUG-2008 21:07:24	54			

*Altitude not explicitly targeted in maneuver designs, assumes spherical model for Enceladus

†Flyby differences may appear large due to cancelled maneuver(s)

‡Reference trajectory target conditions not implemented (e.g., biased approach maneuver)

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Maneuver Staffing & DSN/DOM Deliveries

- OTM-160
  - Staffing: Emily Gist, Paul Stumpf
  - File Deliveries: 25-JUL-2008 17:00 PDT
- OTM-162
  - Staffing: Emily Gist, Paul Stumpf
  - File Deliveries: 02-AUG-2008 16:00 PDT
- OTM-163
  - Staffing: Yungsun Hahn, Powtawche Williams
  - File Deliveries: 07-AUG-2008 21:00 PDT

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Figure 2. T45-E4 Encounter Strategy Presentation Package (slides 1-10)

III.A.1. Maneuver Performance History

Slide 3 of figure 2 gives the recent history of the maneuvers in terms of ΔV, grouped by each targeted encounter. This information is useful for the project to get an overview of trends in maneuver design and execution. In the maneuver performance history, the executed, cancelled and upcoming maneuvers are listed, with descriptions of the orbit locations and the corresponding predicted ΔV statistics. For executed maneuvers, the design and reconstructed ΔVs and burn types are given. If a maneuver is not performed, it is labeled as cancelled, deleted, etc. The predicted ΔV statistics (mean, 1-σ, and 95%) are computed via LAMBIC, using the reference trajectory for the deterministic ΔVs and the encounter conditions. These ΔV predictions account for both maneuver and orbit determination (OD) statistical variations. Since the reconstructed and predicted ΔVs include maneuver execution errors, the reconstructed ΔVs, as opposed to the design ΔVs, are compared to the predicted ΔVs to determine the predicted ΔV errors.

III.A.2. Maneuver Performance Per Encounter History

To compare the maneuver performance per encounter, slide 4 of figure 2 lists the reference trajectory deterministic ΔVs and design and reconstructed ΔVs for the Saturn tour of recent encounter spans. This history provides a comprehensive view of how the maneuver performance compares to the ΔV predictions over a large period of time by assessing the 'navigation cost'. This cost across each encounter arc is defined as the difference between the total actual ΔV and the total reference trajectory ΔV. The reference trajectory deterministic ΔV only includes the trajectory-shaping maneuvers (i.e., cleanup and first targeting maneuvers), whereas the reconstructed ΔV incorporates the statistical maneuvers (i.e., approach maneuvers). The navigation ΔV costs for most of the encounter spans were less than 1 m/s, which is the average statistical cost per encounter of the prime and extended missions.[5,6] Any negative value ΔV denotes propellant savings usually due to maneuver cancellations and/or target biasing.

III.A.3. Upcoming Maneuvers

Slide 5 of figure 2 summarizes the forthcoming maneuvers through the end of the encounter span covered by the meeting. For each maneuver, the prime and backup maneuver times are given, along with the descriptions of the corresponding orbit locations and maneuver targeting strategies. Targeting strategies are typically maneuver optimization chains for cleanup maneuvers and standard B-plane conditions for targeting maneuvers (i.e., $\mathbf{B}\cdot\mathbf{R}$, $\mathbf{B}\cdot\mathbf{T}$, and time-of-flight).[5,6] For this particular example, additional operational events (e.g., maneuver product delivery dates for science pointing updates) and comments are also provided.

III.A.4. Impact Probabilities

During the Cassini tour of Saturn, there are intervals when the spacecraft will be on a trajectory which, without correction, will impact Titan or one of the other major satellites. These uncorrected intervals can be quantified with probabilities of impact given failure, herein referred to as impact probabilities. These probabilities, together with B-plane plots of the delivery dispersions, help the project assess the importance of performing each maneuver.

The 1-σ delivery dispersions following each upcoming maneuver (black ellipses/crosshairs) relative to the impact radii of the encounters[a] (red ellipses) are shown on the B-plane plots on slides 6 and 7 in figure 2. In general, four B-plane plots are provided; the prior approach maneuver mapped past its targeted encounter to the upcoming flyby (slide 6), and the maneuvers targeted to the upcoming flyby (slide 7). In this example, three B-plane plots are shown since only two maneuvers are targeted to E4, as opposed to the usual three. Information such as the impact probability, the period of vulnerability, and the 1-σ delivery dispersion dimensions and orientation are also given along with each B-plane plot. The delivery dispersions and resulting impact probabilities are computed in a Monte Carlo process via LAMBIC, using the same setup that produced the predicted ΔV statistics found in the maneuver performance histories (see slides 3 and 4 in figure 2). Impact probabilities of less than 1.0E-6 are listed as *Nil.* The period of vulnerability is the time span following the execution of a maneuver when the spacecraft is susceptible to an impact of a targeted body. It is defined to be the time to the next maneuver or encounter, whichever occurs first.

[a]The targeted flyby impact radius is the orbital equatorial mean radius, and in the case of Titan encounters, the mean radius plus the atmosphere tumble altitude.

III.A.5. *Trajectory Deviations/Dispersions*

The trajectory plot found on slide 8 of figure 2 gives the deviations of the current trajectory from the reference trajectory and the OD knowledge dispersions during the encounter arc. The red line represents the magnitude of the position differences between the current trajectory and the reference trajectory. This deviation usually signifies a 'built-in' error in the trajectory. A small deviation at an encounter is more likely due to a change in the ephemeris location of the satellite.

The blue-dashed line symbolizes the 95% OD knowledge dispersions propagated through one flyby to the next, generated via the Trajectory Dispersions Program developed by M. Wong.[13] Through Monte Carlo simulations, this tool samples random initial position and velocity errors at the first flyby from a covariance supplied by OD, propagates the trajectory for each sample, and returns the 95th percentile statistical values. The knowledge dispersions show how large the trajectory can deviate from the predicted trajectory due to OD errors alone.

Maneuver, encounter, and Saturn periapsis and apoapsis times are labeled on the trajectory plot. The time between the two encounters and the number of spacecraft orbits and maneuvers between the flybys are also provided. Deterministic maneuver labels are given in bold, whereas statistical maneuver labels are given in bold and italics. In general, the trajectory deviations/dispersions peak at the pericrones, mainly due to timing differences that are augmented by velocity changes at periapsis passages.

III.A.6. *Targeted Encounter History*

The table on slide 9 of figure 2 lists the recent history of the targeted encounter conditions and the achieved flyby differences for each encounter. The $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, and time-of-closest-approach (TCA) target conditions, expressed in EMO2000 coordinates, are defined in the reference trajectory and used in the final designs of the performed maneuvers. The flyby differences from the reference trajectory represent flyby errors for nominally targeted encounters; for biased targets they represent the shifts due to the biasing in addition to the flyby errors. The flyby differences may also appear large due to any cancelled maneuvers at the approach.

III.B. Encounter Strategy Tool

The Encounter Strategy Tool, developed by S. Wagner, was created to facilitate the Cassini Maneuver Team's analysis of maneuvers supporting an upcoming encounter.[14] Development of the tool began in February 2005, when the Saturn tour came into full swing following the Huygens Probe Mission. Around this time, encounters became as frequent as every two weeks, motivating the need for an automated solution to generating presentation materials for the encounter strategy meetings. This tool has been continually maintained to address requests throughout the past few years, up to the handling of "double" flybys[b] which will be first encountered in October 2008.[6] Starting as a mechanism to generate and deliver the encounter strategy meeting presentation package for the maneuver team, the tool has evolved to handle additional navigation tasks, including creating data files for other maneuver analysis programs like the Maneuver Cancellation Tool[15] and the Execution-Error Analysis Tool,[16] and building histories of past maneuvers and targeted encounters accessible through the navigation team's wiki site (navWiki).

Figure 3 gives a high-level view of the architecture of the Encounter Strategy Tool. The program (`enc_strat`) is mainly composed of Perl, MATLAB (wrapped in C shell), and Fortran. The grey-shaded rectangular boxes represent inputs to the tool (e.g., database files and templates). The blue-shaded parallelograms signify the various outputs that the tool generates (e.g., data files, MATLAB figures, EPS, PDF, etc.). The I/O database file that results from running `enc_strat` becomes input to `enc_strat_deliver`.

The presentation package is emailed to the Spacecraft Office (SCO) presenter via `enc_strat_deliver`, an interactive script which also updates the following history pages on the navWiki:

- *Maneuver performance history.* History includes the predicted, designed, and reconstructed ΔVs of all maneuvers planned, since launch, up to the latest encounter arc.
- *Maneuver performance per encounter history.* History includes the total predicted, designed, and reconstructed ΔVs of all maneuvers planned, since the beginning of the Cassini tour, per encounter span up to the latest encounter arc.

[b]Back-to-back flybys of Titan and another icy satellite using no maneuver in between the two encounters.

- *Targeted encounter history.* History covers the planned and reconstructed flyby target conditions of all targeted encounters, including double flybys, accomplished since launch.

Additionally, the script updates several maneuver/encounter information pages on the navWiki using data found in the maneuver database files (see figure 3). These files provide data that define the maneuvers, such as the maneuver names, execution times, performed/cancelled status, etc.; and data that define the encounters, such as the encounter order, targeting conditions, which maneuvers target each encounter, etc. Other files in this database directory also supply staffing, delivery schedules, reconstruction time spans, etc. In general, these database files can be populated far in advance (i.e., they do not need to be determined at the run time of this tool). Several of these database files are also used by the Maneuver Cancellation Tool[15] and other MOPS-MAS scripts. Finally, a navWiki page is created for the current encounter. This page includes navigation predictions of the upcoming encounter and related maneuvers. When reconstructions are available for the maneuvers and the encounter, they are also included on the page. For example, a T45 summary page is generated with a T44-T45 encounter strategy delivery (see figure 8a).

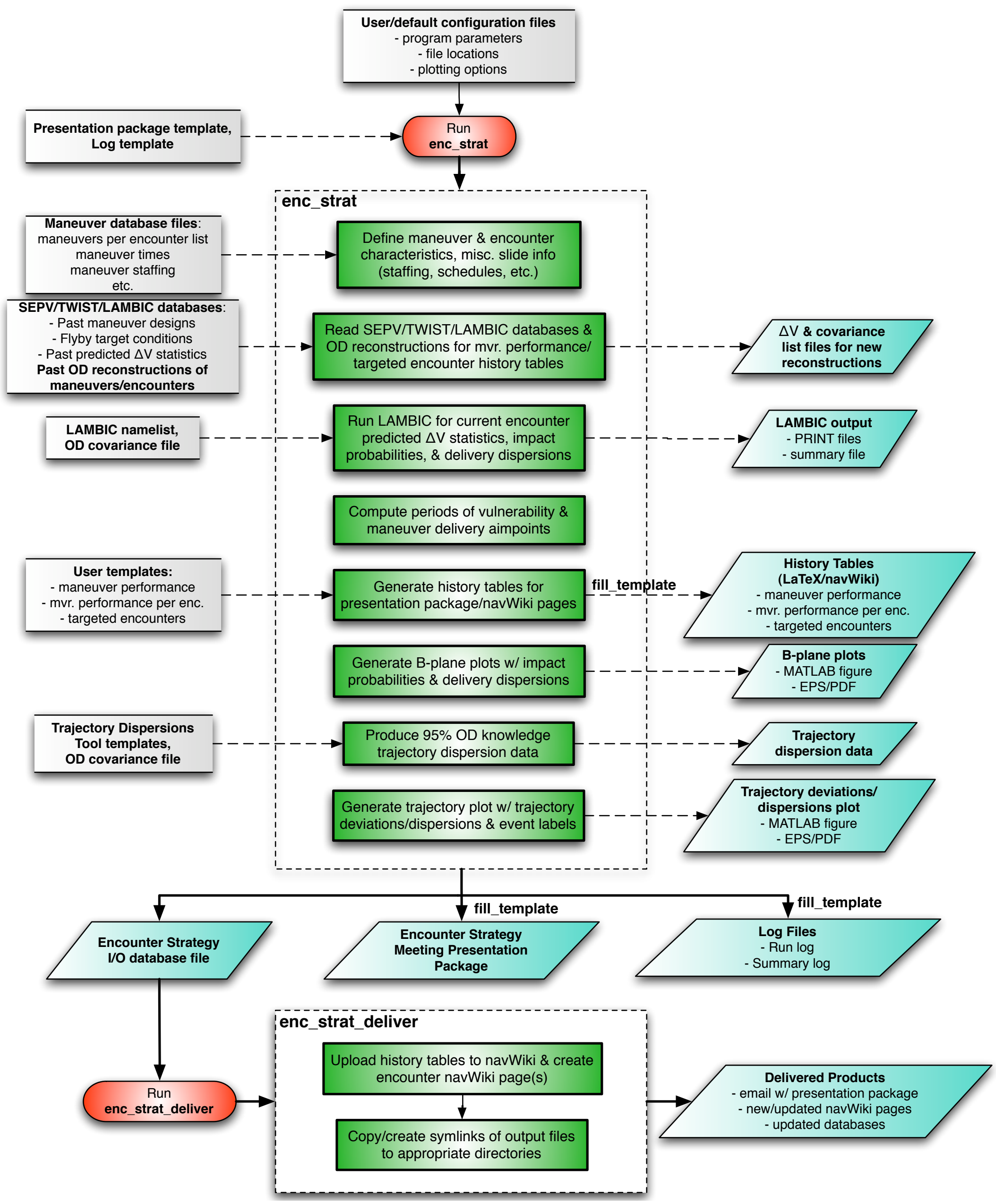


Figure 3. Encounter Strategy Tool

IV. Maneuver Design Reviews

During maneuver review meetings, which include navigation reviews and project-level approval meetings, the maneuver design resulting from a particular orbit determination (OD) solution is presented. Discussion typically begins with how the maneuver affects the targeted encounter and how the execution errors due to the maneuver map to a delivery error at the flyby. Once the effects of the maneuver are outlined, the maneuver characteristics are summarized. The expected doppler shift along the earth-line due to the maneuver and the comparison of two independent verifications of the maneuver design are also shown. Plans to implement a maneuver are finalized at project-approval meetings, where the maneuver design chosen to be commanded to the spacecraft is summarized to the project. Once all issues concerning the implementation of a maneuver are satisfactorily addressed at these meetings, the maneuver is then approved by representatives of each spacecraft team.

IV.A. Maneuver Approval Package

Figure 4 contains the presentation package that was created for the final navigation review of OTM-159, the deterministic targeting maneuver, on MEA, to T45. These types of maneuver-related presentation packages (e.g., maneuver approval, maneuver cancellation, maneuver history, etc.), along with the associated maneuver products, are generated for each OD solution/maneuver design. For a given maneuver, maneuver designs can range from 2 to more than 10 during the Cassini tour. The first two slides in figure 4, the title page (slide 1) and the agenda page (slide 2) are self-explanatory. The last two slides entail a software computation check of the maneuver design (slide 9) and the configuration that was used in the MAS run (slide 10). The rest of the presentation package will be explained in detail in the following subsections.

IV.A.1. Aimpoint/OD Comparisons

Slide 3 of figure 4 shows a typical comparison of a single maneuver's target parameters against the OD prediction of the flyby, along with a summary of the OD 1-σ dispersion errors. For a cleanup maneuver review, additional comparisons are shown of the cleanup maneuver's optimized (intermediate) target, referred to as the maneuver's 'run-out', and the correction left for the next maneuver.

IV.A.2. B-Plane Plots

Slides 4-6 of figure 4 are the typical three B-plane plots that are usually generated and shown at the maneuver review/approval meetings: a close-up of the OD dispersion; the OD dispersion, maneuver disperions, and impact radius[c] ellipses; and a close-up of the delivery dispersion ellipse resulting from the maneuver. The B-plane plot which shows how the maneuver changes the aimpoint dispersion (slide 5) is a graphical representation of the comparison table of slide 3.

IV.A.3. Maneuver Design Characteristics

Slide 7 of figure 4 summarizes the properties of the maneuver. These characteristics include epoch time, targeting strategy, engine type (MEA or RCS), turn angles and rates to the burn attitude, ΔV magnitudes of the burn and turns, and expected burn duration.

IV.A.4. Expected Doppler Plot

The plotted Doppler shift, shown in slide 8 of figure 4, is the Earth-line component of the total expected ΔV of the maneuver. The transitions to and from the burn attitude are also labeled along with the expected burn time. A 1-σ uncertainty on the expected Doppler shift is shown, using the current maneuver execution-error model. Although the Doppler plot provided here is based on the design ΔV, it provides a preview of what to expect for the real-time monitoring of the radiometric data by the OD analyst.

[c]Impact disk of the target body which includes the atmosphere for the Titan flybys.

OTM-159 Maneuver Approval Meeting

Cassini-Huygens Navigation Team

MAS ID O159_k

1

Agenda

- Target vs. 080619_070Sa OD Solution
- OTM-159 Plots
- OTM-159 Maneuver Design and Statistics
- OTM-159 Expected Doppler
- Comparison of MPF & MIF
- Software Configuration Details

2

OTM-159 Aimpoint vs. OD

B-Plane Coordinates and Time

	OTM-159 Aimpoint	OD Solution	Aimpoint minus OD Solution
B (km)	4440.2	126774.7	-122334.5
θ (deg)	133.0	48.6	84.4
$B \cdot R$(km)	3246.4	95082.1	-91835.6
$B \cdot T$(km)	-3029.2	83852.4	-86881.5
Time of Closest Approach (ET)	31-JUL 02:14:16.0	31-JUL 04:41:35.2	-02:27:19.2

080619_070Sa 1-σ Errors

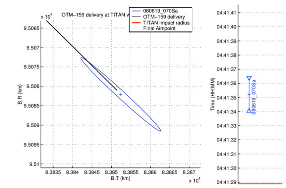
Error Ellipse Semi-major Axis (km)	Error Ellipse Semi-minor Axis (km)	Error Ellipse Theta (degs)	Impact Parameter (km)	Time of Closest Approach (sec)
13.9	1.0	42.7	13.9	1.2

Earth Mean Orbital Plane and Equinox of J2000.0

-

3

OTM-159 B-Plane: OD



Mvr. Flyby Alt. = 1613.4 km

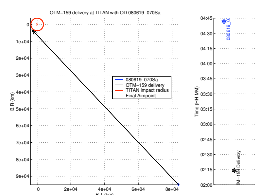
PQ Atmos. = 900.0 km

080619_070Sa Delivery: 13.9 × 1.0 km (1-σ), 42.7°, 1.2 sec; $P_{I/F}$ = *Nil*
OTM-159 Delivery: 57.1 × 5.5 km (1-σ), 64.8°, 3.3 sec; $P_{I/F}$ = *Nil*
Earth Mean Orbital Plane and Equinox of J2000.0

-

4

OTM-159 B-Plane: All



Mvr. Flyby Alt. = 1613.4 km

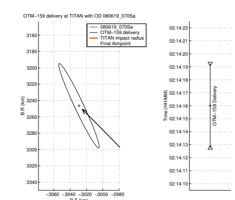
PQ Atmos. = 900.0 km

080619_070Sa Delivery: 13.9 × 1.0 km (1-σ), 42.7°, 1.2 sec; $P_{I/F}$ = *Nil*
OTM-159 Delivery: 57.1 × 5.5 km (1-σ), 64.8°, 3.3 sec; $P_{I/F}$ = *Nil*
Earth Mean Orbital Plane and Equinox of J2000.0

-

5

OTM-159 B-Plane: Delivery



Mvr. Flyby Alt. = 1613.4 km

PQ Atmos. = 900.0 km

080619_070Sa Delivery: 13.9 × 1.0 km (1-σ), 42.7°, 1.2 sec; $P_{I/F}$ = *Nil*
OTM-159 Delivery: 57.1 × 5.5 km (1-σ), 64.8°, 3.3 sec; $P_{I/F}$ = *Nil*
Earth Mean Orbital Plane and Equinox of J2000.0

-

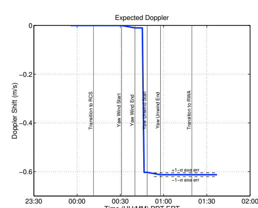
6

OTM-159 Maneuver Design

Maneuver Location: T45 - 38d, 23-JUN-2008 06:24:08 UTC (00:45:14 PDT ERT, Monday)
True Anomaly: -45.4°
Central Angle: 2014.6°
Distance to Saturn: 3.1 R_S
Maneuver Strategy: B-plane (080520 ref) ('B.R','B.T','TF')
Engine Type: MEA
Turn Type: RWA Roll (0.17 °/sec), RCS Yaw (0.26 °/sec)
Total-ΔV Magnitude: 12.1850 m/sec
MPF Total-ΔV Mag.: 12.1792 m/sec (*offset*: 5.77 mm/sec)
Turn-ΔV Magnitude: 2.79e-02 m/sec
Burn Duration: 73.8 sec (1 m 13.8 s) Max 5.0%
Turn Angles: 88.14° (Roll), -84.74° (Yaw)

7

OTM-159 Expected Doppler



2007-02 Execution Error Model

1-σ	Fixed, mm/s	Proportional
Mag	5.00	0.02 %
Ptg	3.00	0.60 mrad

(Earth-line)	Burn	Total
angle (deg)	87.20	87.12
ΔV m/s	-0.593	-0.613
1-σ ΔV m/s		0.008

-

8

Comparison of MPF & MIF

	MPF	MIF	DIFF	Criteria	OK?
Burn ΔV (m/sec)	12.158	12.158	-3.91e-06%	0.02%	Yes
Burn Duration (sec)	73.773	73.773	1.75e-04%	5.00%	Yes
Roll Turn (deg)	88.137	88.137	-7.84e-05mrad	0.20mrad	Yes
Yaw Turn (deg)	-84.738	-84.738	5.28e-05mrad	0.20mrad	Yes

MPF	MPF_O159_k_080619_070Sa.sfdu
MIF	O159_k.mif

9

Software Configuration Details

User who ran SCO-MAS: cgballar
User who ran Listener/MOPS-MAS: Troy D. Goodson
User who configured MOPS-MAS: Christopher G Ballard
User who delivered OD Solution: Kevin Criddle
Sought OD Solution at /cnav/OD/deliveries/080619_070Sa
Sought Input file at /cnav/Man/inputs/OTM159
MAS run O159_k (offline) made Thu Jun 19 12:13:27 PDT 2008

10

Figure 4. OTM-159 Approval Package (slides 1-10)

IV.B. Supporting Packages

Some of the major packages that often are shown in navigation reviews that are generated as part of the MOPS-MAS presentation software are presented here.

IV.B.1. Maneuver Cancellation Package

This presentation package is discussed in detail in section V.

IV.B.2. Maneuver Design History

Each intermediate maneuver solution that is delivered to the navigation team for review via the MOPS-MAS Delivery Tool (see section VI) is captured in a history table. The Maneuver History Tool takes a delivered maneuver design and appends maneuver data to a running history of the specific maneuver. This includes the type of data seen in slides 3 and 7 of figure 4. The history tables come in three forms: a PDF of each solution (delineated by MAS ID number), corresponding OD solution, burn type, ΔV (magnitude, right ascension (RA), declination (DEC)), roll and yaw turns, burn duration, etc.; a condensed version of the data presented in the PDF history table to be included in the text of email notifications, and a tab-delimited, spreadsheet-ready table including a more comprehensive set of parameters of each maneuver design. The PDF of the history is attached to email notifications generated by the MOPS-MAS Delivery Tool (see section VI), along with maneuver approval and cancellation packages. It is also usually presented before the maneuver approval package to show the history of the maneuver solution to the navigation team.

IV.B.3. Post-Maneuver Previews

For cleanup maneuvers determined in an optimization-chain, the next maneuver design is also processed in a separate MOPS-MAS run. The resulting maneuver approval package, renamed 'solution preview', is often shown at the review meetings and is included along with the cleanup maneuver approval package in emails via the MOPS-MAS Delivery Tool (see section VI). The history of these maneuvers are also included alongside the cleanup maneuver's history on the maneuver history PDF packages.

IV.B.4. Maneuver Geometry Package

The geometry package is a collection of MATLAB generated plots and tables of the effects of the maneuvers on the spacecraft trajectory and at the flyby. The package is generated by the Maneuver Geometry Tool developed by T. Goodson. Plots include projections of the spacecraft trajectory with respect to Saturn and the flyby, how the ΔV relates to the target condition gradients and capability directions of the maneuver, and ΔV projections in Cartesian or RTN coordinates.

V. Maneuver Cancellation Discussions

With the rate of cancellations increasing to 1 out of 3 maneuvers during the second year of the Cassini tour, and with an even higher rate of cancellation candidates, streamlining the maneuver cancellation process became a top priority for the Cassini-Huygens Project.[9] This led to the introduction of the maneuver cancellation presentation package by the maneuver team, a package designed to facilitate discussions of canceling a maneuver during navigation maneuver meetings. This package had later evolved to also be an avenue of exploring alternate maneuver strategies, such as delaying a maneuver to its backup location or performing another maneuver in lieu of the maneuver being designed. The presentation package includes side-by-side comparisons of downstream ΔVs of performing/cancelling a maneuver and/or alternate maneuver strategies, contour plots showing how variations in the achieved flyby maps to a downstream ΔV cost or saving, trajectory plots illustrating how the resulting trajectories differ from the reference trajectory, and a checklist used to help decide whether to cancel or perform a maneuver or implement an alternate maneuver strategy.[9,10]

In general, when a maneuver design produces a ΔV less than 9 mm/s (the minimum spacecraft capability) or cancellation is desired, analysis for maneuver cancellation is conducted. The cancellation of a maneuver is favored because it reduces spacecraft use and ground-system stress, usually at a moderate propellant cost. However, it only takes place if certain criteria are met. 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.

V.A. Maneuver Cancellation Package

Figure 5 showcases the presentation package that was created for the OTM-157 navigation reviews. This particular example is the package created using the final OD solution for OTM-157, the approach maneuver to T44, and was instrumental in the decision to cancel OTM-157. These types of maneuver-related presentation packages (e.g., maneuver approval, maneuver cancellation, maneuver history, etc.), along with the associated maneuver products, are generated for each OD solution/maneuver design. For a given maneuver, maneuver designs can range from 2 to more than 10 during the Cassini tour. The first two slides in figure 5, the title page (slide 1) and the agenda page (slide 2) are self-explanatory. The remainder of the presentation package will be explained in detail in the following subsections.

V.A.1. Downstream Trajectory Comparison Tables

The downstream ΔVs resulting from a particular maneuver strategy are compared with the nominal maneuver strategy. The nominal strategy is to perform the maneuver in question and perform future maneuvers as expected. Canceling the maneuver in question and the resulting downstream ΔVs is the usual strategy that is compared to the nominal strategy.

Cancelling a maneuver usually affects the future incoming asymptotes; especially with a cancelled approach maneuver, the next encounter after the upcoming flyby may have incurred a sizable difference in the asymptote direction. The criteria of the right ascension (RA) and the declination (DEC) differences being less than or equal to the predicted 2-σ values has been used in determining if an asymptote change is within expectations.

V.A.2. ΔV Cost Contour Plots

Contour and surface plots are useful in visualizing the downstream ΔV cost range for given OD and maneuver deliveries. Throughout the tour, downstream ΔV penalty plots have been studied for approach maneuver cancellation considerations. This has also been extended to determining if a cleanup maneuver can be cancelled, even before the flyby has been achieved. The contour plots also serve as a linear check to the integrated solutions shown with the downstream ΔV comparison tables (see previous subsection).[17]

For an approach maneuver, the contour and surface ΔV penalty plots provide graphical representations of the total downstream penalty for a given miss from the nominal flyby aimpoint. This penalty assumes implementation of a flyby cleanup maneuver. The OTM-157 contour plot (see slides 4 and 5 of figure 5) supported the downstream ΔV comparison result that cancellation of OTM-157 would not introduce a ΔV cost and that OTM-158 would still be cancelable (OTM-158 was later cancelled).

Reference 17 thoroughly describes how the ΔV contour and surface plots are constructed and used in the maneuver cancellation process. References 9, 10, and 12 also present examples of how the contours were used to assess downstream ΔV costs or savings in the maneuver cancellation decision-making process.

The strategy of 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. Note that prospects for target biasing are limited and are dependent on the encounters science activities. Typically, there is usually only a day or two to present the alternate aimpoint to the scientists. Then the project meets and reaches a decision based on the science and navigation teams analysis and recommendations. Target biasing is discussed in references 12 and 17.

V.A.3. Trajectory Deviations

Trajectory deviations from the reference trajectory occur due to OD and maneuver execution errors. These deviations are controlled at the targeted encounter aimpoints (i.e., there are no position differences at the flyby times), but grow following a maneuver and become magnified at pericrones. Cancelling a maneuver may cause the trajectory deviations to grow larger, possibly affecting planned science instrument pointing. See section III.A.5 for more details.

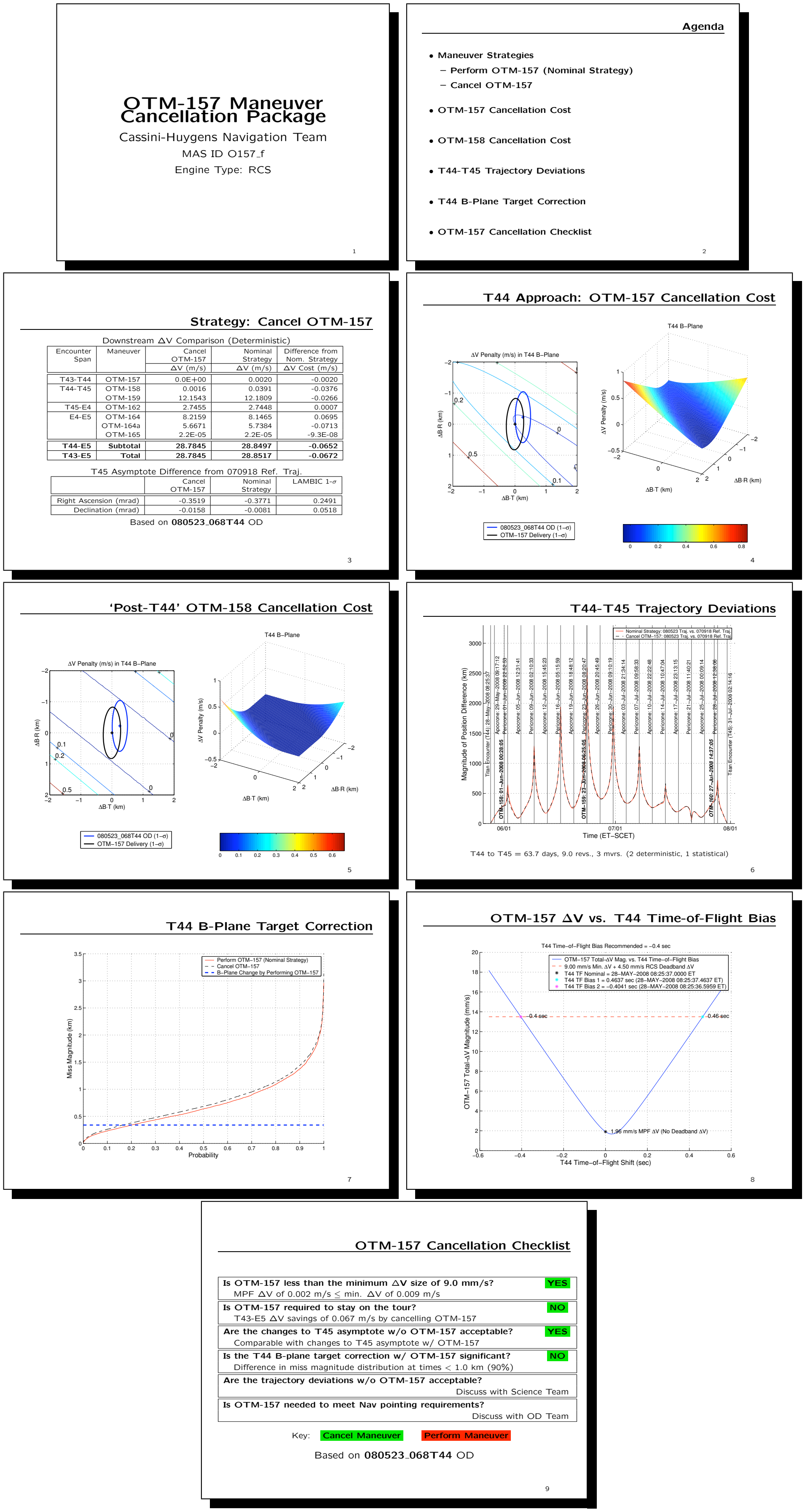


Figure 5. OTM-157 Cancellation Package (slides 1-9)

V.A.4. B-Plane Target Correction

For an approach maneuver, the cumulative probability density function of the B-plane miss magnitudes of the OD and the maneuver delivery ellipses are compared against the desired B-plane correction. If the curves are largely separated, it verifies that the maneuver will make a measurable change in the flyby aimpoint. If the curves are overlapping most of the time, it indicates that the maneuver will not make a change larger than the OD error in the target location, leading to a maneuver cancellation decision. For OTM-157, the target correction is essentially the same with performing or canceling the maneuver, as seen on slide 7 in figure 5. This further supported the cancellation of OTM-157.

V.A.5. Time-of-Flight Bias Plot

When a maneuver is too small to implement, the strategy of biasing the time-of-arrival at a flyby to increase the ΔV is considered. A plot of ΔV versus time-of-flight is then generated during a MOPS-MAS run via a user EXE (Time-of-Flight Biasing Tool) and included in the maneuver cancellation presentation package, as seen on slide 8 in figure 5. This plot contains labels of the two solutions that achieve the desired ΔV magnitude of 9 mm/s or greater. If the decision is reached to 'time bias' a maneuver, then the generated plot of ΔV versus time-of-flight demonstrates how the maneuver team can achieve that goal by altering the maneuver design, usually with the smallest time-of-flight solution. Reference 10 discusses how the two time-of-flight shift solutions are derived and implemented.

V.A.6. Maneuver Cancellation Checklist

The checklist serves an overview of the results of the cancellation analysis and helps point out the navigation team's stance on the cancellation of the maneuver. In this case, having green marks for each point in the checklist shows favor to the cancellation of OTM-157. The criteria for each question on the checklist is either explained in the previous subsections or will be discussed here.

One of the first steps in the cancellation process is determining if the maneuver being considered for cancellation is too small to perform or implement. For Cassini, a maneuver size of less than 9 mm/s was deemed as too small to perform and a maneuver size of less than 1 mm/s too small to implement in the maneuver sequencing commands.

Throughout the frequent cancellation meetings, 1 m/s became one of the metrics for deciding if the downstream ΔV costs would be too great to absorb if the maneuver was cancelled (i.e., the maneuver is required if the total downstream ΔV cost ≥ 1 m/s). Of course, other factors were considered in conjunction with the downstream cost, such as individual downstream ΔV increases, effects on science, and workforce ramifications. The downstream ΔV penalties have been determined by two different methods: comparing the downstream deterministic ΔVs and generating downstream ΔV penalty contour and surface plots at the B-plane of the upcoming encounter.

V.B. Maneuver Cancellation Tool

The Maneuver Cancellation Tool, developed by S. Wagner, was created within the Cassini Maneuver Team to address the mounting interest in maneuver cancellations within the Cassini-Huygens Project.[15] This tool, which is a post-processing script that runs as part of MOPS-MAS, produces a package of comparisons between performing or canceling a maneuver and/or comparisons between alternate maneuver/targeting strategies. Development of this tool began in September 2005, starting with the basic need to evaluate a maneuver for cancellation. Since then, the tool has grown to also handle other maneuver strategies, giving the user the option to create a maneuver 'comparison' package of the different strategies.

Figure 6 shows a top-level view of the architecture of the Maneuver Cancellation Tool. The program (`mvr_cancel`) is mainly composed of Perl and MATLAB (wrapped in C shell). The grey-shaded rectangular boxes represent inputs to the tool (e.g., database files and templates). The blue-shaded parallelograms signify the various outputs that the tool generates (e.g., data files, MATLAB figures, EPS, PDF, etc.). The configuration file from the MOPS-MAS run, along with LAMBIC output generated by the Encounter Strategy Tool, are among the various inputs to the Maneuver Cancellation Tool. A few of the input keys are shown (in bold, at the top) to illustrate the interactivity between the maneuver analyst and the tool. The MVR_CANCEL_WI set of keys represent the variables used to define the nominal strategy of performing a maneuver (i.e., results from the MOPS-MAS run: SEPV output, TWIST output, and spacecraft trajectory file). The MVR_CANCEL_WO set of keys, by default, are the variables used to determine the strategy of canceling a maneuver via separate SEPV/TWIST runs. The MVR_CANCEL_WO files can be instead supplied by the maneuver analyst to represent another maneuver strategy (e.g., maneuver performed at backup location). Two additional strategies can also be specified by the maneuver analyst via MVR_CANCEL_WO2 and MVR_CANCEL_WO3. The OTM-157 maneuver cancellation package that is showcased in figure 5 was generated through the default setup of comparing two maneuver designs, the nominal strategy of performing OTM-157 (via MVR_CANCEL_WI) and the strategy of cancelling OTM-157 (via MVR_CANCEL_WO).

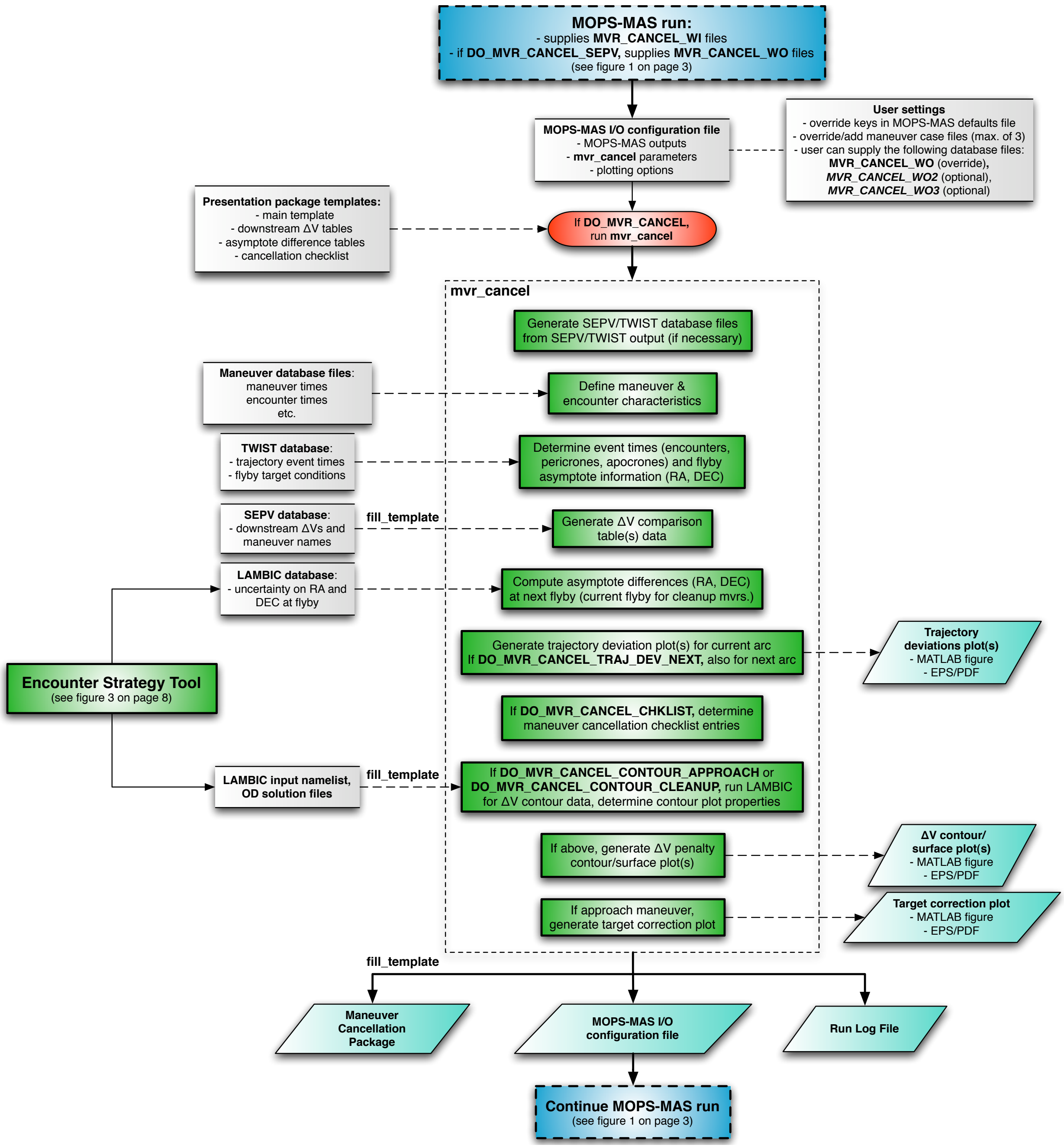


Figure 6. Maneuver Cancellation Tool

VI. Maneuver Products

Once a maneuver is approved or cancelled, the products associated with the maneuver design are released to the project. To reduce the complexity of the delivery process, the MOPS-MAS Delivery Tool was developed in the early years of the Cassini prime mission. In an effort to make the data contained in past maneuver designs and OD reconstructions readily available, the JPL navigation wiki site (navWiki) has been exploited.

VI.A. MOPS-MAS Delivery Tool

The MOPS-MAS Delivery Tool, developed by E. Gist, was created to streamline the maneuver team's delivery process of maneuver products, for internal review by the navigation team, and for external release to the project and the Deep Space Network (DSN). It also forms and sends emails with details of the delivered files and emails containing maneuver information useful in the monitoring of a planned maneuver. The tool even creates/updates maneuver design histories and relevant maneuver information pages on the navWiki.

VI.B. Navigation-Internal Deliveries

Since OD processing is nearly daily during maneuver operations, several designs are usually explored for each maneuver. The number of maneuver designs can range from two to over a dozen, depending on the time between maneuvers. The MOPS-MAS delivery script can be used to send an email notification with a summary of the current maneuver design, with attachments of the current maneuver history; the maneuver approval package; and if generated, the maneuver cancellation package, a preview of the next maneuver, and the maneuver approval package for the backup maneuver (see section III). The maneuver design is also archived in the process of an internal delivery.

VI.C. Cassini-Project Deliveries

Once a maneuver designed has been approved at the project-level, or once it has been officially cancelled, several maneuver products need to be made available for use. The MOPS-MAS Delivery Tool has the option to make these types of deliveries. In one of these 'final' deliveries, the spacecraft ephemeris files needed to predict the trajectory, with or without the maneuver, are delivered to the DSN and to the DOM, which is an officlal database for files used in operations. The maneuver design is not only archived in the process of the external-release delivery, but also added to the maneuver histories on the navWiki.

VI.D. Navigation Wiki

The JPL navigation wiki site, referred to as the navWiki, was introduced near the beginning of the Cassini tour by members of the Cassini Navigation Team. On the Cassini web of the navWiki, meeting notes, technical memos, presentations, and other tidbits of knowledge relevant to the Cassini project are collected. Because the navWiki has become a great resource to the Cassini Navigation Team, it has been recently leveraged to be a one-stop place for navigation histories and data pages. As described in section III, one of the functions of the Encounter Strategy Tool is to create and update the maneuver performance and targeted encounter history tables on the navWiki. The Delivery History Tool, which was developed by S. Wagner as part of the MOPS-MAS Delivery Tool suite, also creates and updates the following history tables based on the MOPS-MAS runs: global history of all maneuvers planned (performed or cancelled) and encounters targeted, design history of all maneuvers performed, and the history of cancelled maneuvers.

VI.D.1. Maneuver/Encounter History Tables

Portions of the global maneuver history page, including the tail-end of the maneuver history, are shown in figure 7. This and other tables are automatically updated with each maneuver delivery or cancellation, via the Delivery History Tool, or with each encounter strategy delivery. Data in these history tables can be sorted for each maneuver parameter (e.g., sort on ΔV magnitude, engine type, etc.). On the global maneuver history table, each maneuver and encounter name is selectable, taking the user to more detailed information. For instance, selecting OTM-159 will lead the user to a summary page on the design of that maneuver (see figure 8b), where maneuver presentation PDFs such as the maneuver approval package used at the final OTM-159 decision meeting can be viewed or downloaded.

Global Maneuver Design History

The maneuver design history table below, which is automatically updated with each maneuver delivery/cancellation, includes all maneuvers planned (TCMs and OTMs), from launch up to the latest OTM performed or cancelled during the Cassini tour. The values in the table are from the maneuver designs, not from the OD reconstructions or telemetry (see Maneuver Performance History for reconstructed values). Encounter information is also provided showing the intended target times (i.e., the target times to be achieved by the final approach maneuvers implemented, not the OD reconstructed values). The flyby differences from the reference trajectory can be found on the Targeted Encounter History page. The data in the table can be sorted for each maneuver or encounter parameter (e.g., sort on ΔV magnitude, yaw turn angle, engine type, inbound/outbound flyby, etc.). Each maneuver and encounter name on the table is selectable, taking you to more detailed information. For instance, selecting OTM-100 will lead you to a summary page on the design of that maneuver, where you can download maneuver presentation PDFs such as the maneuver approval meeting package used at the final OTM-100 decision meeting. A PDF containing most of the data from the global maneuver history table and the intended target conditions (suitable for printing) is located after the table. How many maneuvers have been performed or cancelled since launch, maneuver milestones such as when the 100th maneuver was performed, countdowns, etc. are presented at the bottom of the page (see following links).

If you have trouble seeing the whole table, try using the *plain* skin (see also TWikiSkins).

Last updated on 19 Jun 2008 - 14:54:48 by ChristopherBallard

						Total ΔV (Including Turns)								
Maneuver (Encounter)	**Orbit Location**	**Maneuver Time - UTC/SCET (Encounter Time - ET/SCET)**	**Days to Enc.**	**True Anomaly (degrees)**	**Central Angle (degrees)**	**MPF ΔV (m/s)**	**Magnitude (m/s)**	**Right Ascension (degrees)**	**Declination (degrees)**	**Roll Turn (degrees)**	**Yaw Turn (degrees)**	**Burn Time (sec)**	**Burn Type**	**OD Solution / Cancellation Type (Encounter Type)**
Launch	**L**	**15-OCT-1997 08:43:00**	**193.2**											
Titan-39	**T39**	**20-DEC-2007 22:59:00**	**15.9**	**145.07**										**OUTBOUND**
OTM-140	T39+3d	24-DEC-2007 05:02:00	12.7	167.46	334.97									CANCELLED
OTM-141	T39~apo	29-DEC-2007 12:02:00	7.4	-169.48	311.91	2.0467	2.0524	193.05	68.10	-102.30	-116.00	12.70	MEA	071227_055T40 ?
OTM-142	T40-3d	03-JAN-2008 04:18:00	2.7	-119.08	261.57									CANCELLED
Titan-40	**T40**	**05-JAN-2008 21:31:25**	**47.8**	**145.93**										**OUTBOUND**
OTM-143	T40~per	16-JAN-2008 04:15:00	37.6	79.46	1151.31	2.8750	2.8807	129.56	-1.65	-138.83	-145.46	17.79	MEA	080114_056T41 ?
OTM-144	T40~apo	06-FEB-2008 02:06:00	16.6	-159.10	669.58	37.3909	37.3966	214.99	35.45	-53.29	-121.54	228.23	MEA	080204_056T41 ?
OTM-145	T41-3d	19-FEB-2008 08:36:00	3.4	-143.34	293.95	0.2929	0.2986	64.97	36.86	80.44	-92.72	1.88	MEA	080217_059T41 ?
Titan-41	**T41**	**22-FEB-2008 17:33:12**	**19.1**	**149.69**										**OUTBOUND**
OTM-146	T41~per	01-MAR-2008 22:56:00	10.8	-73.68	405.80	7.0218	7.0276	225.64	-44.76	-78.61	-94.08	42.98	MEA	080228_060E3 ?
OTM-147	T41~apo	07-MAR-2008 07:21:00	5.5	178.33	153.87	1.1153	1.1210	338.72	74.48	90.27	-83.99	6.92	MEA	080306_060E3 ?
OTM-148	E3-3d	10-MAR-2008 07:06:00	1.5	-157.35	129.54									DELAYED
OTM-148-BU	E3-2d	11-MAR-2008 07:06:00	1.5	-143.30	115.47									CANCELLED
Enceladus-3	**E3**	**12-MAR-2008 19:07:17**	**12.8**	**-27.80**										**INBOUND**
OTM-149	E3+1d	13-MAR-2008 23:21:00	11.6	132.19	379.34	2.7542	2.7599	166.45	23.89	157.78	-163.18	16.89	MEA	080312_062T42 ?
OTM-150	E3~apo	18-MAR-2008 06:35:00	7.3	-179.40	330.95	0.0495	0.0540	192.58	-38.75	90.38	-118.73	41.22	RCS	080317_062T42 ?
OTM-151	T42-3d	22-MAR-2008 22:50:00	2.7	-107.67	259.30									CANCELLED
Titan-42	**T42**	**25-MAR-2008 14:28:53**	**47.8**	**150.24**										**OUTBOUND**
OTM-152	T42~per	11-APR-2008 01:04:00	31.4	-82.34	1316.23	3.3229	3.3287	345.96	21.69	58.92	-33.15	20.33	MEA	080408_063T43 ?
OTM-153	T42~apo	26-APR-2008 03:47:00	16.3	-176.31	690.04	0.5065	0.5122	330.97	-34.46	-80.25	-19.09	3.14	MEA	080424_065T43 ?
OTM-154	T43-3d	09-MAY-2008 03:00:00	3.3	-123.04	276.84									CANCELLED
Titan-43	**T43**	**12-MAY-2008 10:03:03**	**15.9**	**156.36**										**OUTBOUND**
OTM-155	T43+5d	17-MAY-2008 01:20:00	11.3	-135.24	658.11	1.1704	1.1762	339.37	26.32	29.93	-36.49	7.21	MEA	080513_068T44 ?
OTM-156	T43~apo	22-MAY-2008 02:13:00	6.3	-178.89	341.86	0.1918	0.1963	164.66	-12.02	16.73	-153.52	159.53	RCS	080520_068T44 ?
OTM-157	T44-3d	25-MAY-2008 01:58:00	3.3	-133.05	296.05									CANCELLED
Titan-44	**T44**	**28-MAY-2008 08:25:37**	**0.0**	**164.53**										**OUTBOUND**
OTM-158	T44+4d	01-JUN-2008 00:27:00	60.1	-141.35	3189.83									CANCELLED
OTM-159	T44~per	23-JUN-2008 06:24:00	37.8	-45.39	2014.64	12.1792	12.1850	32.83	64.36	88.14	-84.74	73.77	MEA	080619_070Sa ?
Maneuver (Encounter)	**Orbit Location**	**Maneuver Time - UTC/SCET (Encounter Time - ET/SCET)**	**Days to Enc.**	**True Anomaly (degrees)**	**Central Angle (degrees)**	**MPF ΔV (m/s)**	**Magnitude (m/s)**	**Right Ascension (degrees)**	**Declination (degrees)**	**Roll Turn (degrees)**	**Yaw Turn (degrees)**	**Burn Time (sec)**	**Burn Type**	**OD Solution / Cancellation Type (Encounter Type)**
							Total ΔV (Including Turns)							

131 maneuvers performed since launch (out of 186 maneuvers planned)

MEA maneuvers	88	47.3%	TCM = 16	OTM = 72
RCS maneuvers	43	23.1%	TCM = 3	OTM = 40
Total executed maneuvers	131	70.4%	TCM = 19	OTM = 112

55 maneuvers cancelled since launch (out of 186 maneuvers planned)

Cancelled maneuvers	47	25.3%	TCM = 5	OTM = 42
Deleted maneuvers	6	3.2%	TCM = 0	OTM = 6
Unneeded maneuvers	2	1.1%	TCM = 1	OTM = 1
Total cancelled maneuvers	55	29.6%	TCM = 6	OTM = 49

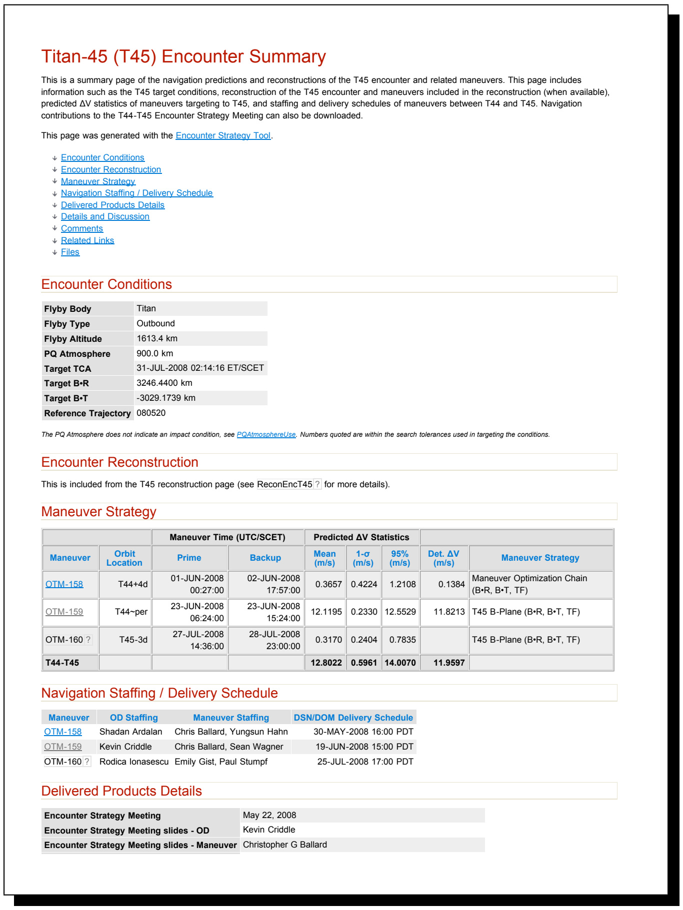
Summary of 186 maneuvers planned since launch

Total executed maneuvers	131	70.4%	TCM = 19	OTM = 112
Total cancelled maneuvers	55	29.6%	TCM = 6	OTM = 49
Total planned maneuvers	186	100.0%	TCM = 25	OTM = 161

Figure 7. Global Maneuver History Page (selected segments)

VI.D.2. *Maneuver/Encounter Information Pages*

As stated before, selecting a maneuver or encounter name on one of the history pages will direct the user to an information page regarding that maneuver or encounter. The encounter pages are produced using data contained in the I/O database files from the Encounter Strategy Tool, and the maneuver pages are generated using the data stored in the I/O configuration/database files from MOPS-MAS. Figure 8 gives examples of the top portions of the generated navWiki pages for T45 and OTM-159.



Titan-45 (T45) Encounter Summary

This is a summary page of the navigation predictions and reconstructions of the T45 encounter and related maneuvers. This page includes information such as the T45 target conditions, reconstruction of the T45 encounter and maneuvers included in the reconstruction (when available), predicted ΔV statistics of maneuvers targeting to T45, and staffing and delivery schedules of maneuvers between T44 and T45. Navigation contributions to the T44-T45 Encounter Strategy Meeting can also be downloaded.

This page was generated with the Encounter Strategy Tool.

- Encounter Conditions
- Encounter Reconstruction
- Maneuver Strategy
- Navigation Staffing / Delivery Schedule
- Delivered Products Details
- Details and Discussion
- Comments
- Related Links
- Files

Encounter Conditions

Flyby Body	Titan
Flyby Type	Outbound
Flyby Altitude	1613.4 km
PQ Atmosphere	900.0 km
Target TCA	31-JUL-2008 02:14:16 ET/SCET
Target B•R	3246.4400 km
Target B•T	-3029.1739 km
Reference Trajectory	080520

The PQ Atmosphere does not indicate an impact condition, see PQAtmosphereUse. Numbers quoted are within the search tolerances used in targeting the conditions.

Encounter Reconstruction

This is included from the T45 reconstruction page (see ReconEncT45 ? for more details).

Maneuver Strategy

		Maneuver Time (UTC/SCET)		Predicted ΔV Statistics				
Maneuver	Orbit Location	Prime	Backup	Mean (m/s)	1-σ (m/s)	95% (m/s)	Det. ΔV (m/s)	Maneuver Strategy
OTM-158	T44+4d	01-JUN-2008 00:27:00	02-JUN-2008 17:57:00	0.3657	0.4224	1.2108	0.1384	Maneuver Optimization Chain (B•R, B•T, TF)
OTM-159	T44~per	23-JUN-2008 06:24:00	23-JUN-2008 15:24:00	12.1195	0.2330	12.5529	11.8213	T45 B-Plane (B•R, B•T, TF)
OTM-160 ?	T45-3d	27-JUL-2008 14:36:00	28-JUL-2008 23:00:00	0.3170	0.2404	0.7835		T45 B-Plane (B•R, B•T, TF)
T44-T45				**12.8022**	**0.5961**	**14.0070**	**11.9597**	

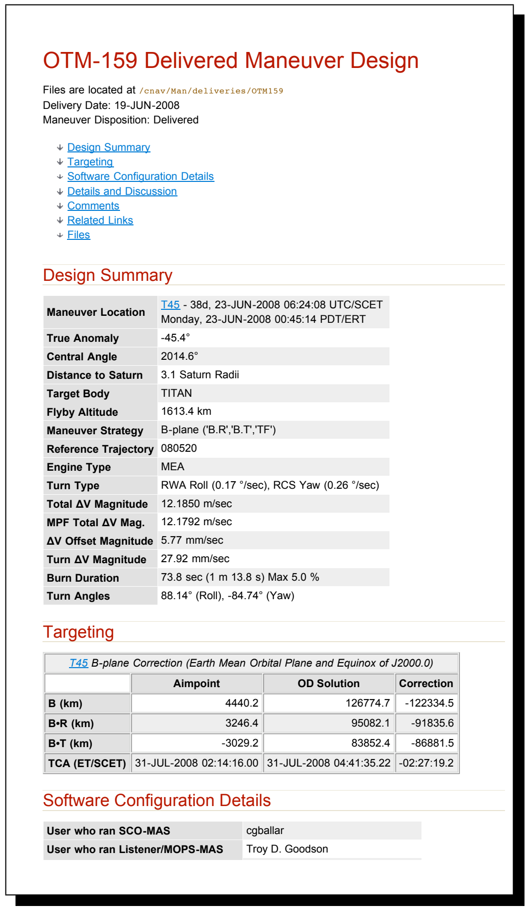
Navigation Staffing / Delivery Schedule

Maneuver	OD Staffing	Maneuver Staffing	DSN/DOM Delivery Schedule
OTM-158	Shadan Ardalan	Chris Ballard, Yungsun Hahn	30-MAY-2008 16:00 PDT
OTM-159	Kevin Criddle	Chris Ballard, Sean Wagner	19-JUN-2008 15:00 PDT
OTM-160 ?	Rodica Ionasescu	Emily Gist, Paul Stumpf	25-JUL-2008 17:00 PDT

Delivered Products Details

Encounter Strategy Meeting	May 22, 2008
Encounter Strategy Meeting slides - OD	Kevin Criddle
Encounter Strategy Meeting slides - Maneuver	Christopher G Ballard

(a) T45 Encounter Summary Page



OTM-159 Delivered Maneuver Design

Files are located at `/cnav/Man/deliveries/OTM159`
Delivery Date: 19-JUN-2008
Maneuver Disposition: Delivered

- Design Summary
- Targeting
- Software Configuration Details
- Details and Discussion
- Comments
- Related Links
- Files

Design Summary

Maneuver Location	T45 - 38d, 23-JUN-2008 06:24:08 UTC/SCET Monday, 23-JUN-2008 00:45:14 PDT/ERT
True Anomaly	-45.4°
Central Angle	2014.6°
Distance to Saturn	3.1 Saturn Radii
Target Body	TITAN
Flyby Altitude	1613.4 km
Maneuver Strategy	B-plane ('B.R','B.T','TF')
Reference Trajectory	080520
Engine Type	MEA
Turn Type	RWA Roll (0.17 °/sec), RCS Yaw (0.26 °/sec)
Total ΔV Magnitude	12.1850 m/sec
MPF Total ΔV Mag.	12.1792 m/sec
ΔV Offset Magnitude	5.77 mm/sec
Turn ΔV Magnitude	27.92 mm/sec
Burn Duration	73.8 sec (1 m 13.8 s) Max 5.0 %
Turn Angles	88.14° (Roll), -84.74° (Yaw)

Targeting

T45 B-plane Correction (Earth Mean Orbital Plane and Equinox of J2000.0)			
	Aimpoint	OD Solution	Correction
B (km)	4440.2	126774.7	-122334.5
B•R (km)	3246.4	95082.1	-91835.6
B•T (km)	-3029.2	83852.4	-86881.5
TCA (ET/SCET)	31-JUL-2008 02:14:16.00	31-JUL-2008 04:41:35.22	-02:27:19.2

Software Configuration Details

User who ran SCO-MAS	cgballar
User who ran Listener/MOPS-MAS	Troy D. Goodson

(b) OTM-159 Maneuver Delivery Page

Figure 8. Maneuver/Encounter Information Pages (top segments)

VII. Closure

MOPS-MAS and other maneuver analysis tools have grown much throughout the duration of the Cassini tour. Born out of a necessity to streamline a complex process across several disciplines, MOPS-MAS has matured to be the prime method of conveying navigation information, from a maneuver analyst's standpoint, to the entire Cassini-Huygens Project. As described throughout this paper, many of the tools that have been developed to work in the context of MOPS-MAS have evolved during Cassini tour operations. This evolution came about in an iterative manner, where software changes were often made to address issues as they materialized. Although the tools described in this paper are specific and tailored to the Cassini mission, the thought processes behind them are good examples to other planetary missions faced with complex schedules. The success of this tool development is clearly seen with the number of presentation packages that are generated, at almost a daily rate. The Cassini Maneuver Team expects further success with their maneuver tools as the Saturn tour continues through the extended mission.

Acknowledgments

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