Updating the Reference Trajectory for the Cassini Solstice Mission

Powtawche N. Valerino

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

The Cassini-Huygens deep-space probe has successfully completed a four-year prime tour and a two-year extended tour of the Saturnian system. Now in a second extended phase called the Solstice Mission, the Cassini spacecraft will continue to gather data as directed by the reference trajectory until 2017. This paper will describe the process of how a reference trajectory update is prepared and delivered to the project by the navigation team during Solstice Mission flight operations. This paper will also document the timeline of products released and utilized, as well as the study to include an Enceladus occultation observation that occurs in 2016.

I. Introduction

A reference trajectory is considered to be the backbone of any mission's navigation plan. It is the road map that contains the finely-tuned details that a spacecraft requires to attain a mission's science objectives. Specifically, the reference trajectory provides predetermined targeting locations according to mission and science sequence planning. Since the Cassini spacecraft is the first man-made satellite solely dedicated to the exploration of the Saturnian system, reference trajectory updates prove to be essential in allowing scientists to gain the most information possible. Prior to Cassini, distant flybys of Saturn made by Pioneer 11, Voyager 1 and 2 spacecraft documented a science-rich environment, one of which motivated the planning of Cassini's science objectives for the tour.

The following provides a high-level overview of the process of updating a reference trajectory during operations. While it is common for all missions to update a reference trajectory during operations, this paper highlights the methods used to respond to science requests during a multiple flyby tour. Specifically, this paper documents the importance of navigation tool robustness, product deliveries, and a timeline that allows for the confirmation of a reference trajectory delivery is documented. With the Cassini mission's complex multiple flyby tour of Saturn's many moons,[1,2,3] this paper shows how the project's teams work together to process and implement an approved plan, all while subject to the project's required downsizing of personnel for the first and second extended missions.

As a result of the reduced budget for the Solstice Mission, the project agreed to no longer make design changes to the targeting locations. While the Solstice Mission reference trajectory science objectives[4] are as abundant as the Prime and Equinox tours, fixing the target locations for subsequent trajectory updates alleviates the need to re-analyze all data products at a high-fidelity level.

To demonstrate the robustness of the reference trajectory update procedure, and respond to high-value science, a small design "tweak" was permitted for analysis. Scientists who manage the Ultraviolet Imaging Spectrograph (UVIS) instrument identified an opportunity to obtain data during an Enceladus plume occultation in 2016. Based on navigation team best efforts, it was proposed to the project that a feasibility study be conducted to determine the ΔV cost of including an Enceladus plume occultation observation in March 2016, which lies between the Titan-117 and Titan-118 flybys. The significance of this request was to capture the proposed Enceladus plume activity during Enceladus apoapsis.[5] Previously, UVIS plume observations have only been taken near Enceladus periapsis.

To achieve this Enceladus plume occultation and maintain the current reference trajectory profile, i.e. targeted flybys locations, various cases to evaluate minimal cost impact were considered. The ΔV cost

*Navigation Engineer, Mission Design and Navigation Section, Jet Propulsion Laboratory, California Institute of Technology, Mail Stop 230-205, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, and AIAA Senior Member.

analysis included the bounded cases of allowing flyby time and altitude parameters to change (1) for all the flybys, and (2) for only the immediate Titan-117 flyby. After reviewing several options, the project chose one case that had little ΔV cost as well as minor effects on the present Solstice Mission reference trajectory. As a result, this small adjustment will be included in the next release of reference trajectory update in 2014.

Finally, as technical roles become streamlined to accommodate a mission end in 2017, this paper also highlights the efforts that will make the reference trajectory delivery process more efficient. In particular, this paper addresses the combining of personnel roles and the evolving interaction between teams during a reference trajectory update throughout the Solstice Mission.

II. Background

For the Cassini Mission, the reference trajectory is the baseline that the spacecraft has referred to throughout its three phases: Prime, Solstice, and Equinox Missions. Figure 1 shows an overview of these phases. This figure presents each mission phase and corresponding year of tour; and the number of Saturn orbits made by the Cassini spacecraft. Cassini's first phase, the Prime Mission, started in 2004 and ended in 2008. As depicted in the figure, the Cassini spacecraft made several flybys of Saturn's largest moon Titan to maintain the orbit, and flybys of other icy satellites such as Enceladus, Phoebe, Tethys, Hyperion, Dione, and Rhea.[6,7,8,9,10]

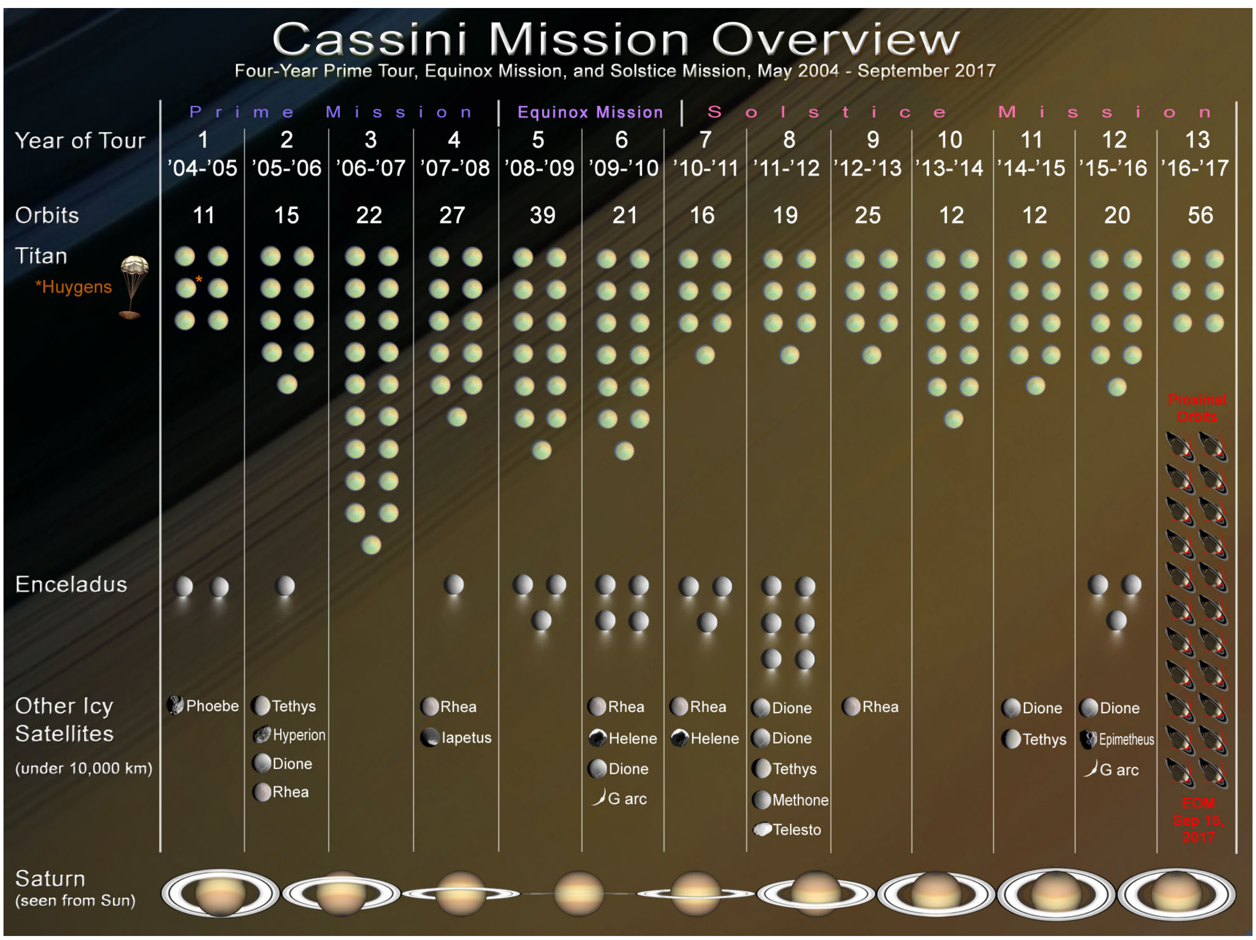


Figure 1. Cassini Mission Overview. *Courtesy of Dave Seal.*

After the Cassini spacecraft achieved its flyby milestones during the Prime Mission, adjustments to the reference trajectory were made to incorporate ephemeris updates and design changes based on the science discoveries. Table 1 lists the corresponding trajectory updates for each phase of the mission. Note that during the Prime Mission, nine formal reference trajectory updates were made.

Each of these updates required major review and collaboration between the mission designer, mission planner, and project science community. With success of the Prime Mission, a healthy spacecraft, availability of propellant, resulting science observations and navigation analysis influenced the design for the Equinox Mission. During the last two years of the prime tour, the science, mission, and navigation teams prepared several feasibility plans for the extended mission. Since the Equinox Mission was just as operations just as operations intensive as the Prime tour, there was time for only one trajectory release (see Table 1). However, during the second extended mission, or Solstice Mission, the plan for reducing navigation personnel does not allow for the opportunity to release frequent trajectory design changes and ephemeris updates. Therefore, only two reference trajectory releases were planned for release during the Solstice Mission. Note that in the development and evaluation of potential reference trajectories, several candidate trajectories were generated by tour designers and analyzed by project scientists, but were not implemented by the project. The following describes the process for updating and delivering these reference trajectories.

Table 1. Reference Trajectory Releases Planned for the Cassini Mission

Mission Phase	*Date Range*	*Targeted Encounters*	*Maneuvers Planned*	*Reference Trajectory Updates*
Prime	Jul 2004 - Jul 2008	52	160	9
Equinox	Jul 2008 - Jul 2010	36	95	1
Solstice	Jul 2010 - Sep 2017	73	214	2

III. Reference Trajectory Update and Delivery during Operations

The baseline reference trajectory published in a navigation plan is the foundation of Cassini's operational activities. It includes includes all the deterministic maneuvers required to control the trajectory from one encounter to the next. Science teams plan their observations assuming the orbit locations specified in the reference trajectory. Since the planning occurs far in advance of the actual observation, the task of delivering the navigation plan and corresponding updates must accommodate the project's daily operations schedule. In addition, the reference trajectory is updated periodically to reflect changes in target conditions, such as flyby altitudes.

The update of the reference trajectory during operations was developed to be robust and allow for flexibility of design changes and additional data processing. As shown in Table 1, there were more reference trajectory updates produced during the Prime Mission rather than the two extended missions. Due to the expected reduction of project staffing, a modified process was established. Figure 2 illustrates the modified process used for the Solstice Mission.

At the beginning of a mission phase, a *navigation plan* is generated. The navigation plan contains the baseline reference trajectory and reflects a compete analysis of full orbit determination covariance inputs and statistical predictions for deterministic and statistical maneuvers in the tour. If there are any target updates to reflect a modified science observation, updates to maneuver locations or changes to tracking schedules. The resulting product is the baseline reference trajectory.

Every few years, a *reference trajectory* update is made by updating the baseline reference trajectory with the most recent spacecraft state, and the most latest planetary and satellite ephemeris. The maneuver and flyby locations do not change, and the resulting product is a high fidelity spacecraft trajectory kernel (spk) file. Prior to the delivery of the spk, the Cassini project will have evaluated and approved the files that will be delivered.

The *reference trajectory delivery* process includes a software suite that wraps the spk files with appropriate headers that are needed to post for operations tool use. These files are acquired by all the various teams on the Cassini project. In addition, the corresponding light time file and Orbit Propagation and Timing Geometry (OPTG) that is used for interpreting spacecraft events at local time. The light time file includes the one-way light time file as a function of spacecraft event time in GMT and the OPTG file contains spacecraft geometric events.

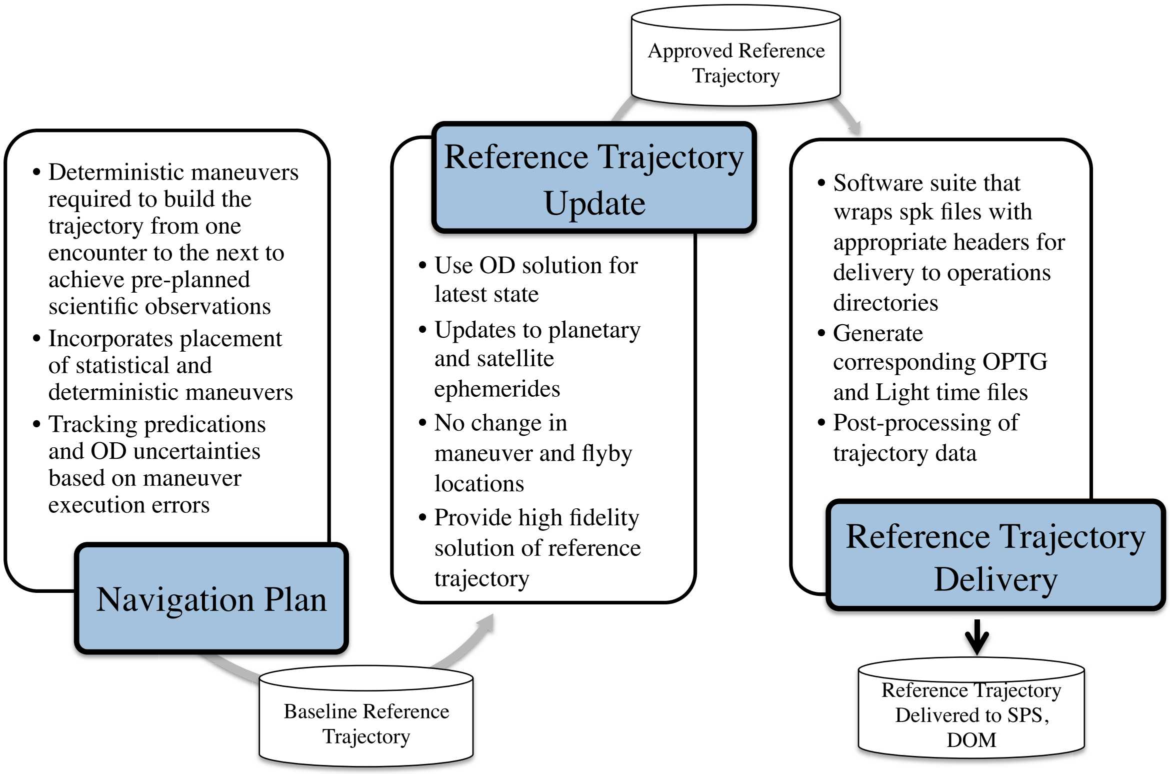


Figure 2. Reference Trajectory Update Process for the Solstice Mission

A. Operation Interface Agreement

With the understanding of staff reduction during the Solstice Mission, the Cassini Project developed an Operational Interface Agreement (OIA) which stated that no major design changes can be made to the reference trajectory. This is due to the fact that a significant design change would require careful analysis of the orbit determination covariances and statistical studies of the maneuvers necessary to achieve the planned flybys. Specifically, the OIA stated the following:

1. The Cassini Navigation Plan for the Solstice Mission will be updated on a two-year cycle. The first two years are considered "fixed" relative to maneuver locations and targeting strategies. Any changes during this period will require a formal change process.

2. The first update will be accomplished in 2011 and will include maneuvers from 2012, and focus on updating the subsequent two years;

3. An update opens up the possibility for minor changes in the requested Deep Space Network tracks and maneuver locations. The ground rules call for no changes in the targeted flybys (time and location).

4. A tentative schedule is to begin the updates in the April/May time frame. The proposed changes can then be reviewed at the June meeting of Project Science Group. The navigation team will then produce the updated reference trajectory incorporating any changes to maneuver locations.

5. Products include: start of reference trajectory until Saturn impact in September 2017; Position difference between this reference trajectory and the previous reference trajectory; Additional trajectory products to be delivered include the spacecraft kernel, planet ephemeris, satellite ephemeris, light time file and OPTG file.

6. List of updated maneuver schedule and ΔV estimates.

B. Development and Implementation Timeline

As listed in item 4 in the OIA, the schedule for the start of a reference trajectory begins in the April/ May timeframe. This is to allow time for review by the project science teams. If, for some reason, the initial release excludes a planned observation, a request for redesign can be made. However, since the OIA did not allow for changes in the time and location for targeted flybys, no deviations from the baseline reference trajectory were expected. After approval, the reference trajectory is then released within a few months.

Once a reference trajectory is delivered, the actual trajectory is not implemented for another six months or more. This is why there is an overlap of the former reference trajectory targets being “fixed” as noted item 1. This time is needed by the project to fold in the updates for sequence, mission, and navigation software. For example, after the release of the Solstice Mission baseline reference trajectory in 2009, the subsequent release was made in 2011, but did not take effect until early 2012.

IV. Enceladus Occultation Study

Although there was an understanding that no major design changes to the reference trajectory could be made during the Solstice Mission, changes with minor impact on the ΔV budget and existing science observations were considered. It was determined that a critical observation was excluded in the baseline reference trajectory. Specifically, an occultation takes place on 11-Mar-2016, bewteen Titan-117 and Titan-118 (during Rev 233). Table 2 shows the location of this occultation with respect to the Solstice Mission targeted encounters.

Table 2. Targeted Encounters for the Solstice Mission.[3,4] *Based on the Solstice Mission Navigation Plan.*

Encounter	Body	Date [ET]	Altitude [km]	Latitude [deg]	Longitude [deg]	In / Out	V-inf [km/s]	Period [days]	Inc. [deg]	Periapsis [RS]
T108 / 211Ti	Titan	11-Jan-2015 19:49:38	970	69.0	1.2	O	5.4	31.9	19.1	6.90
T109 / 212Ti	Titan	12-Feb-2015 17:09:07	1200	78.4	3.1	O	5.4	31.9	8.5	6.22
T110 / 213Ti	Titan	16-Mar-2015 14:30:51	2274	75.0	94.0	O	5.4	28.1	0.3	5.59
T111 / 215Ti	Titan	07-May-2015 22:51:32	2722	-1.1	67.0	I	5.4	18.9	0.3	4.12
D4 / 217Di	Dione	16-Jun-2015 20:12:58	517	79.9	260.2	O	7.3	19.0	0.4	4.13
T112 / 218Ti	Titan	07-Jul-2015 08:10:54	10953	0.6	293.9	O	5.5	21.8	0.5	4.71
D5 / 220Di	Dione	17-Aug-2015 18:34:35	474	84.4	280.5	I	6.4	21.9	0.4	4.71
T113 / 222Ti	Titan	28-Sep-2015 21:38:22	1036	-1.1	61.4	I	5.4	13.9	0.6	2.90
E20 / 223En	Enceladus	14-Oct-2015 10:42:37	1840	79.3	105.5	I	8.5	13.9	0.6	2.90
E21 / 224En	Enceladus	28-Oct-2015 15:23:53	50	-83.7	66.3	O	8.5	13.9	0.6	2.91
T114 / 225Ti	Titan	13-Nov-2015 05:47:41	11920	-14.4	122.5	O	5.3	12.7	1.4	2.54
E22 / 228En	Enceladus	19-Dec-2015 17:50:26	5000	-88.4	352.9	O	9.5	12.9	1.3	2.57
T115 / 230Ti	Titan	16-Jan-2016 02:21:59	3817	-8.4	300.4	O	5.5	16.0	2.4	3.50
T116 / 231Ti	Titan	01-Feb-2016 01:02:31	1400	-83.6	175.3	O	5.4	16.0	16.0	3.81
T117 / 232Ti	Titan	16-Feb-2016 23:53:09	1018	-38.7	284.7	O	5.4	23.9	20.6	5.96
T118 / 234Ti	Titan	04-Apr-2016 19:49:05	990	-63.0	245.2	O	5.4	31.9	27.8	8.14
T119 / 235Ti	Titan	06-May-2016 17:01:50	971	-59.9	178.2	O	5.4	31.9	35.3	9.81
T120 / 236Ti	Titan	07-Jun-2016 14:13:42	975	-36.6	146.5	O	5.4	23.9	42.4	10.45
T121 / 238Ti	Titan	25-Jul-2016 10:05:44	976	-7.0	129.1	O	5.4	16.0	48.7	9.30
T122 / 239Ti	Titan	10-Aug-2016 08:38:19	1599	9.3	126.0	O	5.4	12.0	53.6	7.53
T123 / 243Ti	Titan	27-Sep-2016 04:24:06	1737	21.0	126.0	O	5.4	9.6	57.8	5.59
T124 / 248Ti	Titan	14-Nov-2016 00:02:49	1582	36.2	122.0	O	5.4	8.0	61.4	3.62
T125 / 250Ti	Titan	29-Nov-2016 22:21:25	3223	41.4	127.7	O	5.4	7.3	63.8	2.52
T126 / 270Ti	Titan	22-Apr-2017 06:20:50	979	66.4	94.3	O	5.4	6.5	62.2	1.06

The significance of this request was to observe increased Enceladus plume activity during apoapsis. Based on navigation team best efforts, the Ultraviolet Imaging Spectrograph (UVIS) team requested that the navigation team conduct a feasibility study to determine ΔV cost and to find out if the Enceladus occultation could be included with minimal impact to current trajectory. Prior UVIS plume observations have only been taken near Enceladus periapsis. The importance of this observation is that scientists believe tidal forces would show higher plume activity at apoapsis.[5]

To assess the cost of including the Rev 233 occultation in the reference trajectory, the trajectory had to reflect the smallest increase of ΔV cost while minimally affecting existing observations. First and foremost, the 2011 reference trajectory placed the minimum polar crossing of the Rev 233 Enceladus occultation with star Epsilon-Orionus at 2473 km (Figure 3a). To achieve the occultation, the minimum polar crossing limb must be between 15-20 km. The best way to accomplish this occultation was to allow Titan-115 to float in altitude (since it is already a high altitude Titan flyby; small changes in altitude would not affect flyby science), and adjust the post Titan-117 inclination.

The strategy for the study was to vary the B-plane angle at Titan-117 to achieve the occultation while allowing all the targeted flybys are to "float" in time and altitude. The bounding cases included (1) only allowing Titan-117 to float in time and altitude (to minimize the effects on other flybys) or (2) allow all Titan flybys to float in time and altitude starting at Titan-108 to Titan-126. Other cases that allowed several flybys with high altitudes to float in time and altitude were considered.

Table 3. Enceladus Occultation Study

Trajectory	**ΔV** *cost (m/s)*	*Post-T117 inclination (deg)*	*Min. polar crossing limb alt (km)*	*T115 altitude (km)*	*Achieves T116 UVIS, T117 RSS, and T117 Enceladus occultation*	*Comments*
110818	- -	15.0	>2473.0	3817.4	T116 UVIS, T117 RSS occultations only	- -
Case 1	8.23	16.33	26.9	3520.3	Yes	T115 float only
Case 2	1.50	16.24	24.94	3548.7	Yes	T115, T122, T123 float only
Case 3	1.44	16.29	37.09	3533.2	Yes	T115, T117, T123 float
Case 4	1.14	16.24	24.28	3550.4	Yes	T115, T122, T123, T125 float
Case 4a	2.42	16.26	27.59	3542.1	Yes	T115, T122, T123, T125 float
Case 5	1.03	16.29	39.24	3533.9	Yes	High altitude flybys float
Case 6	0.76	16.296	21.83	3529.7	Yes	All flybys float
Case 7	0.67	16.295	29.71	3530.2	Yes	All flybys float
Case 7a	0.67	16.292	20.0	3531.1	Yes	All flybys float
140114	0.67[a]	16.292	18.81	3531.1	Yes	All flybys float

[a]Does not represent the final cost for the 140114 final delivery; does not include the proximal orbit dust ring model update.

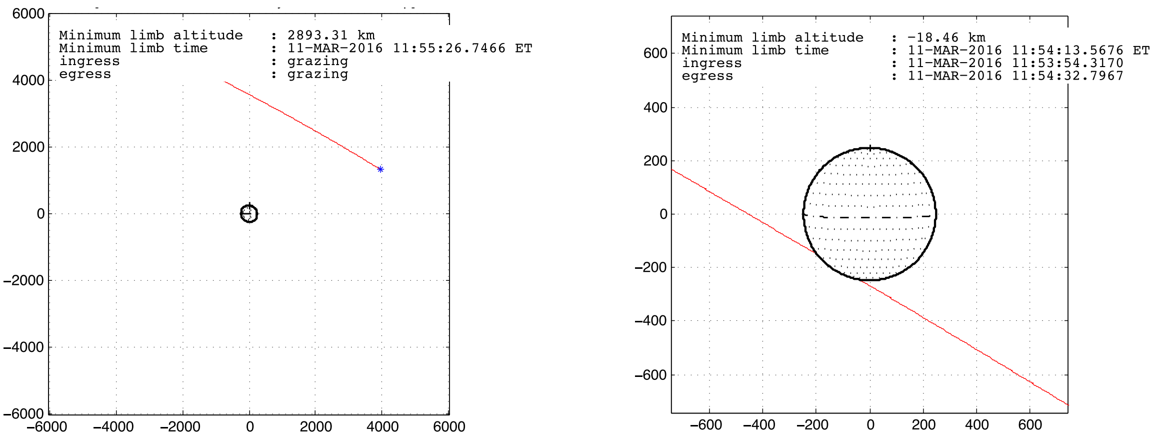
Table 3 lists the resulting ΔV cost for the various cases in which both of the post Titan-117 and variation of Titan altitude and times were adjusted (defined as "float"). Also noted is whether these adjustments maintained the highly valued Titan-116 UVIS and Titan-117 RSS occultations. The best option was case Case 7a, which not only achieved the Titan-117 Enceladus occultation at a small ΔV cost and minimum polar crossing limb altitude (Figure (Figure 3b), but upholds the Titan-116 UVIS and Titan-117 RSS occultations as well (Figures 4 and 5). Unfortunately, a RSS occultation was lost, but scientists felt that the Enceladus occultation had a high priority and aided to the understanding of the Enceladus plume.

V. Summary

This paper summarizes the process for updating a reference trajectory during the Cassini Solstice Mission. While it is common place for missions to update a reference trajectory during operations, this paper reviews the robustness of Cassini's reference trajectory update and delivery methods that are sensitive to the operations environment, as well as allow for the inclusion of a Enceladus plume observation that will take place during March 2016.

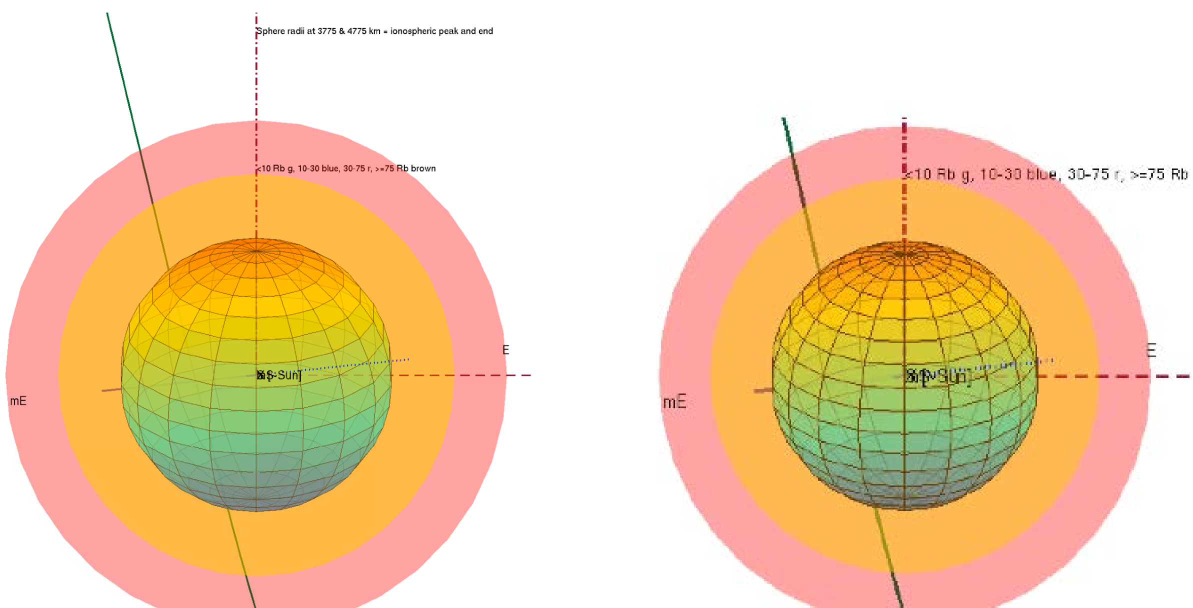
Acknowledgments

The author would like to acknowledge support from the following: Brent Buffington, Duane Roth, Yungsun Hahn, Kevin Criddle, Sean Wagner, and Allen Halsell.



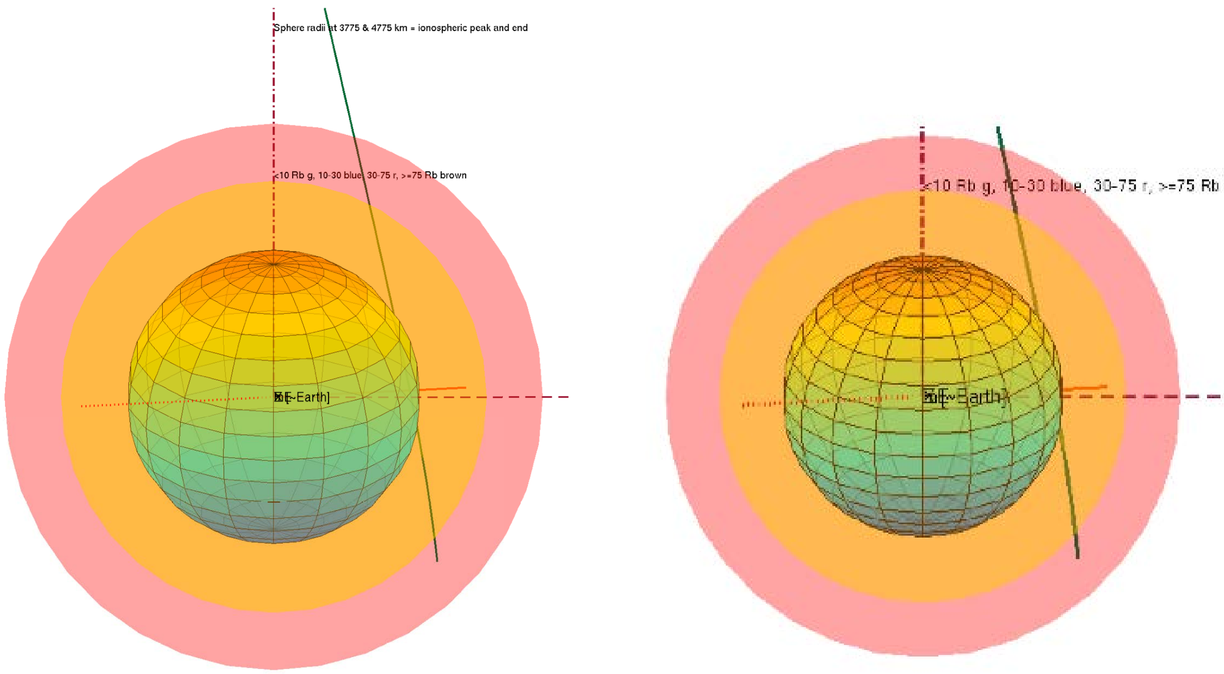
(a) Baseline Solstice Reference Trajectory (b) 140114 Reference Trajectory

Figure 3. Titan 117 Enceladus Occultation. *By adjusting the post Titan-117 inclination in the Baseline Solstice Reference Trajectory and allowing all Titan encounters to "float" in time and altitude, the Enceladus occultation in the 140114 reference trajectory is accomplished with a polar limb crossing 18.81 km.*



(a) Baseline Solstice Reference Trajectory (b) 140114 Reference Trajectory

Figure 4. Titan 116 UVIS Solar Occultation Geometry. *The occultation geometry is upheld with the 140114 reference trajectory design update. The green line indicates the path of the spacecraft during the planned occultation.*



(a) Baseline Solstice Reference Trajectory

(b) 140114 Reference Trajectory

Figure 5. Titan 117 RSS Occultation Geometry. *The occultation geometry is upheld with the 140114 reference trajectory design update. The green line indicates the path of the spacecraft during the planned occultation.*

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference to any specific commercial product, process, or service by trade name, trademark, manufacturer or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

References

[1]Buffington, B., "The Path to Scientific Discoveries: Designing the Cassini Solstice Mission Trajectory," *NASA ASK Magazine, Issue No. 41, pp. 15-18*, Winter, 2011.

[2]Ballard, C. G. and Ionasescu, R., "Flight Path Control Design for the Cassini Solstice Mission," *AAS-AIAA Astrodynamics Specialist Conference , AAS Paper 11-530*, Girdwood, Alaska, July 31-August 4, 2011.

[3]"Cassini Solstice Mission Navigation Plan," *699-101 Update, JPL D–11621*, February 3, 2010.

[4]Smith, J., and Buffington, B., "Overview of the Cassini Solstice Mission Trajectory," *AAS-AIAA Astrodynamics Specialist Conference , AAS Paper 09-351*, Pittsburgh, Pennsylvania, August 9-13, 2009.

[5]Hedman, M.M., Gosmeyer, C. M., Nicholson, P. D., Sotin, C., Brown, R. H., Clark,R. N., Baines, K. H. , Buratti, B. J., and Showalter, B. J., "An Observed Correlation Between Plume Activity and Tidal Stresses on Enceladus," *Nature*, August 08, 2013.

[6]Goodson, T. D., Gray, D. L., Hahn, Y., and Peralta, F., "Cassini Maneuver Experience: Launch and Early Cruise," *AIAA Guidance, Navigation, & Control Conference, Boston, MA*, No. AIAA 98-4224, Aug 1998.

[7]Goodson, T.D., Gray, D.L., Hahn, Y., and Peralta, F., "Cassini Maneuver Experience: Finishing Inner Cruise," *AAS/AIAA Space Flight Mechanics Meeting,* Clearwater, FL, AAS Paper 00-167, Clearwater, Florida, January 23-26, 2000.

[8]Goodson, T.D., Buffington, B.B., Hahn, Y., Strange. N.J., Wagner, S.V., and Wong, M.C., ""Cassini-Huygens Maneuver Experience: Cruise and Arrival at Saturn"," *AAS/AIAA Astrodynamics Specialist Conference, Lake Tahoe, CA, AAS Paper 05-286*, August 7-11, 2005.

[9]Wagner, S.V., Gist, E.M., Goodson, T.D., Hahn, Y., Stumpf, P.W., and Williams, P.N., "Cassini-Huygens Maneuver Experience: Second Year of Saturn Tour," *AIAA/AAS Space Flight Mechanics Meeting, AIAA Paper 2006–6663*, Keystone, Colorado, August 21-24, 2006.

[10]Williams, P.N., Gist, E.M., Goodson, T.D., Hahn, Y., Stumpf, P.W., and Wagner, S.V., ""Cassini-Huygens Maneuver Experience: Third Year of Saturn Tour"," *AAS/AIAA Astrodynamics Specialist Conference, AAS Paper 07–254*, Mackinac Island, MI, August 19-23, 2007.