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The Cassini-Huygens mission was launched on October 15, 1997 as a joint NASA/ESA mission to explore Saturn. After a 7 year cruise the spacecraft will enter orbit around Saturn on 1 July 2004 for a 4 year investigation of the Saturnian system. The Cassini Navigation Team is responsible for designing the reference trajectory and conducting operations to realize this design. This paper describes the strategy for achieving project requirements, the characteristics of the Cassini navigation challenge, and the underlying assumptions.

INTRODUCTION

The Cassini-Huygens spacecraft was launched October 15, 1997 and is currently en route to Saturn, having completed flybys of Venus, Earth, and Jupiter. On July 1, 2004, after becoming the first spacecraft captured into orbit around Saturn, Cassini will begin a four year tour of the Saturnian system, where it will study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites. The Cassini orbiter carries the Huygens probe, which will be the first spacecraft to land on Saturn's moon Titan. Both Cassini and Huygens will study Titan's atmospheric structure and composition as well as Titan's surface topography.

During the tour, the Cassini navigation system supports both the updating of the nominal tour trajectory and the control of the spacecraft's trajectory on the nominal tour. The objective of updating the nominal tour trajectory will be to maintain the pre-planned sequence of encounters while accounting for expected variations in the major satellite ephemerides and, possibly, the Titan atmosphere model.

The tour navigation requires a mixture of radiometric tracking data (Doppler and ranging) and optical images of Titan and the other major Saturn satellites. During the tour the average number of optical navigation images starts at 3 per day at the beginning of the tour, decreases to 1.65 per day after the Tc Titan encounter, and decreases further to 0.5 per day after the T6 Titan encounter.

In addition to spacecraft ephemerides, the Navigation Team will also provide ephemerides for the major Saturnian satellites. Prior to Saturn approach, the ephemerides of the major Saturnian satellites will be known to a 1σ accuracy somewhere between 180 and 1700 km depending upon the satellite and the ground observation schedule. During the approach phase, the optical images will be used to reduce this uncertainty to less than 100 km. Once in the tour phase, the uncertainty will decrease to less than 10 kilometers. The major satellite ephemerides will be updated periodically and delivered to the project in order to maintain the needed accuracy level.

Given the nominal tour trajectory, the maneuver control strategy is to deliver the spacecraft to the targeted encounter condition specified in the current reference trajectory. Between each targeted encounter,

Table 1: THE CASSINI TOUR (T2003-01)[a]

Encounter	Satellite	Time (UTC)	TOF [days]	In / Out	Altitude [km]	B-Plane [deg]	V-Infinity [km/s]	Period [days]	Inc. [deg]	Rev
Ta	Titan	26-Oct-04 15:30	118	I	1200	-39	5.65	47.8	13.8	a
Tb	Titan	13-Dec-04 11:37	165	I	2336	-49	5.65	32.0	8.5	b
Tc	Titan	14-Jan-05 11:05	197	I	60000	180	5.38	33.3	8.6	c
T3	Titan	15-Feb-05 06:54	229	I	950	-43	5.58	20.5	0.3	3
E1	Enceladus	09-Mar-05 09:07	251	I	500	150	6.61	20.5	0.4	4
T4	Titan	31-Mar-05 19:55	274	O	2523	-148	5.61	16.0	7.0	5
T5	Titan	16-Apr-05 19:06	290	O	950	-76	5.63	18.1	21.6	6
E2	Enceladus	14-Jul-05 19:57	379	I	1000	-160	8.12	18.3	21.8	11
T6	Titan	22-Aug-05 08:40	417	O	4015	122	5.60	16.0	16.1	13
T7	Titan	07-Sep-05 07:50	433	O	950	68	5.63	18.4	0.3	14
H1	Hyperion	26-Sep-05 01:41	452	O	1000	180	5.62	18.2	0.3	15
D1	Dione	11-Oct-05 17:58	468	I	500	120	9.03	17.9	0.4	16
T8	Titan	28-Oct-05 03:58	484	I	1446	181	5.52	30.3	0.4	17
R1	Rhea	26-Nov-05 22:36	514	I	500	10	7.28	27.4	0.4	18
T9	Titan	26-Dec-05 18:55	544	O	10429	180	5.49	23.4	0.4	19
T10	Titan	15-Jan-06 11:36	563	I	2042	180	5.48	39.2	0.4	20
T11	Titan	27-Feb-06 08:21	606	O	1812	180	5.51	23.3	0.4	21
T12	Titan	18-Mar-06 23:58	626	I	1947	180	5.48	39.2	0.4	22
T13	Titan	30-Apr-06 20:54	669	O	1853	180	5.49	23.3	0.4	23
T14	Titan	20-May-06 12:13	688	I	1879	180	5.48	39.2	0.4	24
T15	Titan	02-Jul-06 09:12	731	O	1911	179	5.48	23.3	0.4	25
T16	Titan	22-Jul-06 00:25	751	I	950	-92	5.52	24.0	14.9	26
T17	Titan	07-Sep-06 20:12	799	I	950	-24	5.54	16.0	24.7	28
T18	Titan	23-Sep-06 18:53	815	I	950	-81	5.54	16.0	37.7	29
T19	Titan	09-Oct-06 17:23	831	I	950	-75	5.54	16.0	46.8	30
T20	Titan	25-Oct-06 15:51	847	I	950	-11	5.55	12.0	55.4	31
T21	Titan	12-Dec-06 11:35	894	I	950	-121	5.53	16.0	53.3	35
T22	Titan	28-Dec-06 10:00	910	I	1500	-61	5.54	16.0	56.8	36
T23	Titan	13-Jan-07 08:34	926	I	950	-52	5.54	16.0	59.4	37
T24	Titan	29-Jan-07 07:12	942	I	2776	-69	5.54	18.1	59.0	38
T25	Titan	22-Feb-07 03:11	966	O	953	-55	5.83	16.0	58.8	39
T26	Titan	10-Mar-07 01:47	982	O	956	-48	5.83	16.0	56.2	40
T27	Titan	26-Mar-07 00:22	998	O	953	-58	5.83	16.0	52.4	41
T28	Titan	10-Apr-07 22:57	1014	O	951	-66	5.83	16.0	46.9	42
T29	Titan	26-Apr-07 21:33	1030	O	951	-73	5.83	16.0	39.0	43
T30	Titan	12-May-07 20:08	1046	O	950	-79	5.83	16.0	28.0	44
T31	Titan	28-May-07 18:51	1062	O	2425	-84	5.83	16.0	18.0	45
T32	Titan	13-Jun-07 17:47	1078	O	950	-87	5.83	16.0	19.5	46
T33	Titan	29-Jun-07 17:05	1094	O	1942	-8	5.86	22.8	0.4	47
T34	Titan	19-Jul-07 00:40	1113	I	1302	-179	5.86	39.7	0.3	48
T35	Titan	31-Aug-07 06:34	1156	O	3227	-116	5.84	32.4	6.5	49
I1	Iapetus	10-Sep-07 12:34	1166	O	1000	159	2.36	32.0	6.2	49
T36	Titan	02-Oct-07 04:49	1188	O	950	120	5.90	23.8	5.0	50
T37	Titan	19-Nov-07 00:53	1236	O	950	157	5.90	16.0	12.4	52
T38	Titan	05-Dec-07 00:06	1252	O	1300	96	5.92	16.0	26.4	53
T39	Titan	20-Dec-07 22:57	1268	O	953	101	5.92	16.0	38.0	54
T40	Titan	05-Jan-08 21:26	1284	O	949	166	5.91	11.9	47.1	55
T41	Titan	22-Feb-08 17:39	1332	O	959	140	5.95	10.6	56.8	59
E3	Enceladus	12-Mar-08 19:06	1351	I	1000	0	14.59	10.6	56.8	61
T42	Titan	25-Mar-08 14:35	1364	O	950	147	5.96	9.6	63.7	62
T43	Titan	12-May-08 10:10	1411	O	950	-162	5.95	8.0	70.1	67
T44	Titan	28-May-08 08:33	1427	O	1316	-168	5.95	7.1	75.6	69

[a]TOF = time of flight from SOI start. In/Out = flyby inbound (I) or outbound (O). B-plane = B-plane angle relative to the satellite's pole (H1 angle is relative to Saturn pole). Period = spacecraft period after encounter. Inc. = inclination after encounter. Rev = spacecraft revolution # of flyby.

Occultations / Icy Satellites (T3-T9)

Four icy satellite flybys as well as important occultations of Saturn occur during this phase of the tour. The first icy satellite flyby of the tour, E1, occurs between the T3 and T4 flybys. The T4 and T5 flybys then raise the inclination to ~22° to set up the orbit geometry needed for seven radio science near-equatorial occultations of Saturn and its rings between the T5 and T6 flybys (Figure 2). Such occultation passes are only possible in the beginning of the mission because by the end of the mission Saturn's rings are edge on as seen from Earth. The second Enceladus encounter (E2) occurs during the T5-T6 transfer. T6 and T7 then lower the inclination back into Titan's orbit plane for flybys of Hyperion (H1) and Dione (D1) on the non-resonant T7-T8 transfer and a flyby of Rhea (R1) between T8 and T9. The non-resonant T7-T8 and T8-T9 transfers also begin to rotate Cassini's apoapsis towards Saturn's magnetotail.

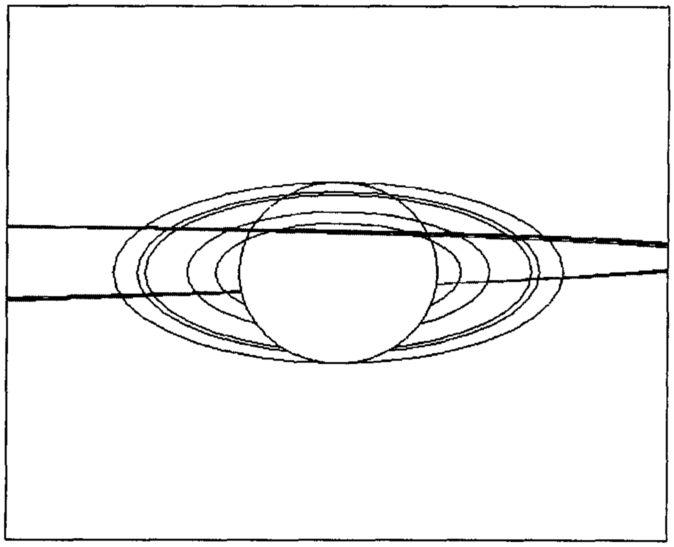

Figure 2: Saturn-Earth Occultations from T5 to T6

Magnetotail Passage (T9-T16)

During this phase of the mission, non-resonant transfers are used to move the apoapsis of Cassini's orbit behind Saturn as seen from the Sun with the goal of moving Cassini into Saturn's magnetotail. In this phase, Titan flybys alternate between inbound (i.e. before Saturnian periapsis) and outbound (i.e. after periapsis) encounters. This is done in such a way as to rotate the apoapsis as quickly as possible into the magnetotail[1,2,5]. At the end of this phase the Cassini apoapsis is in the anti-sun direction and the T16 flyby increases the inclination to ~15° to pass through Saturn's magnetotail.

Pi-Transfer (T16-T33)

For the magnetotail observations, Cassini's apoapsis is behind Saturn as seen from the Sun. From this geometry, Cassini's apoapsis needs to be moved to the other side of Saturn for atmospheric observations. Then the apoapsis will be between Saturn and the Sun to allow observations of Saturn's entire disc in sunlight.

A Pi-Transfer is used to flip the Titan encounter 180° to the other side of Saturn more rapidly than could be done with non-resonant transfers. The Pi-Transfer occurs between T24 and T25, but requires many more flybys to set up the inclination needed for the transfer. The flybys from T16-T24 raise the inclination to the ~59° required for the Pi-Transfer. Then the flybys from T25 to T33 lower the inclination back into Titan's orbit plane so that non-resonant transfers can be used to set up the geometry required for the atmospheric observations. This phase has many low altitude Titan flybys, which are valuable for Titan science. Also, the T20-T21 transfer provides geometry favorable for ring observations.

with the updated satellite ephemerides. Depending upon the changes in the location of the major satellites (primarily Titan), an update to the reference trajectory may be necessary once or twice prior to SOI and possibly three times after SOI.

The second component of the orbit determination process is the determination of the location of the spacecraft in the Saturn system. The plan is to use a combination of both radiometric data (Doppler and ranging) and optical data from the NAC to accomplish this task. The frequency of radiometric tracking passes is listed in Table 4[10]. The same optical data noted above for the satellite ephemeris determination also provides information on the location of the spacecraft relative to the satellites.

Table 4: RADIOMETRIC DATA SCHEDULE DURING TOUR

Mission Phase	Tracking Data Pass Rates	Comments
General	At least one pass per day. Doppler: at least 6 hours per day. Range: at least 3 hours per day.	X-band 2-way Doppler and range. At least 1 hour of tracking per day, on average, from a second DSN complex; tracking from second DSN complex at least four times, evenly spaced, between targeted encounters. At least 2 hours of tracking for every scheduled tracking pass.
Start of S07 Sequence to Titan C	At least two passes per day. Doppler: at least 13 hours per day. Range: at least 6 hours per day.	X-band 2-way Doppler and range from northern hemisphere tracking stations. Requirement relaxed to one pass around middle of two day interval centered on Iapetus non-targeted flyby of 1 Jan 2005.
*Near-Titan Periods	At least one pass per day. Doppler: at least 6 hours per day. Range: at least 3 hours per day.	X-band 2-way Doppler and range. For the interval from pre-Titan maneuver to Titan-12h and the interval from Titan+12h to post-Titan maneuver. At least 2 hours of tracking for every scheduled tracking pass.
Tour Maneuvers	Before maneuver: at least 2 hours of tracking (Doppler and range) within 4 hours prior to maneuver. After maneuver: at least 2 hours of tracking (Doppler and range) within 4 hours after maneuver.	X-band 2-way Doppler and range.

*A near-Titan period is defined as the period from pre-Titan maneuver to post-Titan maneuver.

The third component is the short term prediction of spacecraft and satellite orbits. Accurate prediction is accomplished using the validated models of the gravity fields and the non-gravitational forces acting on spacecraft. Many of the parameters in these models are estimated as a part of the OD process. Due to the perturbations introduced by the Titan flybys, the short term predictions are generally limited to only a few days past the next Titan encounter. The current plan is to publish an updated local spacecraft trajectory as a part of each maneuver design. This update would include the predicted maneuvers and would extend a few days past the next Titan encounter. In a few cases additional deliveries are necessary.

Processing Assumptions

In general, orbit determination shall be performed over data arcs spanning approximately 1.5 spacecraft revs around Saturn, with each arc beginning near Saturn apoapsis and ending near Saturn periapsis. In this manner, each arc has nearly 0.5 revs of overlap with the next arc. Longer arcs are prohibited by integration errors and nonlinearities. In many cases, targeted satellite flybys occur on determine the camera pointing. Two star images in a picture determine the camera pointing completely, with an accuracy that depends on the centerfinding errors of the star images. Additional star images provide incremental improvement to the knowledge of the pointing, since they decrease the pointing uncertainty. If there is only one star image, however, the camera can in principle rotate arbitrarily about the line of sight to the star, and therefore the data content is reduced: the angular separation between the star and the satellite is accurately known, but the "position angle" of the satellite with respect to the star is known only to the extent that the camera's twist orientation is known from other sources. The uncertainty ellipse in the satellite's apparent right ascension and declination will therefore be stretched into a cigar shape, with a long axis perpendicular to the line joining the spacecraft and the star. For this reason pictures with at least two usable stars are superior to one-star pictures.

Table 5: FILTER PARAMETERS (EXCLUDING EPHEMERIS PARAMETERS)

Name	Modeled *A Priori* 1σ Error (Estimated)	Unmodeled *A Priori* 1σ Error (Considered)	Comments
All Phases			
Spacecraft epoch state	150 km - ∞, 100 mm/s - ∞		Solutions are generally insensitive to epoch state error since they are strongly data driven.
Maneuvers	Variable		Depends on nominal ΔV magnitude and propulsion system implemented.
Stochastic camera pointing	1° per axis		RA, Dec, twist angles.
Station locations		2-3 cm per axis	Reference 11
Troposphere		1.0 cm	Zenith range delay.
Ionosphere		4.0 cm day 1.0 cm night	Range delays.
Earth orientation parameters		10 cm per axis	X, Y pole position, TAI-UT1.
Coherent Doppler data	0.2 mm/s		60 second compression.
Ranging data	75 m		
Optical data	Titan = 1 pixel Icy sats= 0.5 pixel Stars = 0.25 pixel		No optical data for SEP < 3° and within 12 hours of a satellite flyby.
Angular momentum desaturations	~5 mm/s		Along spacecraft Z-axis.
RCS science turns	160 mm/s per axis		Near satellite closest approaches.
Tour			
Stochastic non-gravitational acceleration	4.5×10^{-12} km/s^2		Per axis. 12h batches, white noise.
Probe Delivery			
Probe release	1.3 mm/s per axis 12 mm/s per axis		Orbiter uncertainty Probe uncertainty
Detumble	5 mm/s per axis		AACS reconstruction capability
Constant non-gravitational acceleration	2.1×10^{-12}, 6.7×10^{-13}, 7.6×10^{-14} km/s^2		50% of nominal acceleration caused by RTG radiation.

The planet and satellite errors in Table 6, based on planet ephemeris DE410[12] and satellite ephemeris SAT136[13], will improve as additional ground based observations are collected and processed. Substantial improvements will be realized with the addition of optical navigation pictures and radiometric data acquired through satellite flybys.

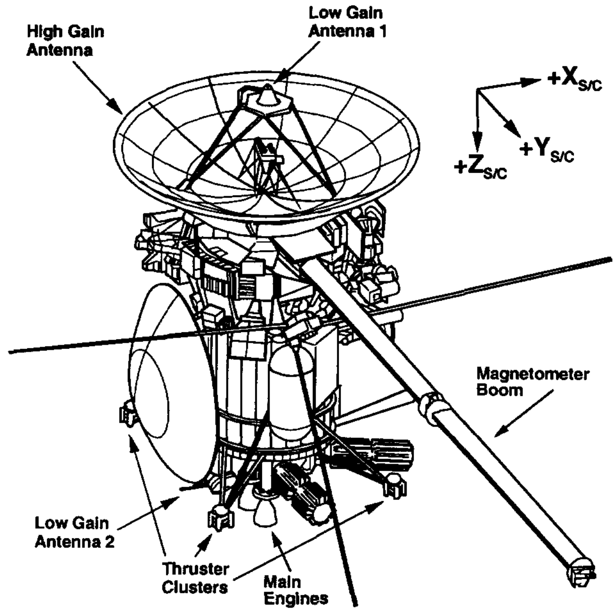

Figure 3: Cassini Spacecraft

The fixed error levels are larger for the main engine while proportional error levels are larger for the RCS. Thus, smaller maneuvers favor the use of RCS. Figure 4 shows the trade off in maneuver execution accuracy versus maneuver magnitude. Currently, the boundary is set at .5 m/s.

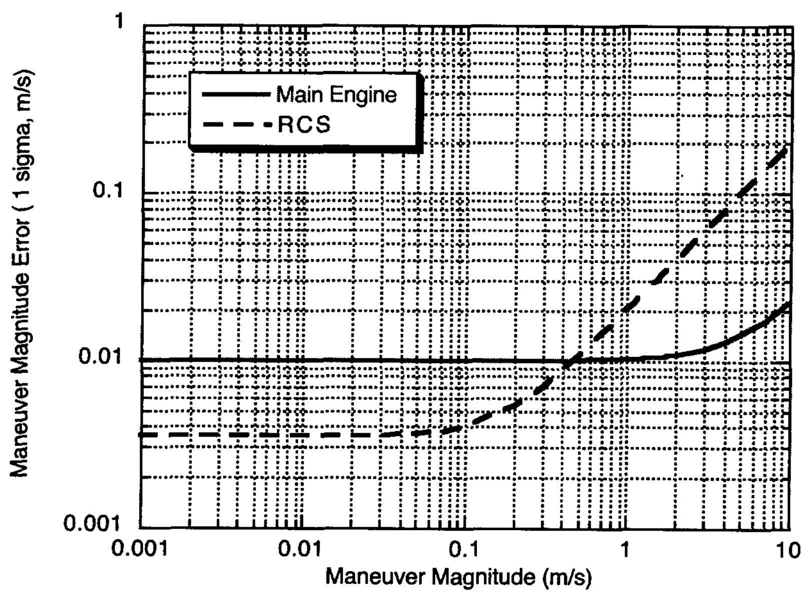

Figure 4: Maneuver Execution Error vs. Magnitude

Note that a Titan flyby at an altitude of 950 km imparts an equivalent ΔV of about 800 m/s to the spacecraft. Since the orbiter has a total ΔV capability after SOI of less than 500 m/s, missing almost any planned Titan flyby would have serious consequences. If this occurred, then a replanning of the remaining portion of the tour would be required.

Furthermore, because of the slope of the curve, changes in the planned altitude cause changes in the Titan ΔV. These errors in the Titan ΔV must be compensated for by maneuvers after the flyby. The slope of the curve at 950 km altitude is 0.21 m/s/km. Thus an error of 5 km in the Titan flyby altitude changes the Titan ΔV by about 1 m/s. Since the correction cannot be applied immediately, the correction cost is generally greater than the initial cost. Allowing the correction to be accomplished by multiple maneuvers and combined with deterministic maneuvers minimizes the spacecraft propellant cost.

Targeting Strategy

A two-maneuver optimization scheme will divide the cost in two parts such that their sum is minimized. However, a two-impulse solution minimizing the cost only in the 'current' leg usually introduces asymptote errors in the downstream legs, which become costly if left unchecked. One way of controlling these asymptote errors is to actively vary the upcoming flyby aimpoint based on the particular flyby errors incurred at the previous flyby, which requires frequent command sequence changes. This amounts to redefining the reference trajectory after each flyby. Due to the short time interval between flybys, active aimpoint variations would be operationally infeasible. Instead, the Cassini Navigation Team has adopted a chained two-impulse maneuver strategy[15,16] as described below, which couples the first and second maneuvers across several encounters but does not involve flyby aimpoint variations once a reference trajectory segment has been chosen. This scheme is illustrated in Figure 7, where a straight line is used as a generic representation of the spacecraft trajectory segment spanning encounters i through i+3, with each 'cross' marking an OTM.

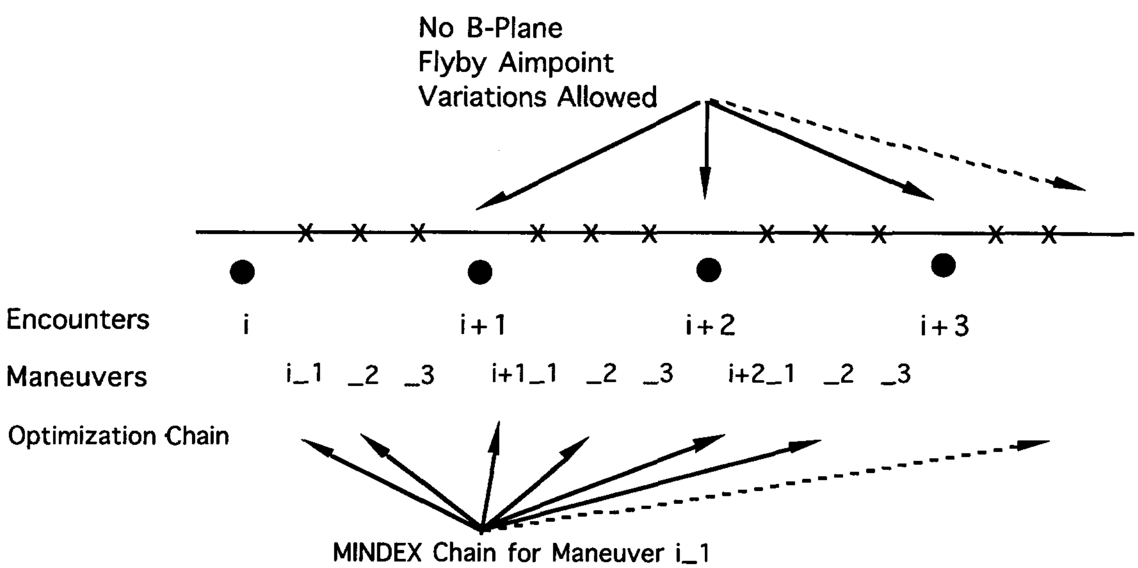

Figure 7: Chained Two Impulse Maneuver Strategy

Note that for N downstream encounters, 2*N maneuvers are being optimized (6*N parameters) and 3*N constraints are in effect (**B•R**, **B•T**, and TF). The third maneuver in each leg is not included since it is best left as a purely statistical final tuning. Hence, the first maneuver in each leg is computed by minimizing a cost function of the following form:

The deterministic ΔV cost for the Post-T3 tour is approximately 287 m/s, while the combined (deterministic + statistical) cost is approximately 400 m/s in the mean, and 430 m/s at the 95% level. Hence, the predicted ΔV estimate for the post-T3 tour is 'heavy' in statistical cost. The spread around the mean is narrow—the difference between the 5% low and 95% high is only about 60 m/s.

Since there are 48 flyby to flyby legs here, this comes to an 'average' of about 9 m/s per flyby at the 95% level. As readily observed in the plot, however, the cost is not spread evenly among encounters. The sharp rises in the early portion of the tour are due to the large deterministic maneuvers in T5-E2, T7-H1, D1-T8, and there is another large one in T40-T41 legs. That three out of these four legs involve transfers either to or from icy satellites underscores the expensive nature of 'squeezing' targeted icy satellite flybys between Titan-Titan encounter sequences.

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