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OVERVIEW OF THE CASSINI EXTENDED MISSION TRAJECTORY

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Due to the highly successful execution of the Cassini-Huygens prime mission and the estimated propellant remaining at the conclusion of the prime mission, NASA Headquarters allocated funding for the development of a 2-year long Cassini extended mission. The resultant extended mission, stemming from 1.5 years of development, includes an additional 26 targeted Titan flybys, 9 close flybys of icy satellites, and 60 orbits about Saturn. This paper describes, in detail, the different phases of the Cassini extended mission and the associated design methodology, which attempted to maximize the number and quality of high-priority scientific objectives while minimizing the total Δv expenditure and adhering to mission-imposed constraints.

Nomenclature

B	impact parameter	r_{asc}	radius of asc. node crossing wrt cb
θ	B-plane angle	r_{dsc}	radius of desc. node crossing wrt cb
i	inclination wrt central body	r_p	periapsis radius wrt central body
J	a cost function	T	orbit period
m	integer number of ga-body orbits	tof	time of flight between encounters
n	integer number of sc orbits	Δv	change in velocity
r_a	apoapsis radius wrt central body	v_∞	hyperbolic excess velocity wrt ga-body

I. Introduction

Cassini-Huygens, a joint mission between the United States National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Italian Space Agency (ASI), is the fourth spacecraft to visit the Saturnian system and the first spacecraft to be captured into orbit about Saturn. During the 4-year prime mission (1-Jul-2004 – 1-Jul-2008), the Cassini-Huygens conducted a spectacularly successful investigation of the Saturn, it's rings, icy satellites, magnetosphere, and Titan. The Cassini spacecraft successfully delivered the Huygens Probe to the surface of Titan (14-Jan-2005), performed 45 targeted Titan flybys, 10 close flybys[a] of icy satellites (including the pre-Saturn Orbit Insertion (SOI) Phoebe flyby), 200 Voyager-class[b] or better distant moon flybys, and 75 orbits about Saturn.[1]

Due to the highly successful execution of the prime mission, the continued quality of science return, and the excellent state of the spacecraft (both spacecraft health and the estimated propellant (Δv) remaining at the conclusion of the prime mission), NASA Headquarters allocated funding for the development of a 2-year long Cassini extended mission (XM). Guidance from NASA Headquarters was to assume an encounter and maneuver frequency similar to that of the the prime mission (i.e. funding would remain at prime mission level for the extent of the extended mission). The resultant Cassini extended mission, stemming from 1.5

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[a]Flyby altitude $\leq$ 2000 km

[b]Flyby altitude $\leq$ 125,000 km for icy moons and $\leq$ 1 million km for Titan

years of development, includes an additional 26 targeted Titan flybys, 9 close flybys[a] of icy satellites (7 of which are Enceladus flybys), and 60 orbits about Saturn.

II. Science Objectives

Over 75 total scientific objectives were requested by the five different Saturn Discipline Working Groups[c] (DWG's) to further increase the understanding of the Saturn system over the 2-year extended mission. These objectives stemmed from the desire to, address new discoveries (Enceladus' south polar plume, Titan's methane lakes, Dione mass loading, etc.), take advantage of new temporal and spatial opportunities (Titan and Saturn seasons, rings equinox viewing, Enceladus plume variability, etc.), respond to theoretical advances (importance of Titan and Enceladus organic chemistry, dynamics of satellites imbedded in the rings, etc.), and obtain additional data to further address the AO[d] objectives (high resolution RADAR coverage of Titan, occultations, etc.). In addition, these scientific objectives, with particular emphasis on high resolution Titan and Enceladus coverage, lend themselves well to providing essential data necessary for future missions to the Saturn system.[3]

To better understand the trade space and interactions between different scientific objectives, a sub-set of the scientific objectives, referred to as design drivers, were identified (Appendix B). Design drivers are scientific objectives that correspond to observational geometries that narrowed the tour design trade space; Not all science objectives were design drivers. This set of design drivers was further separated into two categories: time critical and geometric. Time critical design drivers consisted of observations that can only be carried out during a specific finite time period. Geometric design drivers consisted of scientific objectives that could be carried out at anytime during the XM, as long as the geometric constraints were met. Identifying these characteristic differences allowed the tour designers to strategically place specific drivers, discern which drivers were mutually exclusive, and/or which drivers where compatible. Since in trajectory design, the optimization of a problem consists not only of minimizing the total expended propellant, but also maximizing the number of quality science objectives achieved in a finite time period, the better the tour designer can understand the outcome and implications of the choices made, developing an intuition for the problem at hand, the more efficient (science return as a function of Δv and time) the end product will be. This was particularly true for the development of the Cassini extended mission due to the high number (and intricacy) of requested science objectives, the complexity of the Saturnian system, and the truly three-dimensional nature of the trade space.[4]

III. Constraints

In addition to the challenges pertaining to balancing and assessing the vast quantity of complex, high-level science objectives levied on the tour design, operational constraints need also be considered and heavily influenced the tour design. Some constraints are simple due to the orbital mechanics, while others pertain to spacecraft and/or ground system operational limitations.[5]

Ring Plane Crossings: Saturn's rings are a fascinating system consisting of an intricate intertwining of moonlets, dust, water-icy, and other constituents with distinct structures varying temporally and spatially in density and size. While the solar system's most massive and diverse ring system is one of intrigue from a scientific investigation point of view, they are a navigational hazard. Specifically, spacecraft ring plane crossings inside 2.347 RS[e] (i.e. inside the outer edge of the F ring) and between 2.73 and 2.917 RS (the G ring) must be completely avoided. In addition, due to the finite thickness of the G ring ($\pm$ 720 km), low inclination ring plane crossings within the F-G ring gap (2.347 - 2.73 RS) must be checked to assure the spacecraft does not traverse a significant portion of G ring. Lastly, the total probability of loss of mission due to particle impact per year must not exceed 1.25%.[6]

[c]Cassini Discipline Working Groups: Icy Satellites, Titan, Rings, Saturn, and Magnetospheric and Plasma.
[d]Saturn system objectives in the NASA and ESA Announcements of Opportunity[2]
[e]RS = 60,330 km (Saturn equatorial radius at 1 bar surface)

Minimum Flyby Altitudes: Due to torques imparted to the spacecraft by the dense atmosphere that completely enshrouds Titan, a minimum Titan altitude must imposed in order to maintain control authority throughout a given flyby. During the design of all XM candidate tours, the minimum Titan flyby altitude was set at 1000 km based on the the Titan Atmospheric Modeling Working Group's (TAMWG) best estimate of Titan's atmosphere and the predicted spacecraft control capability over the XM. Once the final tour was selected, the AACS team then determined the actual flyby-specific altitudes based on the TAMWG atmospheric model, spacecraft attitude profiles, and RCS thruster control authority.

For Enceladus, the minimum flyby altitude was set to 100 km for flybys with closet approach (c/a) latitudes $\geq 70°$ S (i.e. flybys that penetrate deep into Enceladus' plume), and 25 km for all other flybys. The lower bound for all other icy satellite flyby altitudes was set at 100 km.

Solar Conjunction: Coherent two-way Doppler measurements ($\sim$6–8 hrs. in duration) at regular intervals ($\sim$1 day) are required to accurately determine the orbit(s) of the spacecraft to the precision necessary to navigate a tour of similar intensity and aggressiveness as the extended mission.[7] However, during solar conjunction (when the Sun-Earth-Probe angle (SEP) becomes $\leq 7.5°$), the radio signal must propagate through the solar plasma, making the data noisy and of limited (if any) use. This phenomenon puts restrictions on certain mission critical events, namely maneuver and flyby times. Specifically, 1) prior to solar conjunction, at least two good days of tracking (without flybys or other maneuvers) must be obtained at SEP $\geq 10°$, 2) no maneuver can be performed below 5° SEP (telemetry data cannot be downlinked and doesn't allow time for a backup maneuver), and 3) after solar conjunction, maneuvers must be at least three days after 10° SEP to allow for two days of tracking plus an additional day to design the maneuver. In addition, the deeper the flyby is in solar conjunction, the higher the flyby altitude must be due to the growth in error from the tracking at 10° SEP used for the approach maneuver.

Time of Flight Between Flybys: A sufficient amount of time is needed between successive targeted flybys to accurately determine the spacecraft's orbit, and design, uplink, and perform two deterministic[f] and one statistical orbital trim maneuver (OTM). This requirement puts a lower limit on the time-of-flight (*tof*) between encounters. As with the prime mission, this limit was set to 16 days for the XM (since staffing levels would remain the same). An exception to this rule is a scenario referred to as a "double flyby" in which a two flybys occur sufficiently close ($\sim$2-3 days) to one another that no OTM's can be performed between the two encounters. Instead, only one body is targeted while the desired flyby of the other body is accomplished as a result.[7,8] In addition, the flyby that is not directly targeted must have a higher flyby altitude. Double flybys were proven navigationally feasible and highly valuable from a science return point of view during the prime mission.

Available propellant: The predicted Δv from the bi-propellant propulsion system available at the beginning of the XM was approximately 351 m/s.

Mission Duration: As previously stated, NASA HQ directed a two year duration for the Cassini XM.

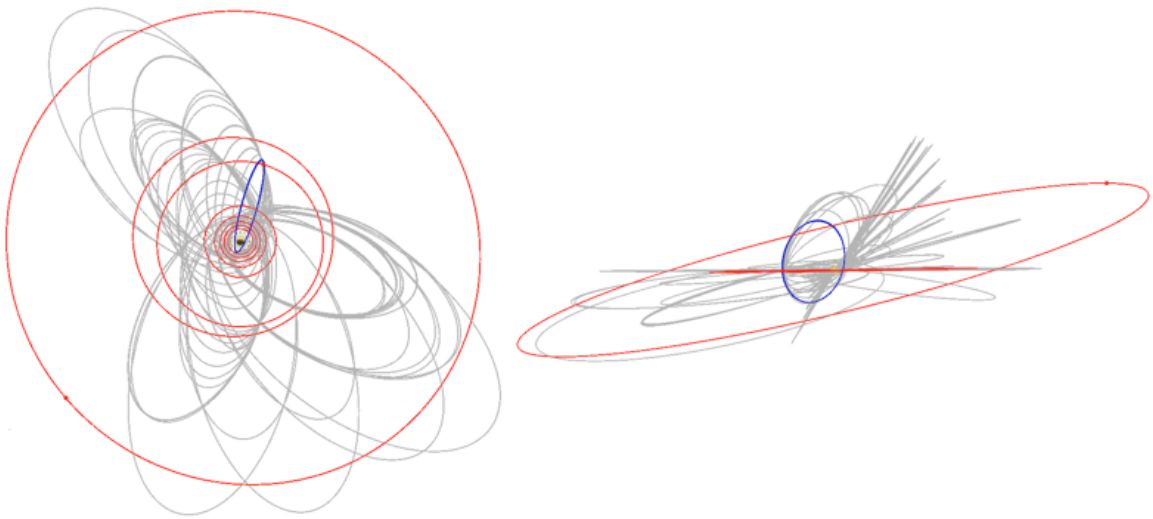
IV. Initial Conditions

The extended mission initial conditions consist of a highly inclined (74.8°) short period resonant transfer (4:9[g].), having a periapsis altitude of 2.65 RS, and a petal orientation of approximately 11:00 local Saturn Time (LST) (Fig. 1). The first Titan flyby (T45) in the extended mission is an outbound flyby occurring at the ascending node, and has a v_∞ of 5.879 km/s (Table 1).

Table 1. Initial conditions for the Cassini extended mission.

Inclination	Resonance[g]	Period	V-infinity	Periapsis	In/Out Flyby	Node @ Titan Flyby
74.8º	4:9	7.1 days	5.879 km/s	2.65 RS	Outbound	Ascending

[f]Special cases do exist where only one deterministic maneuver is utilized between targeted encounters.
[g]Titan-to-spacecraft orbit revolution ratio, *m:n*



(a) (b)

Figure 1. Four-year Cassini prime mission (grey) with the last transfer highlighted in blue and the eight inner icy satellites (red); *(a) Saturn north-pole view (Sun towards top of page), and (b) Saturn equatorial-plane view.*

V. Tour Selection Process

The extended mission tour was designed over a 1.5 year period starting in January 2006. Each major iteration of candidate tours was tied to one of four Cassini Project Science (PSG) meetings which took place every three to four months during the design period. Prior to each of these meetings, about a half dozen candidate tours were released to the science community for evaluation and discussion at the subsequent meeting. The candidate tours were designed in an attempt to fulfill the ranked list of science observational geometries previously mentioned (see Section II). At each meeting, iteration and interaction between the three trajectory analysts and over 200 Cassini scientists from the United States and 17 European nations reduced the number of tour classes and candidate tours considered for further investigation until a single tour remained.

Twelve classes of tours were identified which encompassed the likely range of possible designs and during the 1.5 year design period, 29 candidate tours spanning 10 of these classes were designed. The design complexity increased as software evolved[4,9] and the interaction of the science objectives became better understood, hence, each iteration of tours significantly improved the science returns as evaluated by the Cassini science DWG's. At each step of the process, the tours were evaluated and ranked using a wide variety of science criteria. The feedback obtained from each meeting heavily influenced the subsequent crop of tours.

The fourth and final Project Science meeting held in January 2007 culminated in the selection of the final extended mission trajectory. Lastly, an additional three months was used to tweak and refine tour geometries of the selected trajectory to further optimize science and move maneuver locations to minimize Δv costs and increase operational robustness.

VI. Tour Design

For Saturn gravity-assist tours with high a v_∞ such as Cassini, Titan is the "tour-engine"; Titan is over 58 times as massive at Saturn's second largest moon, Rhea, and is the only Saturnian satellite sufficient in mass to power the Cassini tour. A single 1000 km Titan flyby provides the Cassini spacecraft a gravity-assist Δv of approximately 800 m/s. As a result, gravity-assist tours are built as a sequence of Titan-to-Titan transfers: even if another moon is encountered, the leg is designed principally to return to Titan.[4] If Cassini can't return to Titan, it has "fallen off the tour" and must either execute a potentially large maneuver

to return to Titan or remain in the same Saturn-relative orbit. The requirement to always return to the same moon results in three basic[h] types of same-body transfers: resonant, non-resonant, and pi-transfers.[10,11]

A resonant transfer has a time-of-flight (*tof*) that is an integer multiple of the gravity-assist body's period and the flybys at either end of the transfer occur at the same place in the gravity-assist body's orbit. Because of this, the encounters' longitude occurs on a fixed line from the central body and the resonant transfer may be inclined. A resonant transfer is typically labeled as *m:n*, where m is the number of gravity-assist body revs and n is the number of spacecraft revs.

A non-resonant transfer's time-of-flight is not an integer multiple of the gravity-assist body's orbit, and the flybys occur at different longitudes in the gravity-assist body's orbit. Other than the special case of a pi-transfer, the flybys of a non-resonant transfer do not occur at the same longitude and, therefore, constrain the spacecraft's orbit plane to be the same as the gravity-assists body's orbit plane.

A pi-transfer is a special case of a non-resonant transfer where the time-of-flight of the transfer is an integer multiple of the gravity-assist body's period plus one half. The flybys of a pi-transfer occur on a line with the central body and these transfers are inclined. In fact, they typically must be inclined with the specific inclination determined by the v_∞ magnitude.[11] A pi-transfer changes the local solar time of the gravity-assist body encounter by approximately 12 hours (i.e., 180° to the opposite side of Saturn).

VII. Trajectory

The Cassini prime mission is the most complex gravity-assist tour ever flown. The extended mission maintains this level of design and navigation complexity in order to meet and balance a myriad of disparate scientific objectives requested by the Cassini discipline working groups within the 2-year timeframe. The current reference trajectory design, 080520,[12] consists of 26 targeted Titan flybys, 9 close flybys of icy satellites (7 of which are of Enceladus), 60 orbits about Saturn, and implements an 8-day pi-transfer, and three double-flybys (see Section V). Tables 2 and 3 summarize all targeted and non-targeted (periapsis under 100,000 km) encounters in the extended mission.

During the different phases of the tour, different science objectives dominate the tour design. Some science objectives are time critical (Enceladus south polar optical remote sensing (ORS), Rings equinox, etc.) while other objectives are geometrically driven (orbit petal orientation, occultation intercept latitudes, inclination profiles, etc.), both of which can require several Titan flybys to achieve. The Cassini extended mission tour design process attempted to maximize the number and quality of high-priority scientific objectives that could be met while minimizing the total Δv cost for the 2-year mission. The different phases of the XM are shown in Figure 2 as a plot of inclination vs. time, and will be covered in detail in the subsequent sections. The following tables and figures summarize all relevant quantities and parameters associated with the Cassini extended mission.

[h] With large maneuvers or large third-body perturbations, leveraging transfers or other tricks are possible.

Table 2. Cassini Extended Mission Targeted Flybys[i]

Encounter	Body	Date [ET]	Altitude [km]	B-Plane Angle [deg]	In / Out	V-inf [km/s]	Period [days]	Inc. [deg]	Periapsis [RS]
T45 / 78Ti	Titan	31-Jul-2008 02:14:16	1613	126.8	O	5.9	7.4	74.4	3.94
E4 / 80En	Enceladus	11-Aug-2008 21:07:24	50	90.0	I	17.7	7.4	74.5	3.95
E5 / 88En	Enceladus	09-Oct-2008 19:07:45	25	90.0	I	17.7	7.3	74.5	3.94
E6 / 91En	Enceladus	31-Oct-2008 17:15:56	200	90.0	I	17.7	7.3	74.5	3.95
T46 / 91Ti	Titan	03-Nov-2008 17:36:28	1100	6.6	O	5.9	8.0	70.5	4.27
T47 / 93Ti	Titan	19-Nov-2008 15:57:33	1023	151.1	O	5.9	8.0	72.2	5.21
T48 / 95Ti	Titan	05-Dec-2008 14:26:50	960	164.1	O	5.9	8.0	72.9	5.76
T49 / 97Ti	Titan	21-Dec-2008 13:00:57	970	110.2	O	5.9	9.6	69.0	9.09
T50 / 103Ti	Titan	07-Feb-2009 08:51:57	960	59.9	O	5.9	11.9	65.3	13.57
T51 / 106Ti	Titan	27-Mar-2009 04:44:42	960	114.0	O	5.9	16.0	61.7	19.67
T52 / 108Ti	Titan	04-Apr-2009 01:48:53	4150	178.5	I	5.5	16.0	61.7	18.69
T53 / 109Ti	Titan	20-Apr-2009 00:21:51	3600	169.3	I	5.5	16.0	61.4	16.94
T54 / 110Ti	Titan	05-May-2009 22:55:21	3244	158.4	I	5.5	16.0	60.6	15.07
T55 / 111Ti	Titan	21-May-2009 21:27:47	965	146.8	I	5.5	16.0	58.8	12.17
T56 / 112Ti	Titan	06-Jun-2009 20:01:06	965	132.8	I	5.5	15.9	55.7	9.52
T57 / 113Ti	Titan	22-Jun-2009 18:33:41	955	121.9	I	5.5	15.9	51.2	7.21
T58 / 114Ti	Titan	08-Jul-2009 17:05:09	965	113.2	I	5.5	15.9	44.5	5.30
T59 / 115Ti	Titan	24-Jul-2009 15:35:09	955	106.2	I	5.5	15.9	34.8	3.85
T60 / 116Ti	Titan	09-Aug-2009 14:04:59	970	100.0	I	5.5	16.0	21.1	2.93
T61 / 117Ti	Titan	25-Aug-2009 12:52:44	970	161.1	I	5.5	24.0	12.2	4.29
T62 / 119Ti	Titan	12-Oct-2009 08:37:30	1300	61.4	I	5.6	19.0	0.6	3.20
E7 / 120En	Enceladus	02-Nov-2009 07:43:04	100	90.0	O	7.7	19.0	0.5	3.21
E8 / 121En	Enceladus	21-Nov-2009 02:10:56	1604	82.0	I	7.8	19.0	0.5	3.20
T63 / 122Ti	Titan	12-Dec-2009 01:04:20	4850	-146.7	O	5.5	16.0	4.9	2.60
T64 / 123Ti	Titan	28-Dec-2009 00:18:05	955	-94.5	O	5.5	16.0	21.6	3.03
T65 / 124Ti	Titan	12-Jan-2010 23:11:42	1073	86.1	O	5.5	16.0	5.2	2.59
T66 / 125Ti	Titan	28-Jan-2010 22:29:55	7490	52.7	O	5.5	17.5	0.3	2.89
R2 / 127Rh	Rhea	02-Mar-2010 17:41:42	100	-98.8	I	8.6	17.6	0.4	2.91
T67 / 129Ti	Titan	05-Apr-2010 15:51:44	7462	180.0	I	5.5	20.4	0.3	3.53
D2 / 129Di	Dione	07-Apr-2010 05:17:16	504	0.0	I	8.4	20.4	0.4	3.53
E9 / 130En	Enceladus	28-Apr-2010 00:11:23	100	90.0	O	6.5	20.5	0.3	3.54
E10 / 131En	Enceladus	18-May-2010 06:05:11	200	122.6	I	6.5	20.5	0.3	3.52
T68 / 131Ti	Titan	20-May-2010 03:25:26	1400	130.7	O	5.5	16.0	12.1	2.76
T69 / 132Ti	Titan	05-Jun-2010 02:27:33	2044	-89.2	O	5.5	16.0	2.0	2.64
T70 / 133Ti	Titan	21-Jun-2010 01:28:23	955	-93.6	O	5.5	16.0	18.8	2.97

[i] B-plane = B-plane angle relative to the satellite's mean equator of epoch, In/Out = flyby inbound (I) or outbound (O), Period = Spacecraft period after the encounter, Inc. = Inclination after the encounter, Periapsis = Spacecraft periapsis distance to Saturn after the encounter.

Table 3. Cassini Extended Mission Non-Targeted Flybys

Flyby	Body	Date [ET]	In/ Out	Alt. [km]	V-inf [km/s]	C/A Phase [deg]
80Mi	Mimas	11-Aug-2008 21:49	O	81527	19.1	137
85Mi	Mimas	17-Sep-2008 16:51	I	61679	18.3	139
87Te	Tethys	02-Oct-2008 11:04	I	78641	17.6	70
90Mi	Mimas	24-Oct-2008 10:26	I	57301	18.3	155
92En	Enceladus	08-Nov-2008 21:52	I	52805	16.8	128
93Te	Tethys	16-Nov-2008 20:42	I	57067	15.9	41
94Te	Tethys	24-Nov-2008 08:46	I	24243	15.2	159
102Rh	Rhea	02-Feb-2009 10:44	I	97432	10.4	82
114Di	Dione	11-Jul-2009 03:13	O	86636	9.2	62
115Te	Tethys	26-Jul-2009 18:16	O	68376	9.5	89
118Di	Dione	20-Sep-2009 16:53	O	97915	9.8	94
119Rh	Rhea	13-Oct-2009 16:56	I	40383	9.0	82
119Mi	Mimas	14-Oct-2009 06:34	O	44195	7.9	102
119Te	Tethys	14-Oct-2009 10:11	O	85266	11.9	76
121Rh	Rhea	21-Nov-2009 17:36	O	24416	8.7	58
123Te	Tethys	26-Dec-2009 00:37	I	52926	11.8	77
125Di	Dione	27-Jan-2010 11:48	O	45085	8.7	106
126Mi	Mimas	13-Feb-2010 17:23	O	9532.2	5.8	99
129Mi	Mimas	07-Apr-2010 13:47	O	97421	10.3	124
129Te	Tethys	07-Apr-2010 14:59	O	70794	6.4	103
132Te	Tethys	03-Jun-2010 12:57	O	52611	9.6	99
132Rh	Rhea	03-Jun-2010 20:32	O	69386	8.0	102

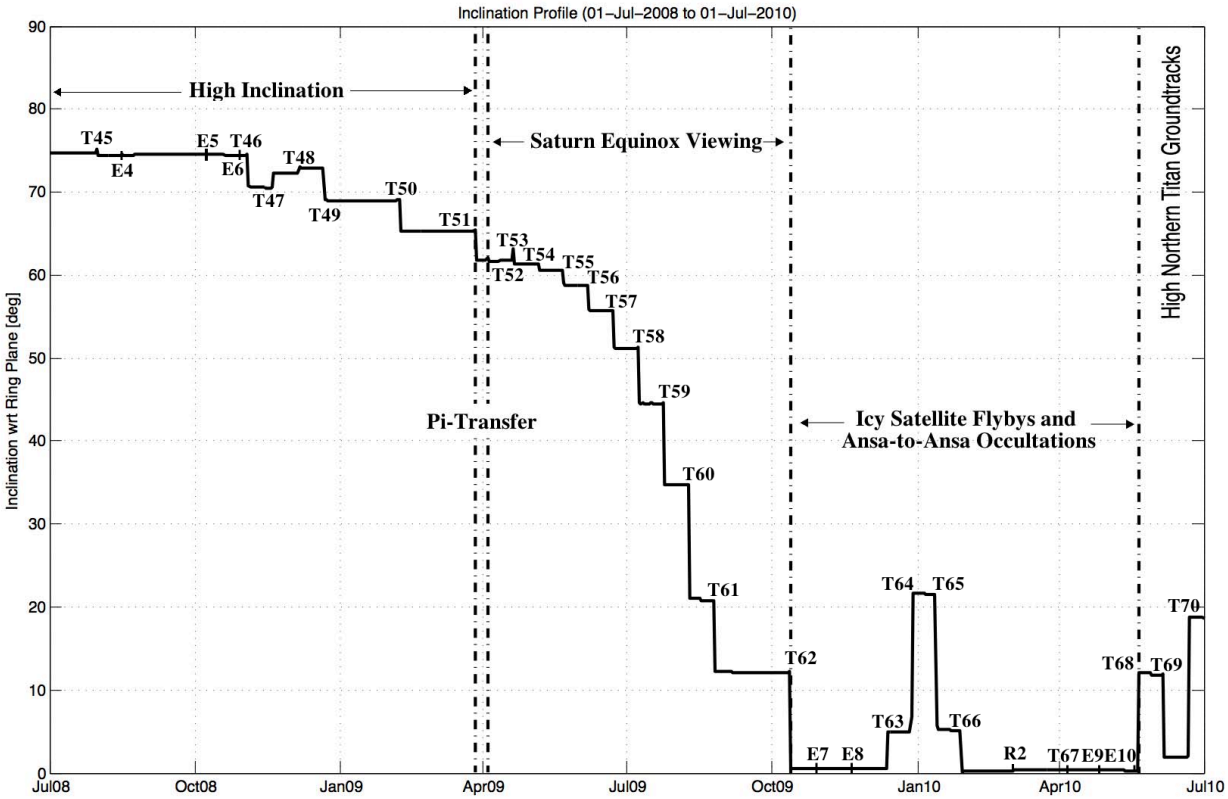
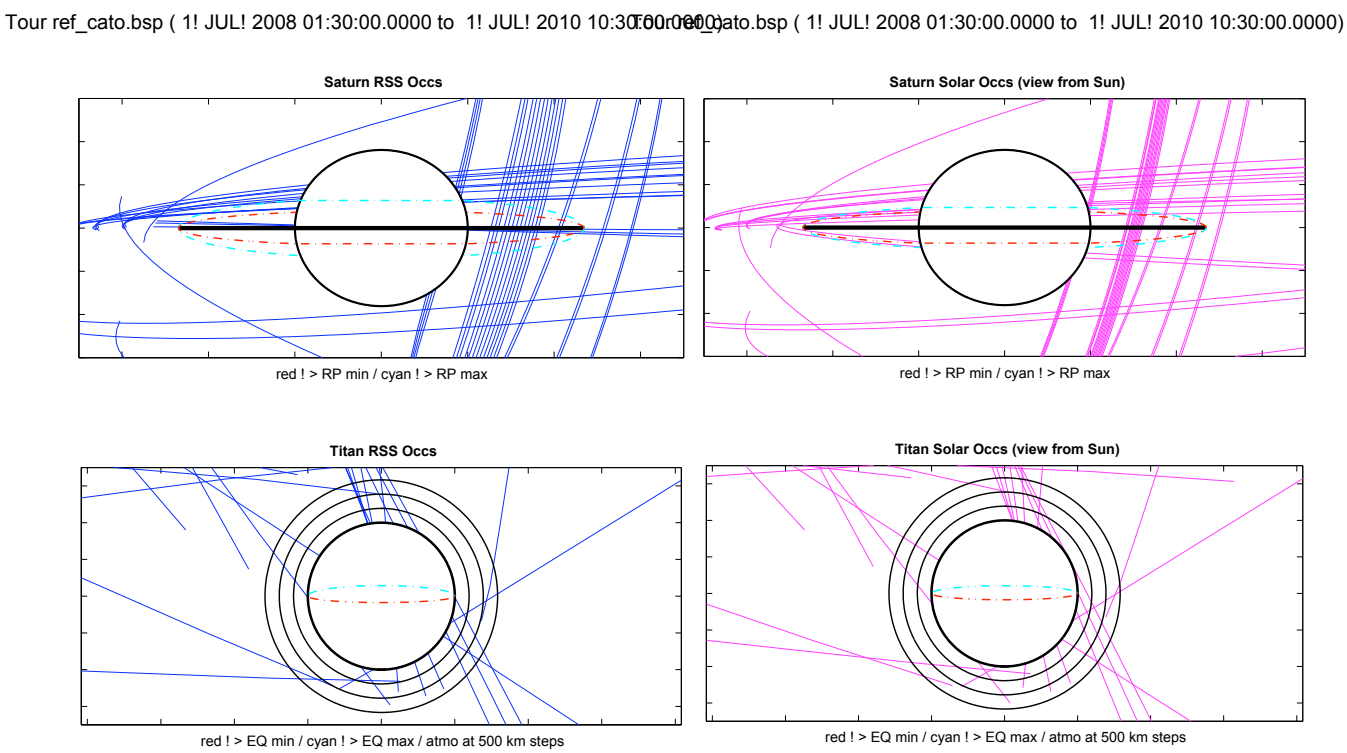


Figure 2. Cassini extended mission inclination profile (Saturn mean equator), including the major phases of the tour.



(a) (b)

Figure 3. Saturn, Rings, and Titan occultations; *(a) Earth (i.e. radio science), and (b) solar.*

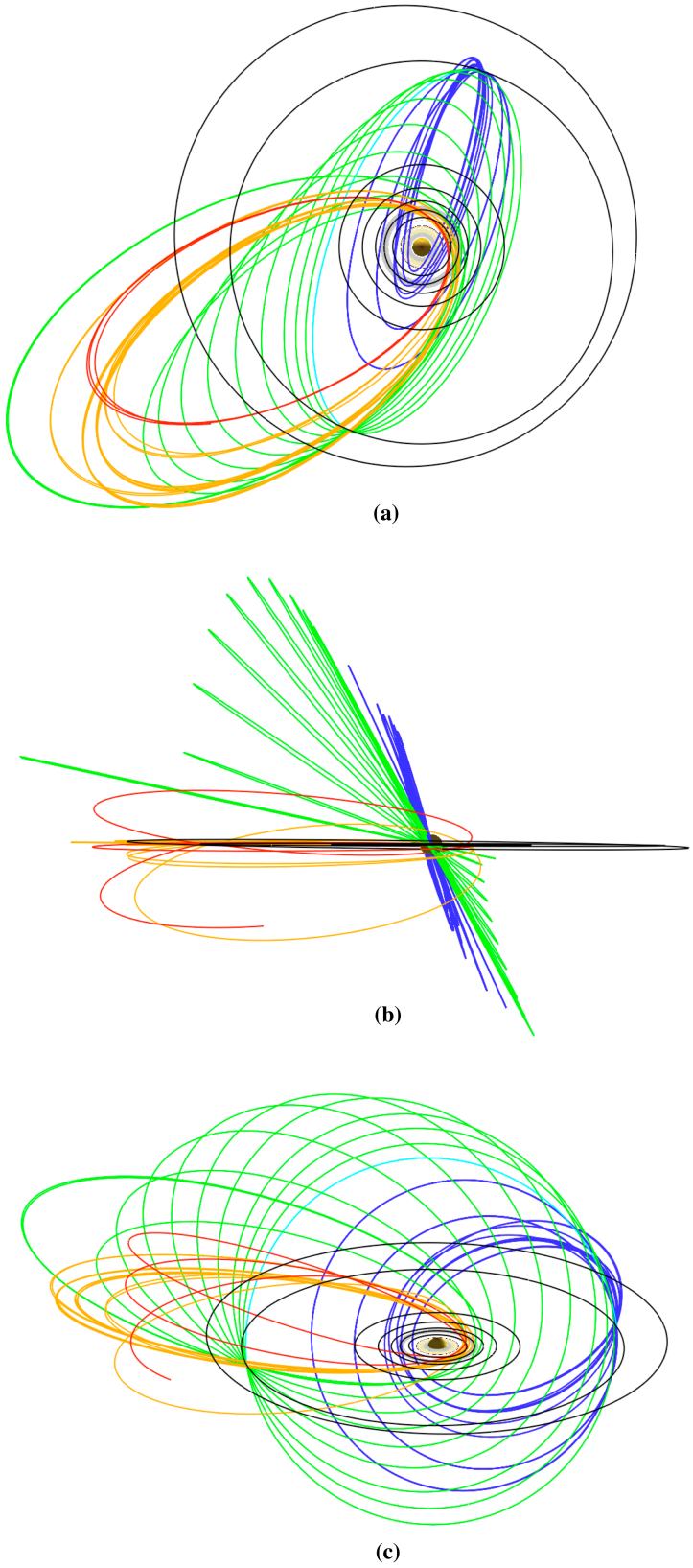


Figure 4. Two-Year Cassini Extended Mission Petal Plot; *(a) Saturn north-pole view (sun direction towards top of page), (b) Saturn equatorial-plane view, and (c) oblique view. Key to phases: blue - high inclination, cyan - pi-transfer, green - equinox viewing, orange - icy satellite flybys and ansa-to-ansa occultations, and red - high northern Titan groundtracks.*

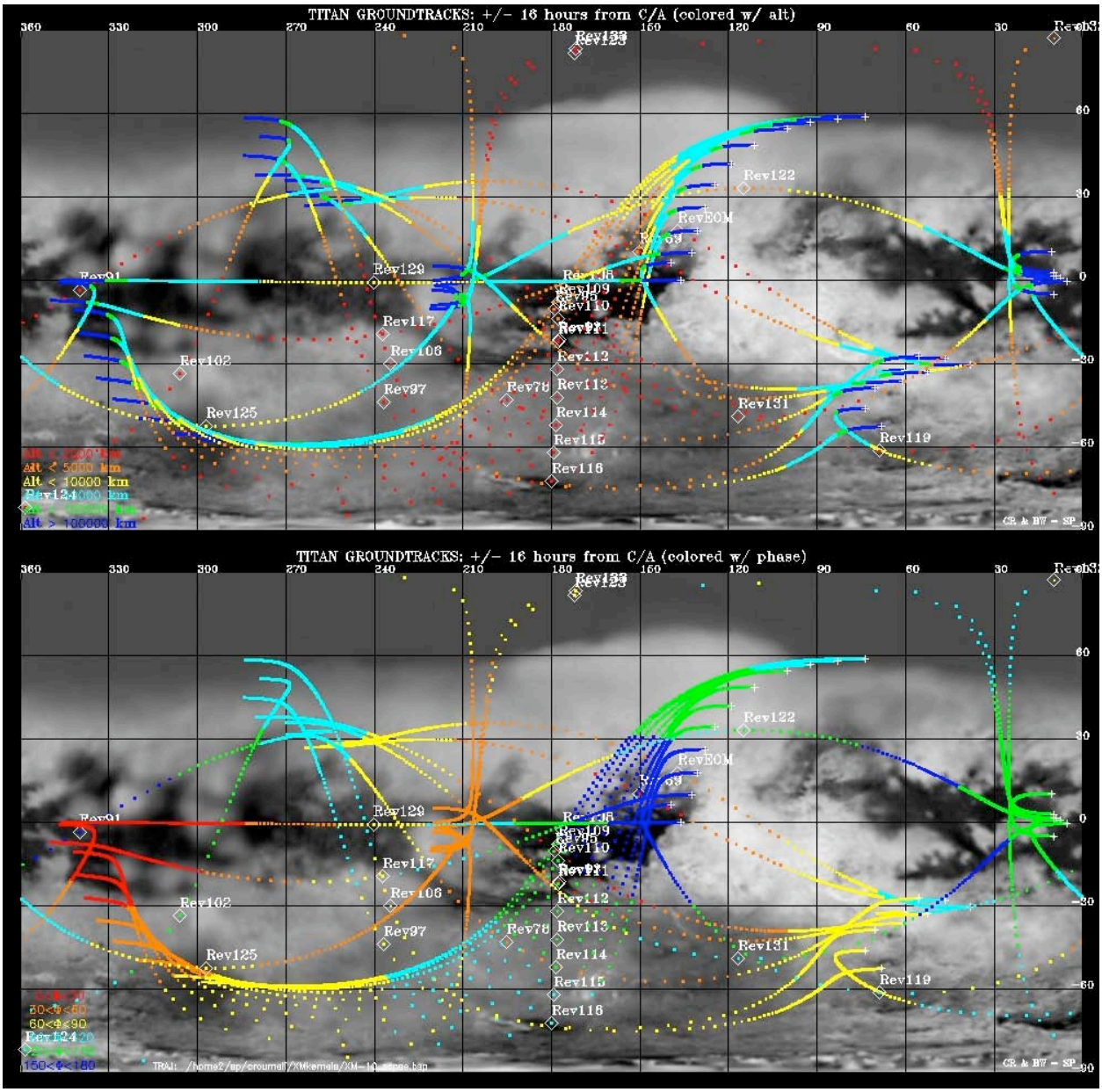


Figure 5. Titan Groundtracks with Color Contoured Altitude and Phase Profiles.[j]

[j]Figures provided by Chris Roumeliotis.

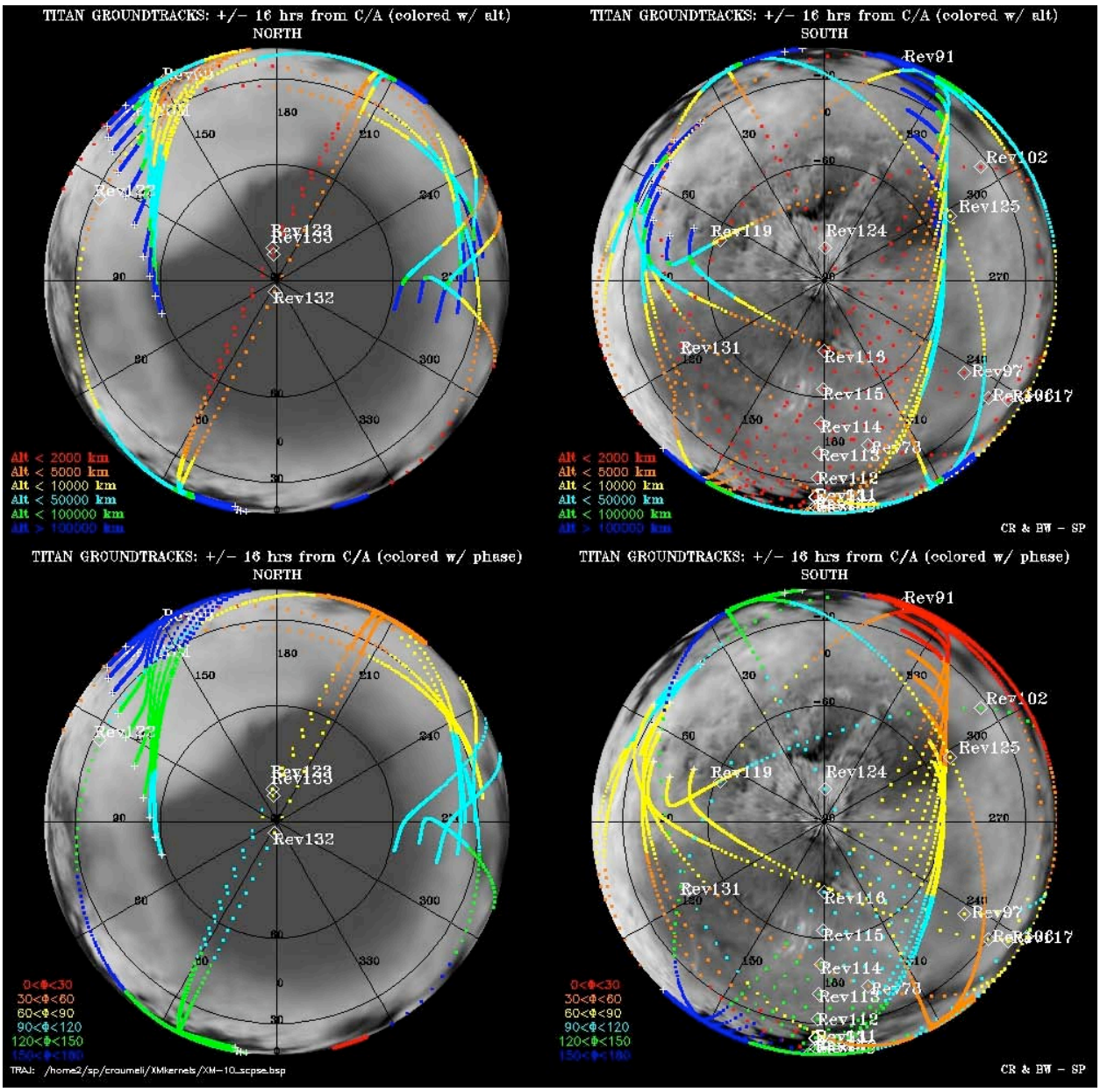


Figure 6. Polar Titan Groundtracks with Color Contoured Altitude and Phase Profiles.[j]

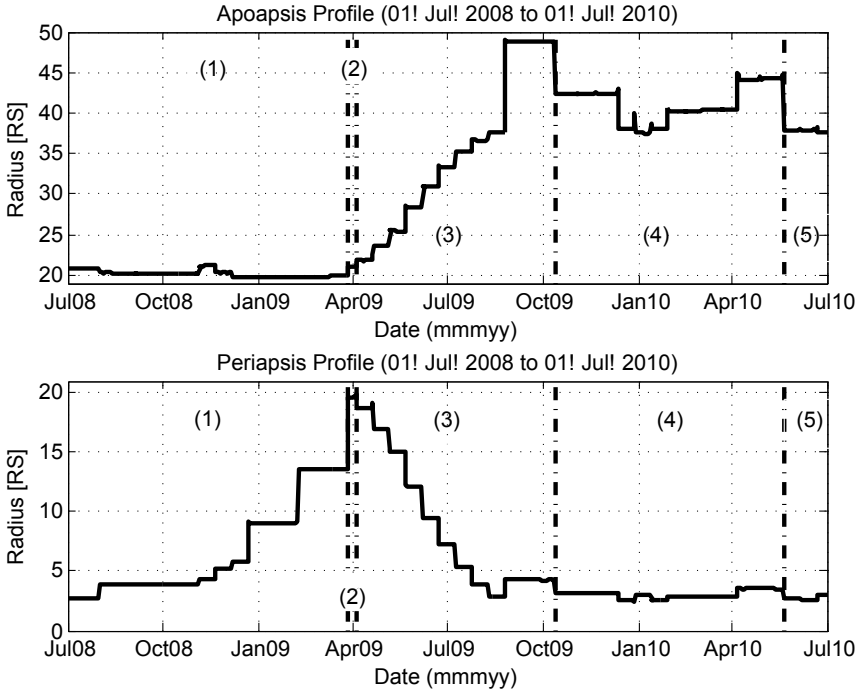


Figure 7. Saturn-Centered Apoapsis and Periapsis Profiles (Saturn Mean Equator). *Tour phases: (1) High inclination, (2) Pi-transfer, (3) Saturn equinox viewing, (4) Icy satellite flybys and ansa-to-ansa occultations, and (5) High northern groundtracks.*

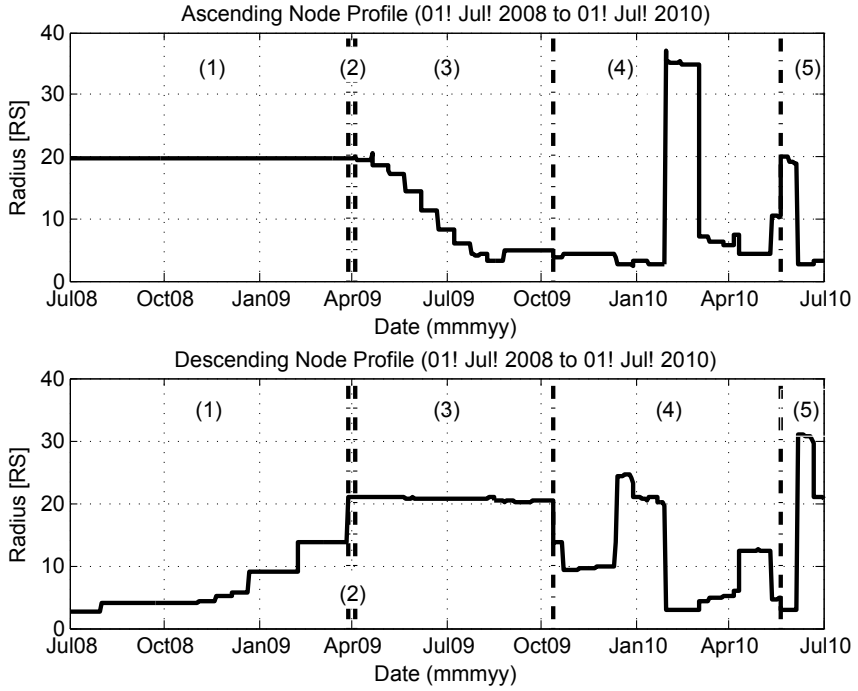


Figure 8. Saturn-Centered Ascending and Descending Node Crossing Profiles (Saturn Mean Equator). *Tour phases: (1) High inclination, (2) Pi-transfer, (3) Saturn equinox viewing, (4) Icy satellite flybys and ansa-to-ansa occultations, and (5) High northern groundtracks.*

VII.A. High Inclination Phase (T45 – T51)

The first phase of the extended mission was designed for two main purposes. The first was to maintain a high inclination (i >65°), which would be beneficial to both the Magnetospheric and Plasma Science Group (MAPS) and the Rings Working Group (RWG). For MAPS, one of the highest priority extended mission objectives was additional *in situ* measurements of Saturn's auroral region[13] to complement a set of five auroral observations taken near the end of the prime mission (between 19-Apr-2007 and 31-May-2007). Furthermore, the observations needed to spaced sufficiently forward in time (relative to the first set) to give the MAPS team the ability to change observation strategy arising from any discoveries made during the prime mission. These auroral observations are best accomplished by using highly inclined short-period orbits to minimize the spacecraft's altitude relative to Saturn when passing through the 15 RS L-shell[k] (with the assumption the auroral region is located at, or near, 75° north latitude). Based on the XM initial conditions and the pressure to satisfy a large number of science objectives in only two years, fulfilling these objectives at the beginning of the extended mission was the most efficient use of time. The transfers between T45 and T48 provide 15 additional 15 RS L-shell crossings below 5 RS.

For the RWG, the additional high inclination orbits will provide favorable geometry (the inclination must be greater than approximately 63.5° due to the declination of bright UV and IR stars) for a high number of stellar occultations (UVIS and VIMS) that penetrate the densest parts of the B-ring.[13]

The second main design driver for this phase of the XM was to increase the vacant node distance near 20 RS to set up the geometry needed for the 8-day pi-transfer (see Section VII.B).

As is true with all phases of the tour, while a particular set of goals drives to large extend what is done, it is the intent to fulfilled, in unison, as many DWG's scientific objectives as possible over a finite amount of time (i.e. a discrete set of transfers). This first phase of the XM was no different. For the Icy Satellites Working Group, a high number of low altitude targeted Enceladus flybys was a very high priority due to the discovery (by the Cassini spacecraft during the prime mission) of thermally anomalous fissures emanating water ice (i.e., geysers) in excess of 250 km from Enceladus' south polar region (lat >75° S).[14–17] By implementing a 6:13 resonance at a 74.4° inclination for the T45-T46 transfer, three low altitude Enceladus flybys (E4, E5, and E6) were attained. All three have similar geometries to E3 (last Enceladus flyby in prime mission), occurring at descending nodes with high northern latitude inbound asymptotes and high southern latitude outbound asymptotes. E4 and E5 are both targeted flybys, having flyby altitudes of 50 and 25 km respectively.[18] However, since E6 was part of a double flyby (see Section III), the flyby was limited to a 200 km closest approach (c/a) altitude. Both E4 and E6 have B-plane angles of 90° to minimize the spacecraft's flyby altitude over Enceladus' south pole. The E5 B-plane angle was set to 70° in order to render a 90° S egress intercept latitude for the planned UVIS stellar occultation occurring near closest approach (Fig. 9).

Lastly, the T45 to T51 sequence was chosen to concurrently obtain a mid northern latitude near-diametric Titan RSS occultation (T46), and a low solar phase groundtrack over the Huygen's landing site for the Visual and Infrared Mapping Spectrometer (VIMS) instrument team (T47).

VII.B. 8-Day Pi-Transfer (T51 – T52)

The Titan Working Group (TWG) requested several Titan flybys in the dusk sector (LST between 15:00 and 21:00) due to the sparse distribution of them in the prime mission (only two). In addition, MAPS requested low inclination orbits with apoapsis in the dusk sector to map Saturn's magnetosphere. Given the high inclination at the beginning of the extended mission, a pi-transfer is the most efficient way to change the LST of the Titan encounters. The T51-T52 transfer implements an outbound-to-inbound 8-day pi-transfer at a 61.7° inclination, changing the Titan encounter from 10:00 to 22:00 LST, and the corresponding petal orientation (i.e., apoapsis location) from 11:00 to 19:30 LST. Once the inclination is reduced to 0.4° (Titan's inclination), non-resonant transfers can be used to move apoapsis and obtain numerous Titan encounters in the dusk sector.

[k]Parameter used to describe the set of magnetic field lines that cross a planet's magnetic equator at a number of planet-radii. Each L-shell intersects/connects to specific latitudes on a planet, an hence, are often used to locate/describe phenomenon.

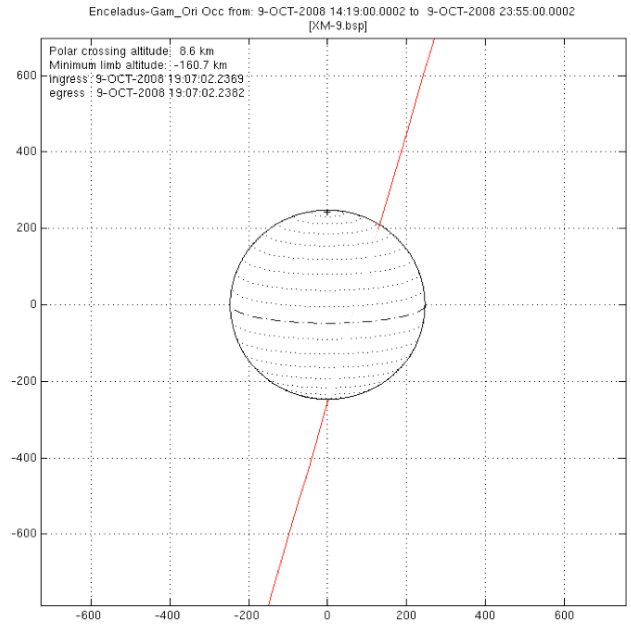


Figure 9. E5 UVIS Stellar (Gamma Orionis) Occultation

VII.C. Saturn Equinox (T52 – T62)

Saturn's equinox[l] will occur near the middle to the XM (11-Aug-2009), a geometry that will not recur for another 15 years. It was the Rings Working Group's highest ranked extended mission objective (and arguably, one of the highest ranked overall XM objectives) to observe this event from an inclination greater than 15°, and observe the surrounding time (±1-2 months) from an inclination greater than or equal to 10° with the requirement to place apoapses over the northern hemisphere for thermal observations of the rings heating up.[13]

The T52-T62 sequence of flybys sets up the correct inclination profile for rings equinox viewing while maximizing the number of minimum altitude Titan flybys (for *in-situ* atmospheric measurements and high resolution radar mapping). The first three flybys (T52 – T54), were designed for quality high northern latitude and equatorial RSS and UVIS occultations. In addition, by forcing these flyby altitudes to be higher, the T54 – T62 Titan flyby altitudes could be minimized and hence maximize the inclination of the associated transfers. The T61-T62 transfer implements a 3:2 resonant transfer to avoid the 2009 solar conjunction period. Lastly, the T62 flyby was used to render the spacecraft's orbit in the same plane as Titan's (0.4° inclination).

VII.D. Icy Satellites and Ansa-to-Ansa Occultations (T62 – T68)

This phase of the tour is dominated (in time) by equatorial orbits via non-resonant transfers designed to obtain six of the nine close icy satellite flybys, two of the three ansa-to-ansa ring occultations[m], long un-obstructed (by the rings) observations of Saturn, and mid-northern latitude Saturn occultations.

The fourth and fifth Enceladus flybys of the extended mission, E7 and E8, occur on the T62-T63 non-resonant transfer. Unlike the first three Enceladus flybys (E4-E6) that were highly inclined with asymptotes near the poles that precluded low altitude direct sampling of the plume, the Enceladus flybys occurring on equatorial orbits (E7-E10) have inbound/outbound asymptotes near the equator which allows arbitrarily low sampling of the plume since the c/a can be placed[n] at any latitude (the corresponding c/a longitude will be offset

[l]Moment when the Sun crosses Saturn's ring plane.

[m]Occultation in which the spacecraft traverses from one side of the farthest part of the rings from the disk of the planet, referred to as the ansa, to the other ansa as seen from Earth.

[n]For a given icy satellite flyby, a Δv-optimal set of flyby parameters exist. The freedom to vary the flyby parameters to increase scientific return is usually associated with a Δv cost.

by ±90° from the asymptote longitude). As a result, both E7 and E9 (occurring between T67 and T68), were optimized for *in situ* measurements of Enceladus' plume by selecting a 90° B-plane angle, which places c/a directly over 90°S latitude, and setting the flyby altitude to 100 km. The E8 flyby was optimized for optical remote sensing; the B-plane angle was set to 82°, rendering the groundtrack directly along an illuminated thermally anomalous fissure (referred to as "tiger stripes" and believed to be the source of Enceladus' plumes and the E ring), which corresponded to a closest approac h altitude of 1604 km (Δv optimal altitude given the 82° B-plane angle). In addition, the T62-63 non-resonant transfer rotates the tail petal clockwise (decreases LST) to set up the correct petal orientation for the first RSS ansa-to-ansa ring/Saturn occultation.

The T63 flyby was designed to obtain an acceptable MAPS mid-tail Titan wake crossing and set up the correct inclination needed for the first ansa-to-ansa ring occultation (Fig. 10). The latter involved adjusting the inclination (on the order of 0.0025°) to maximize the free-space baseline (FSB), which is the duration of the time interval between the top of the ionosphere (68,000 km) and the inner edge of Ring C (ring radius of 74,500 km), on each side of Saturn.[19] The ingress and egress FSB for the first ansa-to-ansa occultation are 7.7 and 4.9 minutes respectively.

The T64 and T65 flybys were designed in unison to achieve a high northern Titan groundtrack and a second RSS ansa-to-ansa (A2A) ring occultation. Since T63 to T64 is a 16-day resonant transfer, executing a successive 16-day transfer (T64-T65) will result in a maximum inclination change (i.e., the entire gravity assist Δv goes into cranking, no pumping[9]), and a corresponding high northern groundtrack (82° N c/a latitude). Using the same approach, cranking in the opposite direction (i.e., a T65 B-plane angle on approximately the opposite side of Titan as T64) to reverse the max inclination change will set up the correct inclination for the second ansa-to-ansa occultation on the T65-T66 transfer. However, unlike the first ansa-to-ansa occultation where a sufficient ingress and egress FSB was achieved, the second ansa-to-ansa egress FSB was compromised in order to fine-tune the inclination (on the order of 0.0025°) to obtain a distant RSS Enceladus plume occultation with a polar crossing altitude of 46 km (Fig. 11). The plume occultation will occur approximately 2.18 hours before the start of the second ansa-to-ansa occultation. The ingress and egress FSB for the second ansa-to-ansa occultation are 4.6 and 0.2 minutes respectively.

The T66 flyby lowers the inclination back down into Titan's orbit plane, and implements a non-resonant transfer to obtain a 100 km targeted Rhea flyby. In addition, the two closest non-targeted flybys of the XM occur on the T66-T67 transfer: Mimas (9517 km) and Helene (1806 km). This transfer was also designed to get numerous empty (i.e., no icy satellite flybys with altitudes $\leq$ 10,000 km) periapsis passages for the Saturn Working Group (SWG).

The last transfer in this phase, T67-T68, is a non-resonant transfer designed to obtain three close icy satellite flybys, one of Dione and two of Enceladus. The Dione flyby, D2, is a 500 km targeted flyby, and has been optimized for MAPS by constraining the B-plane angle to 0° in order to fly through the center of the downstream plasma wake (closest approach: 72° W, 0° N). Of the two Enceladus flybys, E9 is a targeted flyby optimized for *in situ* measurements (previously discussed), and E10, in a similar fashion as E6, is part of a double flyby (occurring only two days prior to a T68), and has a 200 km flyby altitude. A plot of all Enceladus flybys (including E1 – E3 from the prime mission) comparing their relative traversals through the plume can be found in Figure 12.

Figure 10. First Ansa-to-Ansa Ring Occultation (25-Dec-2009). *Spacecraft path as seen from Earth in red.*

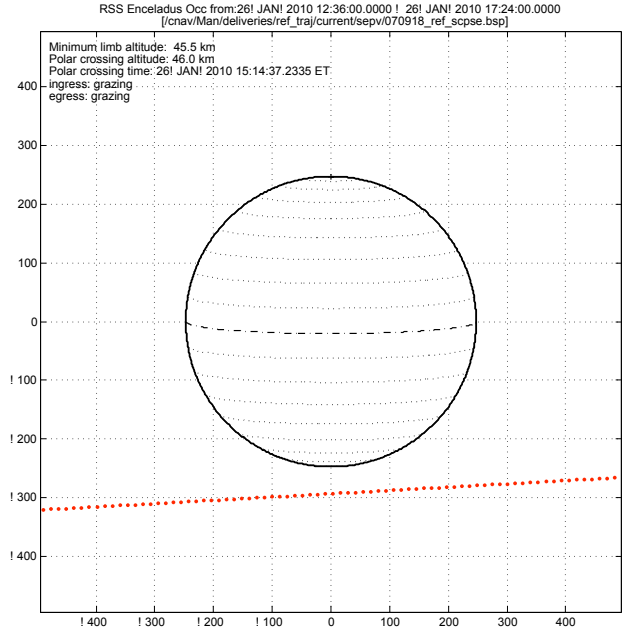


Figure 11. 26-Jan-2010 RSS Enceladus Plume Occultation

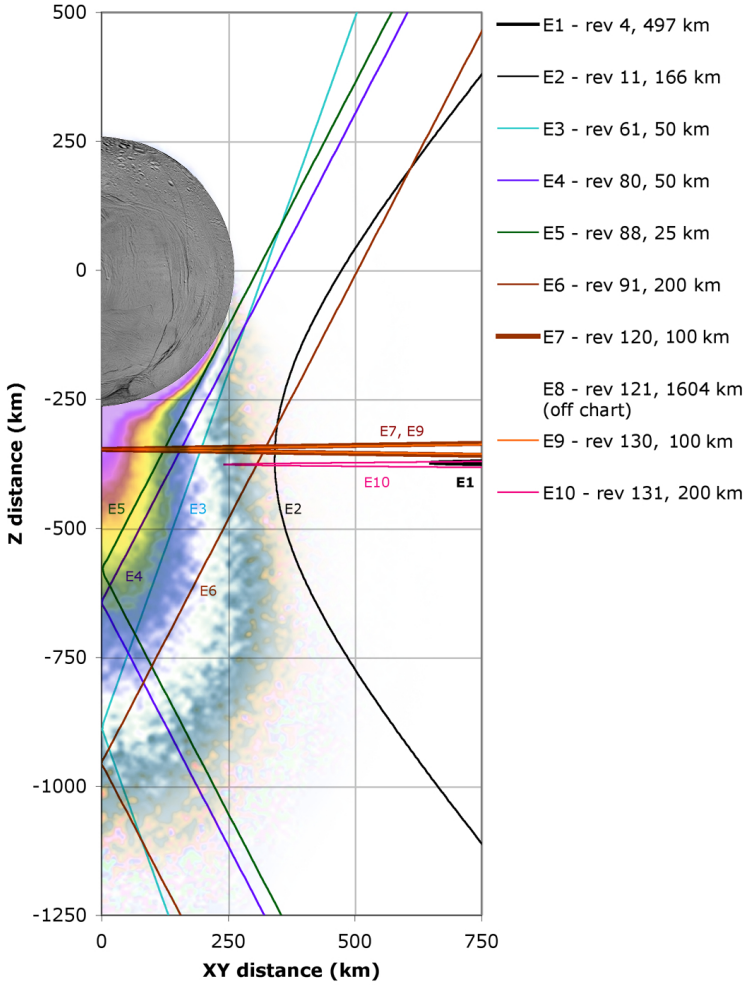


Figure 12. Cassini plume penetration passes (prime and extended mission).

VII.E. High Northern Titan Groundtracks (T68 – T70)

The final phase of the Cassini extended mission consists of a series of successive 16-day transfers designed for Titan gravity measurements, two additional high northern Titan groundtracks, and a third A2A occultation.

The T68 flyby, designed for an RSS gravity pass, has a flyby altitude of 1400 km, an SEP angle of 112°, and a hyperbolic inclination of approximately 49°. Similar to T65, the 2100 km T69 flyby reverses the majority of the max inclination change induced by the T68 flyby, setting up the correct inclination (1.96°) for the third ansa-to-ansa occultation and attaining a high northern groundtrack with inbound asymptotic and closest approach phase between 60° and 90° for VIMS observations. The last Titan flyby in the Cassini extended mission, T70, continues cranking up in the same direction using a 1:1 resonant transfer (16-day), obtaining a third high northern Titan groundtrack. Lastly, it should be noted, while the T70 altitude is currently 955 km,[18] the flyby altitude will be lowered at a future date for Dual Technique Magnetometer (MAG) science (want to go as low as possible to search for an intrinsic magnetic field) pending analysis done by the AACS and Thermal teams to determine a minimum safe spacecraft attitude and altitude.

VIII. Potential Debris Hazards

A small number of potential debris hazards have been identified in the Cassini extended mission. At present,[18] no pre-emptive measures have been implemented to avoid these potential hazards since further analysis is required to validate their individual severity (or lack thereof). However, parametric studies have been done to address the implications (Δv costs, trajectory deviations, and identification of decision deadlines) of avoiding each potential hazard.

VIII.A. G-Ring Crossings

During the 2-year extended mission, the Cassini spacecraft will have two G-ring crossings, one on 27-Jan-2010, and the other one rev later on 13-Feb-2010. The first skirts the inner edge of the G-ring, the second the outer edge, and hence, both will implement a high gain antenna (HGA) to ram spacecraft orientation to maximize spacecraft protection.[20] However, the first crossing has the added distinction of crossing at the longitudinal center of a bright arc feature (longitudinally localized, near the inner edge) in the G-ring that is believed to consist of much larger (centimeter- to meter-sized) particles than the nominal dust grain population (1 to 10 micrometers).[21] While the spacecraft does not pass directly through the bright arc feature, a number of trajectories were built to quantify the Δv costs associated with increasing the distance from the arc (Fig. 13). In all options portrayed in Figure 13, the trajectory deviations can be localized between T65 and T66, and will not adversely affect the second ansa-to-ansa occultation. Currently,[18] the Project has decided not to implement any sort of tweak since, 1) this event occurs well into the XM, 2) additional data can be gathered to make a better informed decision, and 3) there is no Δv cost associated with delaying the decision.

VIII.B. Close Icy Satellite Flybys

Due to the discoveries of a plume emanating from Enceladus' south polar region[14–17] and a potential equatorial debris disk (denser, discrete rings or arcs of material might also exist) about Rhea,[22] potential dust hazards exist for all low altitude Enceladus and Rhea flybys.

In the case of the low Enceladus flybys that are currently set to penetrate the plume (E4, E5, E7, and E9), their individual altitudes can be varied ±50 km at a Δv cost of approximately ±0.5 m/s per flyby, and trajectory deviations can be localized to ±1 Titan flyby (i.e., Titan flyby on each side of the Enceladus flyby).

For the Rhea-2 (R2) targeted flyby, the closest approach latitude is approximately 81° N (Fig. 14), hence, even if an equatorial ring structure is confirmed, it should pose no threat to the spacecraft's safety. However, if for some reason large particles were thought to reside in higher latitudes, the R2 altitude can be varied from 50 - 1000 km for less than 0.2 m/s. The trajectory deviations associated with the altitude change could be localized to ±2 Titan flybys.

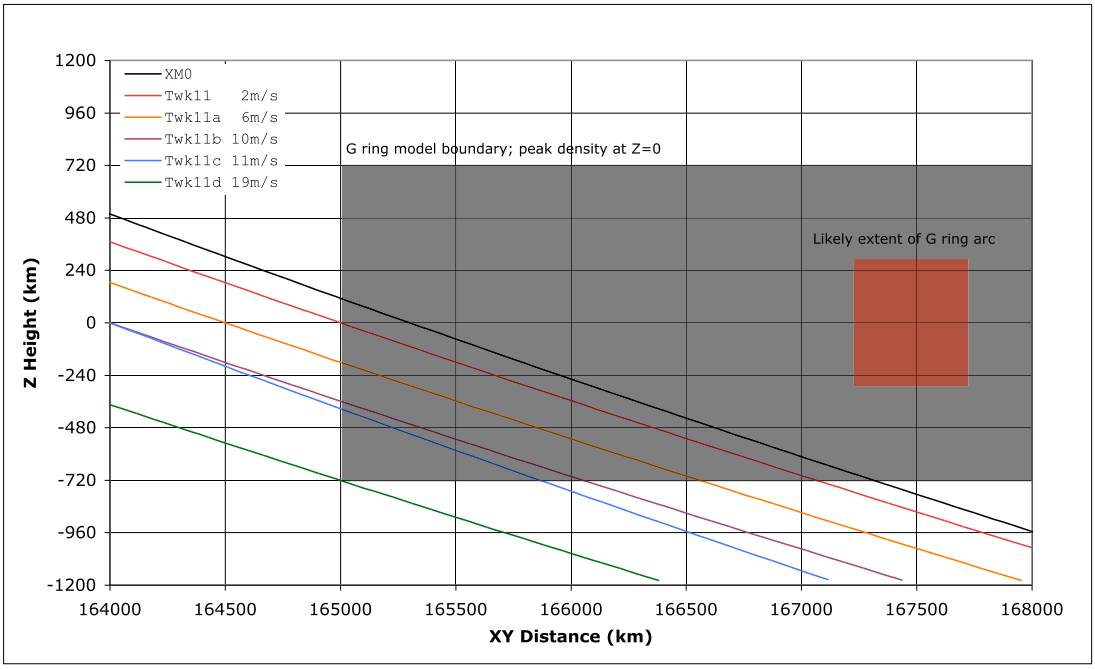


Figure 13. 27-Jan-2010 G-Ring Crossing Trajectory Options

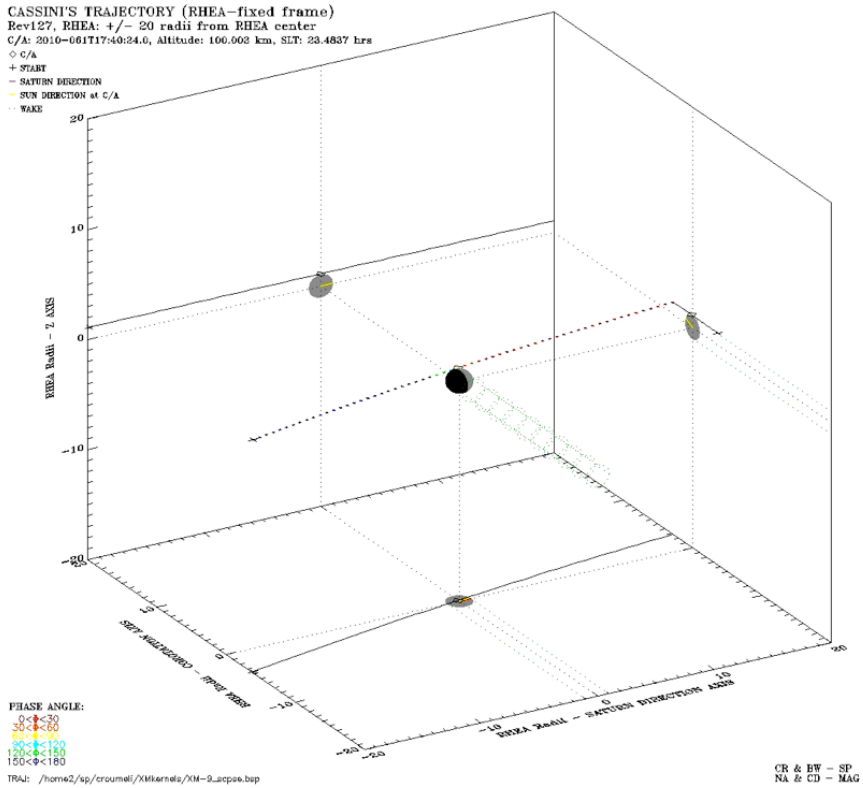


Figure 14. 100 km Rhea-2 (R2) Flyby on 02-Mar-2010

IX. Prime and Extended Mission Merge

The 070620 XM reference trajectory [2] was the first official Project-wide released extended mission reference trajectory. The 070620 XM reference merged the 070209 prime mission reference trajectory (27-Nov-2006 – 1-Jul-2008)[23] with the PSG chosen XM-9n (modified version of PF-6h9) extended mission trajectory (1-Jul-2008 – 1-Jul-2010), and spanned from 11-Apr-2008 to 1-Jul-2010. Since additional minor changes (i.e., maneuver placements, icy satellite target tweaks, etc.) to the XM were foreseen, two reference trajectories were carried simultaneously for operations, a prime mission reference (070209) and an extended mission reference (070620). The start of the 070620 XM reference began at OTM-152 (T42 clean-up maneuver) since it was the last maneuver in the prime mission prior to S40 (first science planning sequence to be affected by the trajectory deviations between T44 and T45 due to the merge). Trajectory deviations (w.r.t. 070209) begin at OTM-155 (T43 clean-up maneuver) since T44 is the only flyby in the prime mission allowed to vary (i.e., be included in the global optimization of the cost function J, deterministic Δv).

X. Reference Trajectory Updates

Updates to the nominal Cassini reference trajectory are done both out of necessity (i.e. spacecraft safety concerns) and to improve the science return based on new information/theory. During the prime mission, there were 11 total reference trajectory updates[24] done for both aforementioned reasons. The extended mission thus far has been no different, requiring two separate reference trajectory updates since it's initial 20-Jun-2007 release.

The last targeted Enceladus flyby in the prime mission (E3) was lowered from 100 km down to 25 km in the 060323 reference trajectory contingent on further assessment of spacecraft safety issues related to the spacecraft flying through the plume in excess of 14 km/s.[25] While it was shown the E3 25 km altitude could be navigated with high confidence and there was a very low probability of the spacecraft's safety being compromised (based on current plume models), the Project decided (16-August-2007) to raise E3 from 25 to 50 km predicated on the small incremental science return loss of doubling the altitude, and the fact that there will be seven additional Enceladus flybys in the XM (i.e., not last chance to get highest resolution data). Furthermore, since there would be little time to analyze the data from E3 to potentially adjust E4, E4 was preemptively raised to 50 km. As a result, the 070209 (prime mission) and 070620 (extended mission) references trajectories were updated and merged to produce the 070918 reference trajectory. The 070918 reference trajectory spans from 18-Sep-2007 to 1-Jul-2010, and used the 061122_034Sa OD delivery for the satellite and planetary ephemerides.

As previously mentioned (see Section VII.A), the 25 km E5 flyby was optimized for a near-vertical UVIS stellar occultation that traversed the entire plume structure. However, once the assignment of c/a times during each icy satellite flyby in XM was decided on by Cassini Icy Satellites Planning Team (SOST) to the different instrument teams, UVIS was not allocated the E5 flyby. Instead, the flyby was given the the MAPS team. As a result, the 080520 reference trajectory [o] update changed the nominal E5 B-plane angle from 70° to 90° to minimize the spacecraft's flyby altitude over Enceladus' south pole just as was done in the original design of the E4 flyby (also allocated to MAPS).[12]

Acknowledgments

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[o] Current reference trajectory at the time of this writing.

References

[1]Cassini Navigation Plan, August 2003.

[2]Matson D. L. Spilker, L. J. and J. P. Lebreton. The Cassini/Huygens Mission to the Saturnian System. *Space Science Review*, (104):1–58, 2002.

[3]Matson, D. Extended Mission Science Objectives (Presentation). *Cassini Extended Mission Review*, February 2007.

[4]Buffington, B., and Strange, N. Patched-Integrated Gravity-Assist Trajectory Design. In *AAS /AIAA Astrodynamics Specialist Conference,* Mackinac Island, MI, AAS Paper 07-276, August 19-23 2007.

[5]A. A. Wolf. Touring the Saturnian System. *Space Science Review*, (104):101–128, 2002.

[6]Cassini Project Policies and Requirements, Rev. E, May 2001.

[7]Cassini Extended Mission Navigation Plan, March 2008.

[8]Buffington, B., Ionasescu, R., and Strange N. Addition of a Low Altitude Tethys Flyby to the Nominal Cassini Tour. In *AAS/AIAA Astrodynamics Specialists Conference,* Lake Tahoe, CA, Aug. 2005, AAS Paper 05-270, August 2005.

[9]Strange, N., Russell, R., and Buffington, B. Mapping the V-infinity Globe. In *AAS /AIAA Astrodynamics Specialist Conference,* Mackinac Island, MI, AAS Paper 07-277, August 19-23 2007.

[10]Uphoff, C., Roberts, P. H. and Friedman, L. D. Orbit Design Concepts for Jupiter Orbiter Missions. In *AIAA Mechanics and Control Conference,* Anaheim, California, Aug. 1974, AIAA Paper 74-781, August 1974.

[11]Strange, N., and Sims, J. Methods for the Design of V-Infinity Leveraging Maneuvers. In *AAS /AIAA Astrodynamics Specialist Conference,* Quebec, Quebec, August 2001, AAS Paper 01-437, August 2001.

[12]Buffington, B. 080520 Reference Trajectory Update. *JPL IOM 343M-08-0XX*, TBD 2008.

[13]Cassini Extended Mission Science Objectives, Revision 1: Final Tour Selection, February 2007.

[14]M.K. Dougherty *et al.* Identification of a Dynamic Atmosphere at Enceladus with the Cassini Magnetometer. *Science*, (311):1406, 2006.

[15]C.J. Hansen *et al.* Enceladus Water Vapor Plume. *Science*, (311):1422, 2006.

[16]C.C. Porco *et al.* Cassini Observes the Active South Pole of Enceladus. *Science*, (311):1393, 2006.

[17]J.R. Spencer *et al.* Cassini Encounters Enceladus: Background and the Discovery of a South Polar Hot Spot. *Science*, (311):1401, 2006.

[18]Buffington, B. 070918 Reference Trajectory Update. *JPL IOM 343M-07-012*, TBD 2007.

[19]Marouf, E. Personal Communications, May 9, 2007.

[20]D. Seal. XM dust crossing Jan. 27, 2010. *email communication*, May 10 2007.

[21]M.M. et al. Hedman. The Source of Saturns G Ring. *Science*, (317):653, 2007.

[22]et al. Jones, G.H. The Dust Halo of Saturns Largest Icy Moon: Evidence of Rings at Rhea? *Nature*, (Pre-print (submitted March 1, 2007), 2008.

[23]Pelletier, F. 070209 Reference Trajectory Update. *JPL IOM 343j-2007-008*, March 1 2007.

[24]Strange, N., Buffington, B., and Jones, J.B. In-Flight Trajectory Changes to the Cassini-Huygens Prime Mission. In *AAS /AIAA Astrodynamics Specialist Conference,* Honolulu, HI, AIAA Paper 2008-6750, August 19-23 2007.

[25]Buffington, B. 060323 Reference Trajectory Update. *JPL IOM 343M-2006-003*, September 2006.

Appendix A: B-Plane Description

Planet or satellite approach trajectories are typically described in aiming plane coordinates referred to as "B-plane" coordinates[?] (see Figure 15). The B-plane is a plane passing through the target body center and perpendicular to the asymptote of the incoming trajectory (assuming two-body conic motion). The "B-vector," $\mathbf{B}$, is a vector in that plane, from the target body center to the piercing-point of the trajectory asymptote. The B-vector specifies where the point of closest approach would be if the target body had no mass and did not deflect the flight path. Coordinates are defined by three orthogonal unit vectors, $\mathbf{S}$, $\mathbf{T}$ and $\mathbf{R}$, with the system origin at the center of the target body. The $\mathbf{S}$ vector is parallel to the spacecraft $\mathbf{V}_\infty$ vector (approximately the velocity vector at the time of entry into the gravitational sphere of influence). $\mathbf{T}$ is arbitrary, but it is typically specified to lie in the ecliptic plane (Earth Mean Orbital Plane and Equinox of J2000.0 (EMO2000)), or in a body equatorial plane (Earth Mean Equatorial Plane and Equinox of J2000.0 (EME2000)). Finally, $\mathbf{R}$ completes an orthogonal triad with $\mathbf{S}$ and $\mathbf{T}$ (i.e., $\mathbf{R} = \mathbf{S} \times \mathbf{T}$). A target point can be described in terms of the B-vector dotted into the $\mathbf{R}$ and $\mathbf{T}$ vectors ($\mathbf{B} \cdot \mathbf{R}$ and $\mathbf{B} \cdot \mathbf{T}$). The spacecraft state in the B-plane can be represented by the following six quantities: $\mathbf{B} \cdot \mathbf{R}$, $\mathbf{B} \cdot \mathbf{T}$, TF (time-of-flight), $\mathbf{S} \cdot \mathbf{R}$, $\mathbf{S} \cdot \mathbf{T}$, and C_3. $\mathbf{S} \cdot \mathbf{R}$ and $\mathbf{S} \cdot \mathbf{T}$ are the declination and right ascension of the incoming asymptote $\mathbf{S}$ and C_3 is the vis-viva integral (V_∞^2). The B-plane error (miss) is determined by $\Delta\mathbf{B} \cdot \mathbf{R}$, $\Delta\mathbf{B} \cdot \mathbf{T}$, and ΔTF; the asymptote error is determined by $\Delta\mathbf{S} \cdot \mathbf{R}$, $\Delta\mathbf{S} \cdot \mathbf{T}$, and ΔC_3.

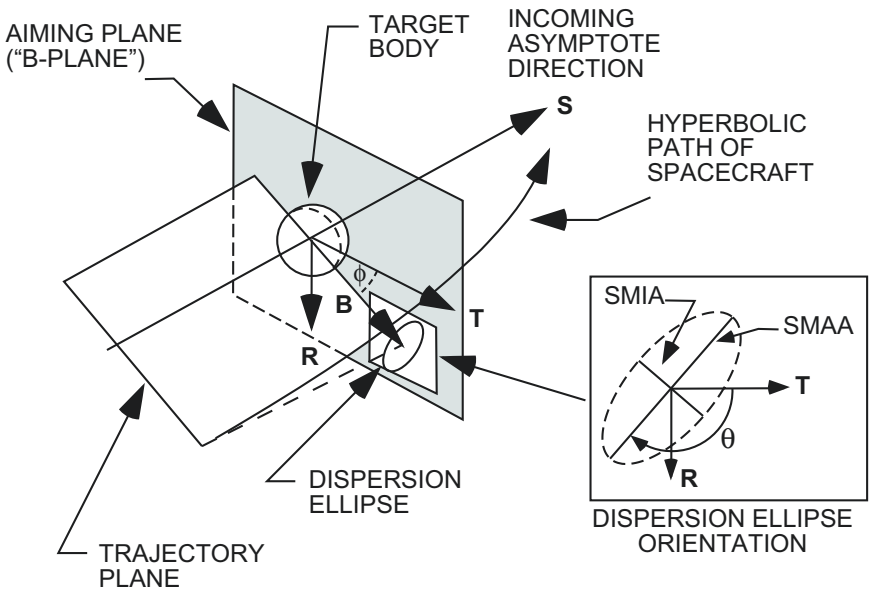

Figure 15. B-Plane Coordinate System

Appendix B: Tour Design Drivers

Table 4. Complete list of Cassini XM tour design drivers.

#	Drivers	Description
1	**Enceladus: phase < 60º**	ORS coverage of S. Pole, at phase < 60º for >= 30 min.
2	**Enceladus: phase > 150º**	ORS coverage of plume vents near S. Pole at phase > 150º for >= 30 min.
3	**Enceladus: early S. pole ORS**	ORS coverage of S. Pole, at phase < 60º for >= 30 min. (driver #1) coverage ASAP since portion of S.Pole heading into darkness for ~15 y
4	**Enceladus: high number of flybys**	5-7 "close" targeted or psuedo-targeted flybys with differing observational requirements
5	**Enceladus: plume penetration**	s/c c/a <250 km alt., below 70º S. latitude, inc << 45º and preferably inc = ~0º (CDA/INMS)
6	**Iapetus**	Currently not required. Would become a driver if required. ISS desires imaging of 300º W longitude and RSS desires flyby near equatorial ridge.
7	**Occs: rings ansa-to-ansa**	RSS diametric ansa to ansa occultation like first 7 revs of prime mission but at low ring opening angle (Earth declination of 2-6º). Inc typically < 10º.
8	**Occs: rings stellar**	Certain stars only available for inc > ~65º. 8 revs required post-T45, >= 12 preferred.
9	**Occs: Saturn high latitude**	RSS and solar Saturn occultations at latitudes > ~45º. 12 Northern and 6 Southern latitude occultations required.
10	**Occs: Saturn near equatorial**	RSS and solar Saturn occultations at latitudes <= ~45º. 12 Northern and 6 Southern latitude occultations required.
11	**Occs: Titan high latitude**	RSS and solar Titan occultations at latitudes > ~45º. >= 3-4 Northern mid-latitude preferred.
12	**Occs: Titan near equatorial**	RSS and solar Titan occultations at latitudes <= ~45º. >= 2 near equatorial and Northern mid-latitude preferred.
13	**Revs: MAPS auroral campaign**	Orbits that cross the auroral oval field lines at L-shell equal to 15 Rs for simultaneous MAPS/SWG campaigns <= 5 Rs range. Observations in S41 to influence observations in S43 (or beyond) which spans ~Aug 9, 2009-Sept 13, 2009. Typically requires inc > ~ 65º and Rp < 4.5 Rs
14	**Revs: UVIS auroral campaign**	10 hour opportunities at latitudes above 60º (north or south), within 20 Rs, and at phase > 90º to ensure good UVIS auroral imaging. Duration requirement difficult to meet at start of EM.
15	**Revs: distant apoapses**	Apoapsis distance > 50 Rs (>= 6 revs) (Saturn composition)
16	**Revs: dusk**	Revs with apoapsis in dusk Saturn LTST for MAPS
17	**Revs: equatorial**	Revs with inc < ~.5º (>= 4 dedicated "Saturn flybys") for VIMS/RADAR
18	**Revs: magnetotail**	Revs with apoapsis near midnight Saturn LTST to get magnetotail MAPS coverage
19	**Revs: solar wind**	Simultaneous measurement of solar wind (MAPS) and Saturn aurora (UVIS, ORS) which requires distant apoapses (> ~70 Rs) and phase from 75-105º and 75-145º.
20	**Rings: equinox ORS**	Inc. from ~10-30º during 4-5 month period centered about Equinox which occurs Aug. 11, 2009 (ORS)
21	**Titan: dusk c/a**	Titan c/a at 18 h LTST (dusk) (MAPS)
22	**Titan: eclipse c/a**	Titan c/a after at least 2 h of eclipse (MAPS)
23	**Titan: low asypmtotic phase**	ISS requirement for Titan observations
24	**Titan: low c/a phase**	VIMS requirement for Titan observations
25	**Titan: surface coverage**	a) RADAR: fill gaps,b) ISS: low phase on asymptote, fill gaps, c) VIMS: low phase at c/a