(Preprint) AAS 16-142

CASSINI NAVIGATION: THE ROAD TO CONSISTENT SUB-KILOMETER ACCURACY SATELLITE ENCOUNTERS

Julie Bellerose[*], Sumita Nandi[†], Duane Roth[‡], Zahi Tarzi[§], Dylan Boone[§], Kevin Criddle[§], and Rodica Ionasescu[§]

This paper reviews the orbit determination performance for the last five years of the Cassini Mission Solstice Tour. During this period of time, Cassini had more than 30 satellite encounters, including Titan, Rhea, and Dione. We report on the navigational flyby accuracy, comparing post-flyby reconstructions and encounter predictions, and discuss the performance improvement and challenges over the years. Finally, we give an overview of the "Grand Finale" end of mission planned for 2017.

INTRODUCTION

Cassini launched in 1997, and has now completed its prime mission, its Equinox first extended mission, and 3 years of its Solstice second extended mission. The extended missions were named to correspond with the applicable season at Saturn. Since its arrival at Saturn in 2004, Cassini has completed more than 230 orbits around the planet. The prime mission included 45 flybys of Titan, 4 of Enceladus, and 9 of other icy satellites. The Equinox mission added 26 Titan encounters, and 12 more Enceladus and icy satellite flybys, and the Solstice mission has added 46 Titan encounters, 12 Enceladus, and 12 other icy satellite flybys. At the time of this meeting, Cassini has just entered the last Inclination Phase (Inc-3), getting ready for the final act. Over this period, there have been several papers describing the orbit determination process and performance up through 2012 [1,2,3,4,5,6]. This paper gives a high-level overview of the changes in orbit determination strategy since 2012 and a summary of the recent navigation performance.

In 2010, the Solstice mission was approved to continue exploring the Saturn system for seven more years. The Solstice Mission timeline, with color-coded sub-phases, is shown in Figure 1[7]. After the first inclination phase (In-1, 2010, ending with T79), Cassini came back to the equatorial region (Eq-1, until June 2012), then returned to higher inclinations in three different inclination phases that lasted 3 years (In-2A from 0 deg to 60+ deg, In-2B from 60+ deg to 40 deg, and In-2C from 40 deg to 0 deg), to come back to its last equatorial phase this year (Eq-2). In the last six months of the mission, Cassini will traverse the D-ring twenty-two times, passing just a few thousand kilometers from Saturn's cloud top. This last mission sub-phase, referred to as Proximal Orbits in Figure 1, has been named Cassini Grand Finale. The Cassini spacecraft will be disposed of during its final orbit, heading toward the planet and flying into Saturn's atmosphere on September

[*] OD Lead, Cassini Navigation Team, Jet Propulsion Lab, Caltech Institute of Technology.
[†] Mission Design and Navigation Staff, Jet Propulsion Lab, Caltech Institute of Technology.
[‡] Navigation Chief, Cassini Navigation Team, Jet Propulsion Lab, Caltech Institute of Technology.
[§] OD Analyst, Cassini Navigation Team, Jet Propulsion Lab, Caltech Institute of Technology.

22nd 2017. Smith and Buffington presented the scientific motivation behind the design in 2009[8] and 2010[9]. The extended trajectory also had to satisfy many operations and safety constraints[7].

During the past 11 years, Cassini has provided a wealth of new science discoveries, described in thousands of scientific papers (see Cassini Solstice mission website for latest[10]). Experience over the long mission duration has also evolved better science support products through process enhancements and in-flight calibrations. For instance, satellite encounter accuracy has improved from kilometers at the start of the tour, to typically sub-kilometers in the last three years (even less than 100 meters for a few encounters!) – a remarkable attainment considering the large distance between Earth and Saturn. This was achieved from a combination of careful maneuver performance analysis, improved orbit determination strategies, and improved ephemerides of the natural bodies in the Saturn system. In addition to improving science return, the established nature of the operations has made it a fruitful training ground for new engineers.

While the improvements to the navigation accuracy has been a long process, this paper focuses on those lessons learned and adopted strategies in the past 3 years of operations. We characterize the navigation process performance in terms of the latest targeted encounter results, and we discuss some navigation challenges. Finally, we give an outlook of the work involved in completing the next one and a half year of the mission.

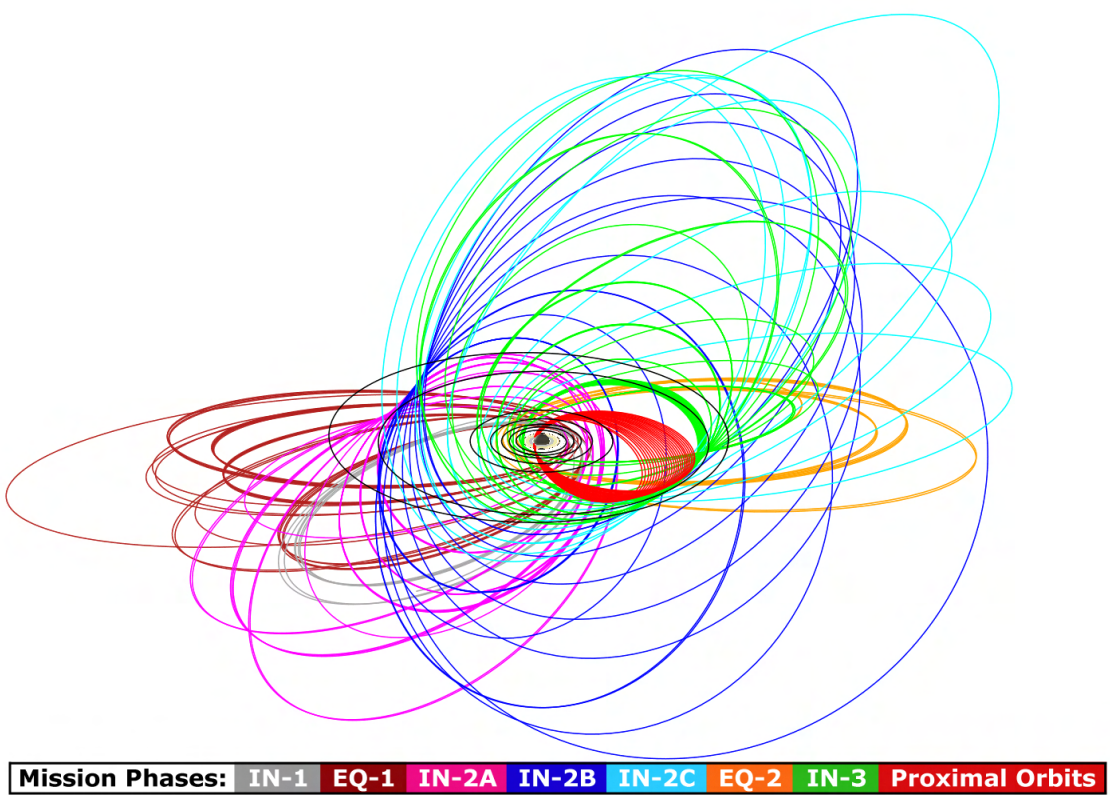


Figure 1. Solstice mission Saturn-centered trajectory oblique view[7]. The coloring scheme represents the various phases of the trajectory, either at inclination or in the equatorial region. The small red set of orbits corresponds to the proximal orbits phase.

NAVIGATION OVERVIEW

Navigation Operations Structure

Prior to flying the prime and follow-on missions, the mission designers create a reference trajectory, which satisfies the science requirements within the constraints of the spacecraft's hardware and operations constraints. The concept behind Cassini Navigation operations is to return the spacecraft to the reference trajectory at the time of targeted flybys as well as a few other predetermined control points. The spacecraft position is allowed to deviate from the reference between targeted encounters. A secondary (but obviously important) goal is to maintain ephemeris knowledge to the level required to quickly acquire spacecraft signal from Earth at any time and support science performed away from encounters. The process to implement this includes estimating the current spacecraft trajectory and associated parameters with their covariance and using this knowledge to compute trajectory correction maneuvers at several times between targeted encounters.

Operations Navigation is divided functionally into two sub-tasks: Orbit Determination (OD) and Flight Path Control (Maneuver). While the OD team estimates the spacecraft states and related parameters and uncertainties, the Maneuver team designs upcoming maneuvers to target upcoming encounters. The navigation analysis is divided temporally into segments focused on a particular targeted encounter, referred to as an 'arc'. Figure 2 below gives an example for the 229T115 arc, where the first encounter was the 22nd flyby of Enceladus (E22 for short) and the second encounter, Titan-115 (T115). The two arcs before and after are labeled 226E22 and 231T116. The overlap between two adjacent arcs provides validation for the current and next arc solutions.

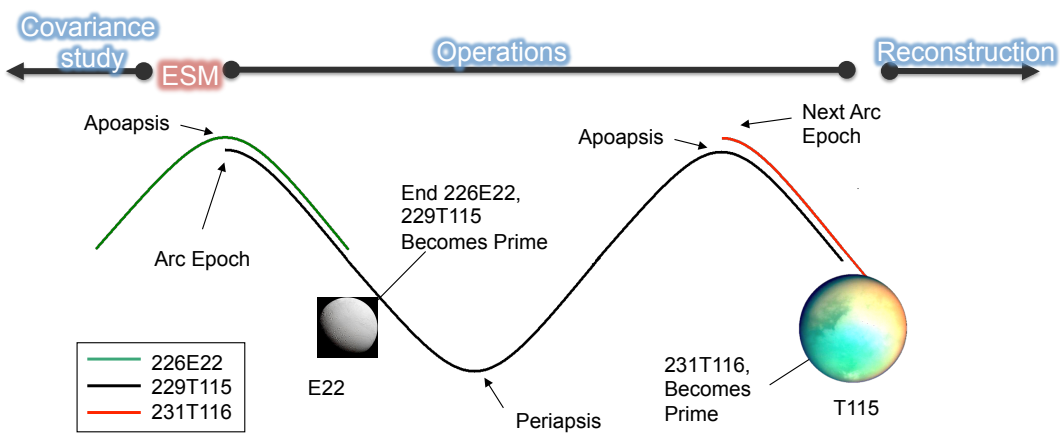


Figure 2. Schematic of the 229T115 arc, including the previous and next arcs, 226E22 and 231T116, respectively. (credit Cassini nav team).

In general, there are three maneuvers between two encounters, two deterministic and one purely statistical. A deterministic maneuver is one with a non-zero value in the reference trajectory, while a statistical maneuver is a placeholder. The first deterministic maneuver post-flyby is referred to as the 'clean-up' maneuver and is typically placed three days post encounter. A second deterministic maneuver is used in concert with the clean-up to target the following encounter. Finally a last statistical approach maneuver can be performed prior to an encounter to reduce target error from accumulated modeling errors or dispersion from previous maneuvers. To illustrate

this, Figure 3 shows the arc encompassing E22 and T115, where Orbit Trim Maneuver (OTM)-434 was the clean-up maneuver for E22 performed three days after E22, OTM-435 targeted T115 located near apoapse (note that one full revolution happened between OTM-434 and OTM-435), and OTM-436 served to refine the approach at T115, performed three days prior to T115. Note that Saturn is drawn close to E22 in this figure, with a line toward Earth, and "Cassini" indicates the position of the Cassini spacecraft on January 17th 2016.

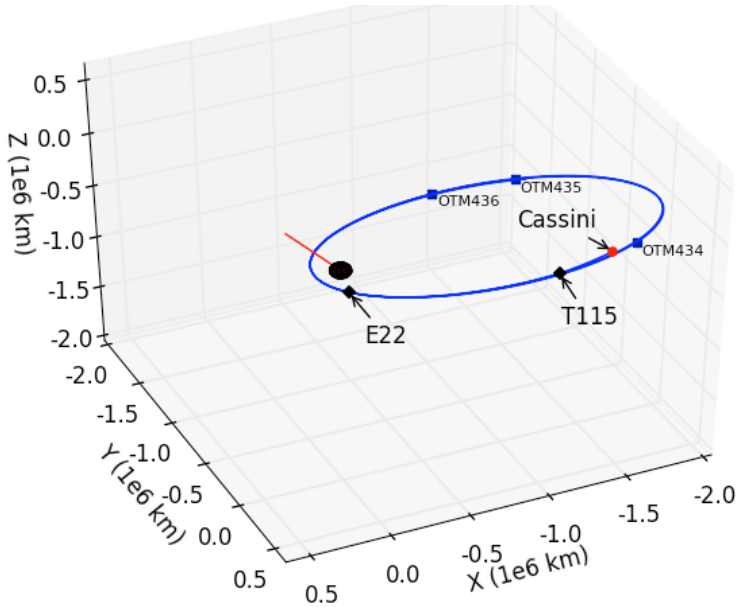


Figure 3. Cassini 229T115 arc, including the clean-up maneuver to E22, OTM-434, the targeting and approach maneuvers to T115, OTM-435 and OTM-436.

Orbit Determination Process

The OD team is responsible for predicting ephemeris accuracy, and supporting operations and science objectives. In that capacity, the team performs three distinct tasks for a given arc; a covariance study to look at upcoming dispersion and flyby accuracy prediction, operations during the given arc, and the arc reconstruction to provide the most accurate ephemeris and enhance science data reduction. The timeline of those tasks corresponds to that shown on Figure 2.

Maneuvers are typically targeted to the "B-plane" of the next flyby. Figure 4 describes the B-plane geometry. The B-plane plane is perpendicular to the asymptote of the incoming trajectory. The B-vector is defined as the vector joining the body center and the point where the asymptote meets the (perpendicular) B-plane. Note that physically, the B-vector indicates the closest point if the body had no mass. Three coordinate vectors are then defined, with S along the incoming velocity, T lying in the ecliptic plane, and R completing the triad. Using this geometry, the target point is described by the R and T components of the B-vector, B • R and B • T. The B-plane error is expressed in terms of those quantities, and the time of flight.

Since maneuvers in an arc are ultimately targeted to B-plane position and time, the state and covariance produced in the OD process is mapped forward to the B-plane of each encounter within an arc. An example of the trajectory error is shown on Figure 4, on the bottom right (dispersion

ellipse orientation). This represents a 1-sigma dispersion, characterized by the semi-major axis, the semi-minor axis, and the orientation. Figure 5 represents the B-plane at T115 shortly after OTM-435 was executed (Dec 29th 2015). Orange indicates the target point and delivery dispersion after maneuver execution, while the red represents the Cassini OD solution using data up to Jan 6th 2016.

Figure 6 gives an example of a pre-encounter covariance product, where B-plane uncertainties mapped to the flyby closest approach as a function of tracking data cutoff can be followed throughout the arc. Line-of-sight frequency uncertainties, science target pointing, and Saturn/satellite ephemeris uncertainties are also tracked throughout. The natural body ephemerides, in particular, are tracked since they can be improved during certain favorable encounters.

OD products from an arc are used for maneuver design operations one week to ten days after the arc epoch, in general after the last OD solution from the previous arc is delivered for the approach maneuver. As tracking data comes in, i.e. Doppler and range, atmospheric calibrations, Earth orientation, and data weights are updated. Depending on the arc timeline, small forces (on or off Earth-line biases for science, system check or calibrations momentum management), and dynamical events are updated as well (more details in Ref 6).

The spacecraft state, OTM parameters, parameters for small burns from turns and momentum management, acceleration from radioisotope thermoelectric generator heat and zero-mean stochastic accelerations are estimated with a linearized least-square estimation process with iteration to manage non-linearities. In addition, a single range bias parameter is estimated to fit errors in the Saturn ephemeris. The stochastic accelerations provide a means to prevent un-modeled dynamic and non-gravitational forces from biasing the estimate of the state parameters. The *a priori* values of these parameters are constrained using values based on the previous arc, or estimates external to the OD process. In addition, the error contribution associated with sensitivity to modeling Saturn ephemeris, Saturnian satellite ephemerides and Earth platform parameters is assessed via including their model parameters, with covariances, in the filter as consider parameters. Table 1 gives typical uncertainties of estimated and consider parameters used. Once a converged solution is obtained, interface products are delivered to the Maneuver team for the upcoming OTM design update. Occasionally, products are delivered to the Science Planning team to update pointing or timing of their observations.

Finally, the arc reconstruction provides the most accurate spacecraft ephemeris and other estimated parameters for science analysis. Some flybys have needed additional care, using post flyby tracking and reconstructed calibrations.

Table 1. Estimated and consider parameter uncertainties. [7] The latest OTM errors are taken from Ref 11, also see Ref 12 for historical data. "*" for less visited satellite such as Hyperion, Iapetus, Phoebe that can have uncertainties 2-5x those of icy moons.

Estimated	Apriori 1 sigma error	Consider	Apriori 1 sigma error
States	< 5 km, < 20 cm /s	Station locations	2 – 5 cm
Small forces	0.25 mm/s – 1.2 mm/s	Troposphere	1.0 cm wet, 1.0 cm dry
OTM (ME)	0.02% proport., 3.5 mm/s fixed	Ionosphere	5 cm day, 1 cm night
OTM (RCS)	0.4% proport., 0.5 mm/s fixed	Earth orientation	10 cm per axis
Stochastics	5 e -13 km/s2	Satellite*	<0.1 km Titan, <km icys
Transponder bias	500 m	Saturn	0.2 km

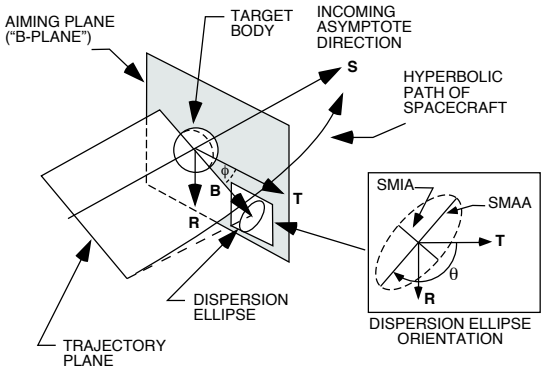


Figure 4. B-plane geometry representation[7].

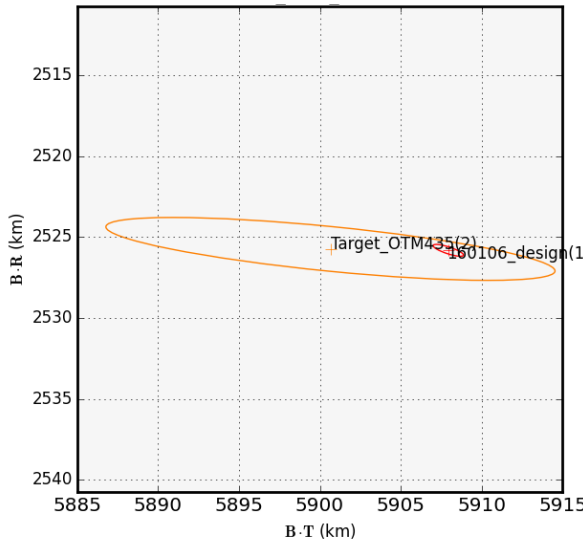
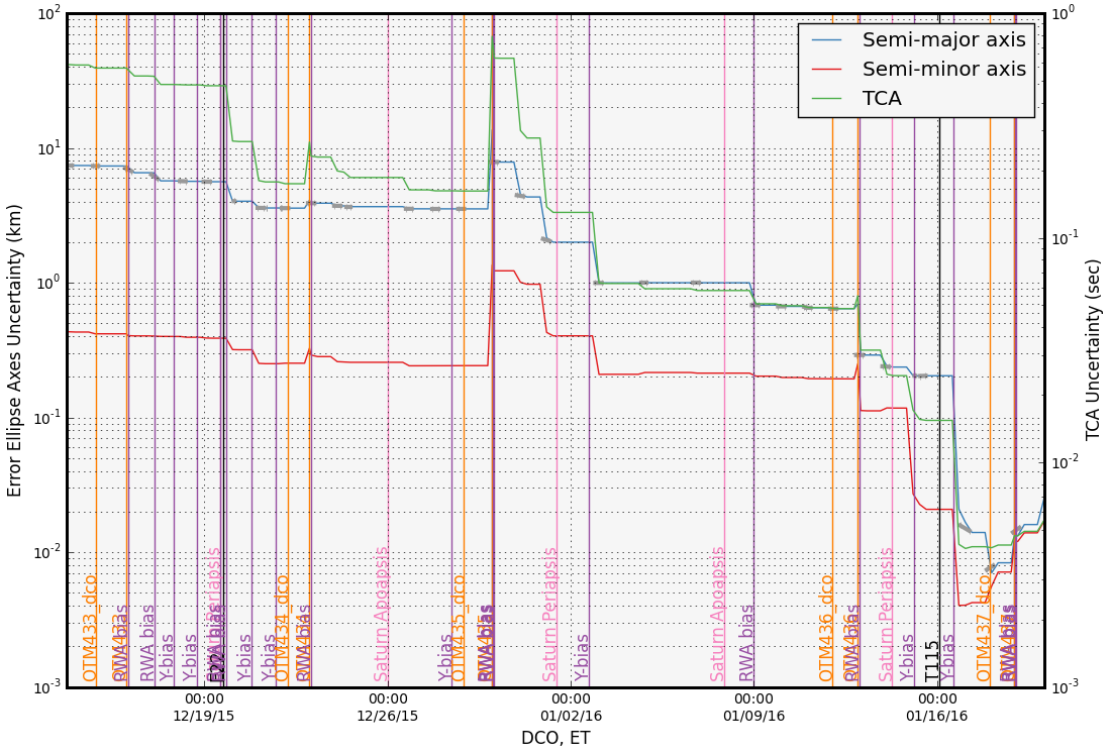


Figure 5. T115 B-plane solution (red), including the target and dispersion from OTM-435 (orange).



OTM	DCO (UTC)	B·R (km)	B·T (km)	Altitude (km)	TCA (s)	SMAA (km)	SMIA (km)
OTM434	22-DEC-2015 04:43:51	0.69	3.51	3.48	0.17	3.57	0.25
OTM435	28-DEC-2015 22:13:51	0.68	3.47	3.44	0.16	3.53	0.24
OTM436	11-JAN-2016 23:58:51	0.27	0.62	0.64	0.05	0.64	0.19

Figure 6. 229T115 B-plane uncertainties from the covariance study.

TARGETED ENCOUNTER PERFORMANCE

Then and Now, what has changed?

There have been significant changes in the Cassini navigation process over the last 11 years that have combined to reduce the satellite encounter accuracy from kilometers to as little as 10s of meters. Much of the improvement is related to better modeling resulting from on-orbit characterization of both the spacecraft and the Saturnian system. Some of the reduction comes from a shift in project priorities on use of propellant. The major contributors are discussed here.

The project is now especially concerned about fuel depletion, which would result in a premature ending for Cassini, and could potentially transgress planetary protection regulations. Latest propellant updates indicate the main engine has about 18 m/s of bipropellant left and the RCS system has 35 m/s of hydrazine available (90th percentile number)[13,14]. Since a Titan encounter imparts a large delta-v, small target misses can result in significant downstream delta-v to return the spacecraft back to the reference trajectory. As a result, the navigation team evaluates the downstream delta-v (and hence, propellant) penalty associated with cancelling each upcoming maneuver, and typically waits to evaluate the maneuver design using OD from the last tracking pass prior to the maneuver to make a cancellation decision. During the Solstice Mission, the threshold above which downstream cost of cancellation has become unacceptable is 70 mm/s compared to roughly 0.5 m/s in the Prime and Equinox Missions. The approach maneuvers are particularly affected, as it is common now to implement a 20-30 mm/s maneuver a few days prior to encounter. In addition to resulting in better targeting, due to the late design cutoff, this process has resulted in smaller deviations from the reference trajectory (even away from encounters), which generally supports better navigation performance. The fourth year of the Cassini Solstice Maneuver experience was detailed by Vaquero et al 2014[11], while Wagner et al 2014[12] describe the effort in updating the OTM error modeling for both main engine and RCS maneuvers from looking at performance statistics. This error modeling has been updated every couple years.

There are extensive product exchanges between the Attitude & Articulation Control Subsystem (AACS) and Navigation teams for ingesting small forces, from activities such as turns for OTMs, spacecraft momentum management, or science related turns, and the process has been refined over the years. Navigation estimates for small forces directed along line-of-sight are used by AACS to improve knowledge of thruster forces. This in turn improves telemetered delta-v values for small forces not directed along line-of-sight. The overall effect is that all small forces are modeled better. In their paper presented in 2008, Ardalan et al[15] explained how telemetry was adapted to better suit navigation needs.

Another major change relates to our knowledge of ephemerides and gravity parameters of Saturn and its natural satellites. The Navigation team used to estimate the planet and satellite ephemerides from arc to arc, using the *a posteriori* states and covariance from one arc as the *a priori* input for the next arc to address errors in the ephemerides of the bodies. Bi-annual updates based on longer tracking arcs were also ingested. These Saturnian system updates also integrate astrometry from Earth-based observations and the Hubble Space Telescope, Doppler tracking from Pioneer 11, Voyager 102, and Cassini, and science imaging and ring occultation data. See Jacobson et al 2006 for more insights into the Saturn and satellite gravity field products generation[16]. By estimating satellite parameters directly, resonant bodies' parameters are also improved greatly. After 11 years of flight and data gathering in the Saturn system, the planetary and satellite ephemerides are now well known, to between a few 100s meters (Titan) to a few kilometers (icy satellites), and thus not estimated anymore with the operational OD process. Satellite ephemerides currently used are sat375, delivered in March 2015[17].

Cassini Optical navigation was originally one more source of data toward improving satellites knowledge. As satellite uncertainties have reduced, the OpNavs now serve to maintain the satellite ephemerides' accuracy and prevent runoff over time. The last OpNav is scheduled for September of 2016.

In addition to the obvious improvement in target-relative position determination from having better satellite ephemerides, changing to a strategy of holding the ephemeris of the natural bodies fixed shifts more information from the tracking data to the estimation of spacecraft state, and reduces the level of error in estimating dynamic parameters that would correlate with the state of the bodies.

Encounter Performance Summary

Table 2 below shows encounter accuracy statistics for each encounter since T80, in Jan 2012. Previous performance was discussed in Pelletier et al 2012[6] and Antreasian et al 2008[4]. The color scheme in the table follows the different phases of the Solstice Mission as indicated in Figure 1. The bold rows indicate flybys discussed in the next section.

The encounter performance at each flyby is quantified by comparing the post-flyby reconstruction to the predicted position at closest approach based on the design of the approach maneuver prior to the flyby. If the modeling and covariances are realistic, we expect the post-flyby B-plane solution to lie within the covariance of the pre-flyby B-plane error ellipse. Table 2 reports the 3D encounter miss in column 4 and corresponding 3D sigma level based on the state error covariance at the last pre-flyby control point in column 5. The 3D error is computed by differencing the pre- and post-flyby state coordinates at target closest approach, while the 3D error sigma is effectively the ratio between this error vector and the one-sigma error ellipsoid in the direction of the difference vector. This is analogous to computing the Euclidean distance of a vector, but weighted by the covariance matrix, which is referred to as the Mahalanobis distance. The relationship between the 3D error sigma and the probability of lying within the covariance ellipsoid specified by the last control point can be expressed in terms of the Gauss error function.

Figure 7 shows Titan encounter misses for the whole tour. On average, the 3D miss is 0.92km, whereas it was 1.45km and 3.1km during the Prime and Equinox Missions, respectively. The Titan ephemeris error improved from ~40km at the beginning of the Tour to a few 100 meters.

Table 2. Encounter Summary, 2012 - 2016.

Target	Date	Altitude (km)	3D error (km)	3D sig	Delivery acc. (%)	Comment
T80	02-Jan-12	29415	0.4	0.6	6	Software transition
T81	30-Jan-12	31131	2.1	1.3	39	sat351
T82	19-Feb-12	3803	1.0	2.1	78	
E17	27-Mar-12	75	1.2	2.2	83	E16 5 mos prior
E18	14-Apr-12	75	0.4	2.3	84	
E19	02-May-12	75	0.5	3.8	99	Saturn underest.
T83	22-May-12	955	1.6	0.9	14	
T84	07-Jun-12	959	1.9	1.9	68	
T85	24-Jul-12	1012	0.7	0.6	5	
T86	26-Sep-12	956	0.2	0.5	2	changed to sat355
T87	**13-Nov-12**	**973**	**1.3**	**4.3**	**99**	**Nav flyby**
T88	29-Nov-12	1014	0.6	2.2	83	
T89	17-Feb-13	1978	0.7	1.0	19	
R4	09-Mar-13	1000	0.4	1.2	29	
T90	05-Apr-13	1400	0.1	0.2	0.1	sat358
T91	23-May-13	970	0.1	0.3	0.6	
T92	10-Jul-13	964	0.5	1.5	50	

T93	26-Jul-13	1400	0.6	1.3	36	
T94	12-Sep-13	1400	0.1	0.5	3.4	
T95	14-Oct-13	961	0.2	1.6	54	
T96	01-Dec-13	1400	0.04	0.3	0.7	Solar conjunction
T97	01-Jan-14	1400	0.2	0.6	6	
T98	02-Feb-14	1236	0.42	3.5	99	3-sig under
T99	06-Mar-14	1500	0.23	0.6	6	sat360
T100	07-Apr-14	963	0.28	1.0	21	
T101	17-May-14	2994	0.06	0.9	14	
T102	18-Jun-14	3659	0.29	2.3	85	2-sig over
T103	20-Jul-14	5103	0.14	0.6	6	
T104	21-Aug-14	964	0.08	0.2	0.3	
T105	22-Sep-14	1400	0.21	1.1	27	sat365
T106	24-Oct-14	1013	0.07	0.9	14	
T107	**10-Dec-14**	**980**	**0.24**	**1.7**	**59**	**Nav flyby**
T108	11-Jan-15	970	0.20	0.4	1.4	
T109	**12-Feb-15**	**1200**	**1.62**	**3.5**	**99**	**1-sig over, sat381**
T110	16-Mar-15	2275	0.05	0.1	0.04	LGA, sat375
T111	07-May-15	2722	0.54	2.2	81	
D4	**16-Jun-15**	**516**	**0.74**	**1.8**	**65**	**approach otm canceled**
T112	07-Jul-15	10953	0.34	1.4	45	approach canceled
D5	**17-Aug-15**	**475**	**0.42**	**1.4**	**39**	**approach canceled**
T113	28-Sep-15	1036	0.13	0.7	7.9	
E20	**14-Oct-15**	**1840**	**1.68**	**2.4**	**87**	**1-sig under**
E21	**28-Oct-15**	**50**	**0.91**	**1.4**	**40**	**approach canceled**
T114	**13-Nov-15**	**11920**	**1.21**	**9.9**	**100**	**2-sig under**
E22	**19-Dec-15**	**5000**	**0.14**	**0.4**	**1.8**	**ap., target otm canceled**
T115	16-Jan-15	3817	0.55	2.5	88	

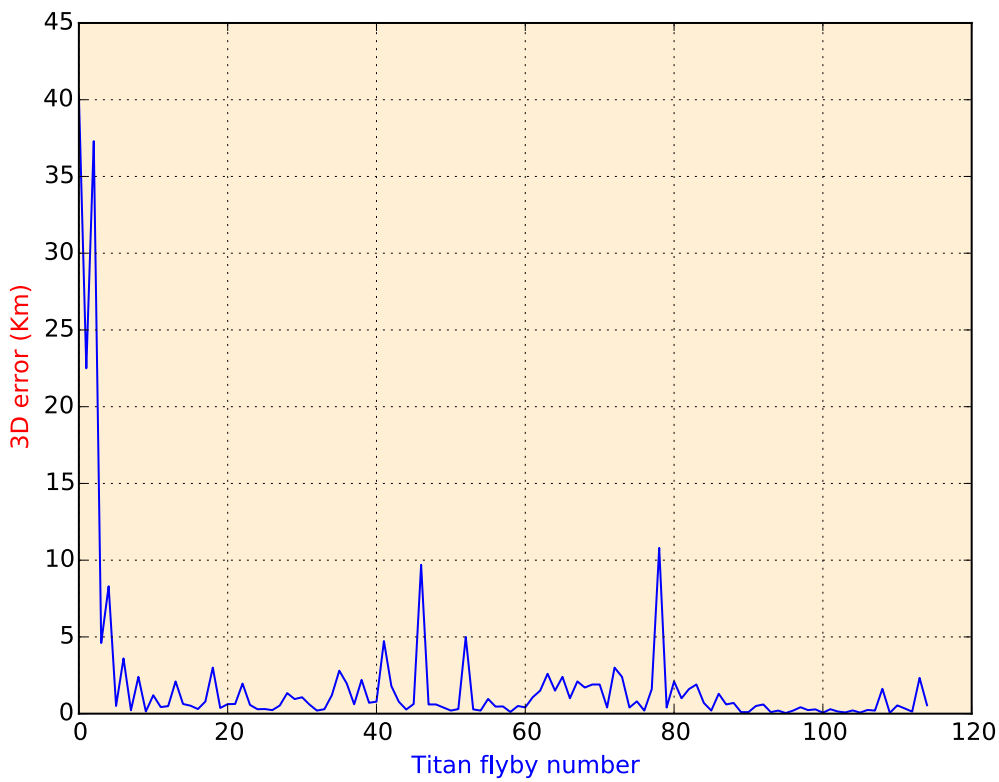


Figure 7. Titan encounter misses (in km) during the whole Cassini Tour.

Those Larger Misses, and Flybys of Interest

Although all satellite encounters offer incredible scientific data, a few will be discussed here either due to their unique science value or their larger than expected miss values.

T87 and **T107** were two dedicated navigation flybys. These encounters were particularly interesting due to their geometry being favorable for obtaining two-way coherent tracking throughout at low Titan flyby. Note that there have been other flybys with tracking, but at higher altitudes and used by the Radio Science Subsystem. The data obtained was used to estimate Titan atmospheric density and correlate with results from the AACS and INMS* teams. A week long arc was used in order to reduce complexity in the estimation process, with a refined model for the Titan atmosphere. Results were presented by both Pelletier[18,19] and Boone[20].

The T109 miss of 1.6 km was partially caused by a 1-sigma overburn of the approach maneuver, but mostly due to a change in satellite ephemeris, which finally did not fit Titan as well as previously. The T114 miss of 1.2 km was caused by a 2-sigma underburn of the targeting maneuver, with the approach OTM canceled.

The Dione flybys (**D4 and D5**) presented a few more challenges, having ephemeris errors in the order of one km, and Gm value, harmonics, and orientation partially defined due to distant past encounters. Many alternate modeling and estimation schemes were compared, including restarting the planet and satellite ephemeris and gravity estimation for more accurate results. The Dione parameters needed slight corrections. However, the miss at D4 was also partially due to a larger error on the ephemeris than expected.

Finally, the most recent icy satellite flybys were those of Enceladus (**E20** to **E22**). These flybys provided views of unseen surfaces, as well as data through the Enceladus plume. Like Dione, Enceladus parameters were more uncertain than for Titan. However, science pictures taken prior to E20 provided reassurance that the Enceladus state in sat375 was accurate to the level of its formal errors. Note that E22 was re-targeted (5km) for fuel savings.

Saturn Periapsis Anomalous Impulse

The last equatorial phase of Cassini (Eq-2, from T110 to T113) offered some more navigation challenges. During this phase, Cassini went from an orbit inclination of 8.5 deg to 0.3 deg (T110), and remained near 0 deg inclination until T113. Then, after two flybys of Dione and two of Enceladus, the inclination increased to 1.4 deg by T114 and E22 in November and December 2015, respectively. Curiously, the OD team observed modeling errors which manifested as small, unexpected delta-vs at some of the Saturn periapses during the equatorial phase. These were usually seen as few sigma shifts in the estimated state mapped to the B-plane between solutions made with data prior to and post Saturn periapsis. In addition, these anomalous delta-vs were also visible in the estimates of small burns before and after the periapsis, where the estimated values could be up to a few mm/s more than telemetered values. While the observed extra delta-vs were small, they were several times larger than the expected error on the small burns, which are calibrated to 0.25 mm/s with the use of post-burn telemetry and therefore, stood out. In order to prevent aliasing into dynamic parameters that impact forward state propagation and parameters of interest for calibration those added delta-vs were accounted for in the estimation process by using larger stochastic acceleration covariances. The magnitudes of the anomalous delta-v have slowly decreased since T114, although are still noticeable especially after a Titan flyby. Those periapsis anomalous delta-vs are plotted by closest approach distances with respect to body radius for Sat-

* Ion and Neutral Mass Spectrometer team

urn, Titan, Enceladus, and Dione flybys in Figure 8, and in terms of Saturn latitude and longitude for the Saturn periapsis only in Figure 9. The delta-v values reported were integrated using the estimated added stochastic accelerations (note that those were not needed at all close approaches). We noted larger anomalies when closer to Saturn, but no other distinct patterns.

Various options are being investigated. In particular, a run-off of the Saturn ephemeris could easily impart a few mm/s difference from the predicted Cassini states. Estimating Saturn parameters in attempt to resolve some of those anomalies have led to correction in the order of a few sigmas. In addition, small corrections in the planet orientation and spherical harmonics will have an impact of all satellite parameters. A new Saturn ephemeris is to be delivered soon by the JPL Solar Dynamics Group. Other possible causes include the ring mass, which will be integrated in our software soon, and a non-constant J_2 for Saturn. The J_2 perturbations are felt twice as much near zero inclination[21]. These are topics of ongoing work.

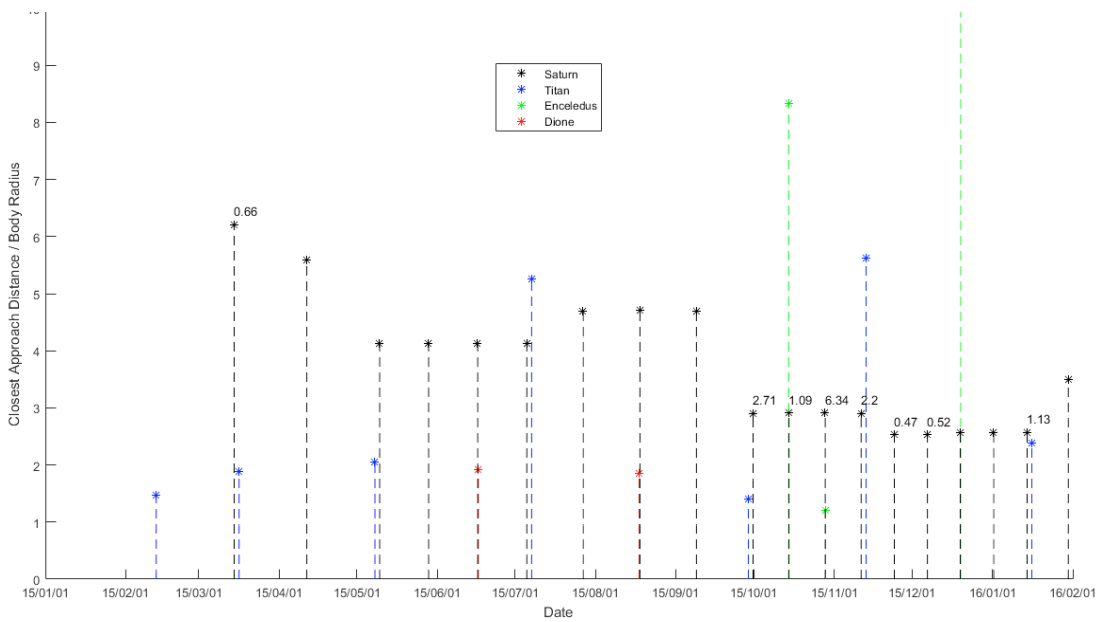


Figure 8. Saturn periapses and satellite flybys, including associated delta-v anomalies (in mm/s).

MISSION STATUS

There are now ten Titan flybys remaining in the Cassini mission, with the last one, T126, occurring on April 22nd 2017. From now on, every encounter will be increasing the Cassini orbit inclination, reaching 63 deg by T126, to prepare for the proximal orbit phase (Cassini Grand Finale). To achieve those remaining flybys, there are twenty-seven OTMs left to execute, with at least four to be performed on main engine (OTMs less than 0.25 m/s are executed with the RCS system). The project has reached the point where, in the case Cassini runs out of main engine bipropellant, it could complete all of the remaining maneuvers on the RCS thrusters system[13]. Still, every maneuver is carefully designed to avoid any unnecessary cost.

Although the mission comes to an end, the concern of running out of propellant has led to the development of additional design tools. In particular, the navigation team developed a tool to investigate alternate end of mission scenarios, taking into account NASA planetary protection protocols. It is with great interest that some of the team mission designers were able to develop tech-

niques using two-body and three-body flyby transfers theories to design feasible alternate endings within the Cassini budget[22].

Nonetheless, everyone on board is eagerly anticipating Cassini's F-ring and proximal orbit phases, depicted in Figure 10. The mission plan during the Cassini Grand Finale is comprised of 22 polar, highly elliptical orbits. The navigation concept for ballistic orbits with no satellite encounters is much different, and the science pointing requirements are only stringent near selected Saturn periapsis events. In order to meet the science requirements, only three maneuvers are planned in the five months after T126 to keep the Cassini trajectory dispersions small[23].

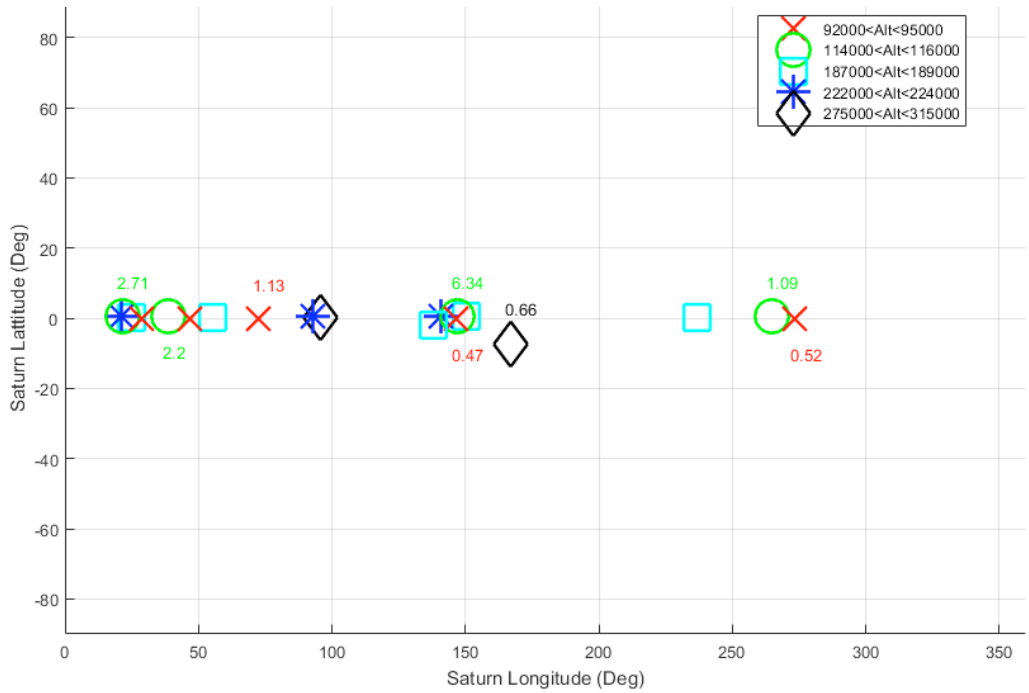


Figure 9. Latitude and longitude of Saturn periapses and associated delta-v anomalies (in mm/s).

CONCLUSION

The Cassini mission has been in orbit in the Saturnian system for more than 11 years, and has returned a wealth of discoveries and operational knowledge in the outer Solar System. In this paper, we reported on the last three years of navigation operations focusing on orbit determination and encounter performance. Modeling and strategy changes over the past years now allow us to navigate bodies at 100s of meters in accuracy, and consider a miss larger than 1 km an outlier. The Cassini Grand Finale will be spectacular - do not miss it!

ACKNOWLEDGMENTS

Although only members of the Orbit Determination Team are listed, the whole Navigation Team should get credit for the work highlighted here. The team is also thankful to Dr. William Folkner and Dr. Robert Jacobson for providing Saturn system ephemerides and gravity products. Additional appreciation goes to the Spacecraft team, particularly the AACS team, for their constant support. The Cassini mission is operated out of the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

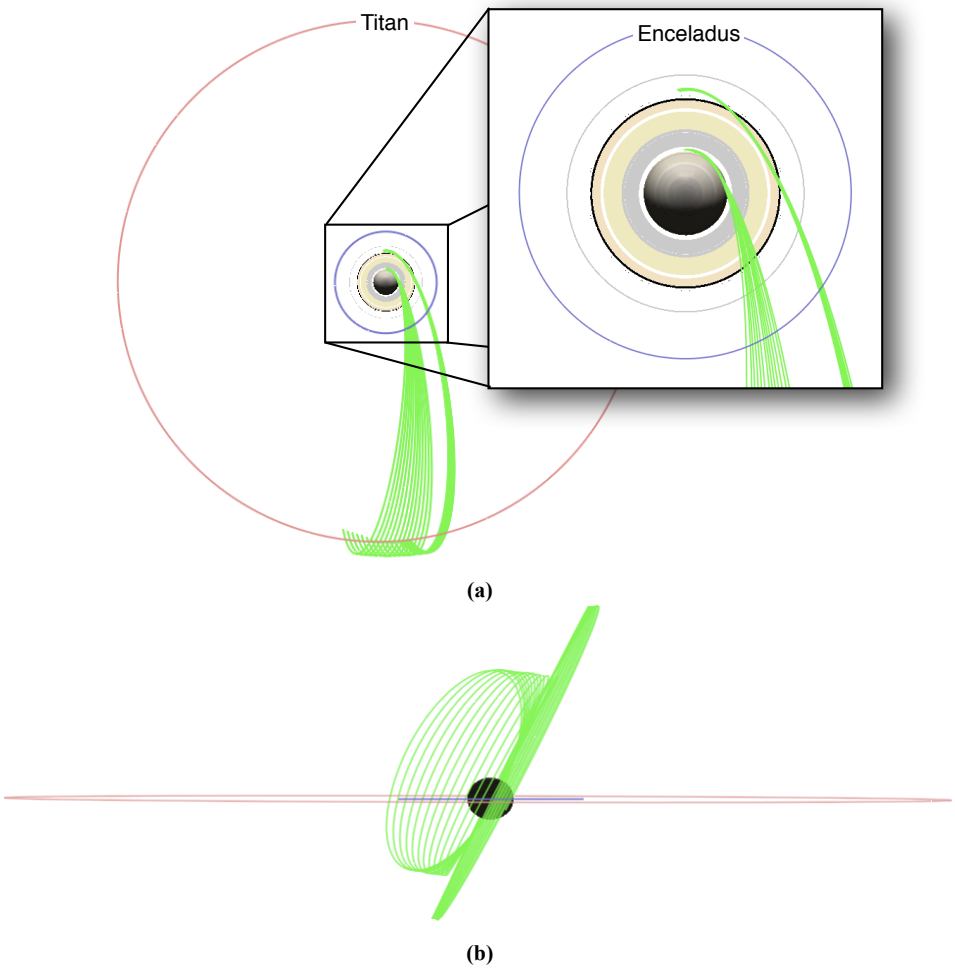


Figure 10. Cassini proximal orbits phase[7] (a) Saturn north-polar view, with spacecraft trajectory (green) above the ring plane showing evolution of node distances, (b) Saturn equatorial view.

REFERENCES

[1] Cassini Navigation Plan, Tech. Report 699-101 Update, D-11621, JPL, August 2003

[2] Cassini Extended Mission Navigation Plan, Tech. Report 699-101 Update, D-11621, JPL, March 2008

[3] P.G. Antreasian, J.J. Bordi, K.E. Criddle, R. Ionasescu, R.A. Jacobson, J.B. Jones, R.A. MacKenzie, M.C. Meek, F.J. Pelletier, D.C. Roth, I.M. Roundhill, and J. Stauch, "Cassini Orbit Determination Performance during the First Eight Orbits of the Saturn Satellite Tour", AAS 05-312, *Advances in the Astronautical Sciences* Vol 123, 2006

[4] P. G. Antreasian, S. M. Ardalan, J. J. Bordi, K. E. Criddle, R. Ionasescu, R. A. Jacobson, J. B. Jones, R. A. Mackenzie, D. W. Parcher, F. J. Pelletier, D. C. Roth, P. F. Thompson, A. T. Vaughan, "Cassini Orbit Determination Results: January 2006 – End of Prime Mission", *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, AIAA 2008-6747, 2008

[5] P.G. Antreasian, S.M. Ardalan, R.M. Beswick, K.E. Criddle, R. Ionasescu, R.A. Jacobson, J.B. Jones, R.A. MacKenzie, D.W. Parcher, F.J. Pelletier, D.C. Roth, P.F. Thompson, A.T. Vaughan, "Orbit Determination Processes for the Navigation of the Cssini-Huygens Mission", *SpaceOps 2008 conference*, AIAA 2008-3433, 2008

[6] F.J. Pelletier, P. Antreasian, S. Ardalan, B. Buffington, K. Criddle, R. Ionasescu, R. Jacobson, J. Jones, S. Nandi, S. Nolet, D. Parcher, D. Roth, J. Smith, P. Thompson, "Cassini Orbit Determination Performance (July 2008 – December 2011)", *SpaceOps 2012 conference proceedings*, Col 1, p.167, 2012

[7] Cassini Solstice Mission Navigation Plan, JPL Internal Document D-11621, 2010

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

[9] B. Buffington, J. Smith, A. Petropoulos, F. Pelletier, J. Jones, "Proposed End-of-Mission for the Cassini Spacecraft: Inner D Ring Ballistic Saturn Impact", *61st International Astronautical Congress*, Prague CZ, 2010

[10] Cassini Solstice Mission website, Saturn.jpl.nasa.gov, last updated 2016

[11] M. Vaquero, Y. Hahn, P. Stumpf, P. Valerino, S. Wagner, and M. Wong, "Cassini Maneuver Experience for the Fourth Year of the Solstice Mission", AIAA/AAS Astrodynamics Specialist Conference, AIAA 2014-4348, 2014

[12] S.V. Wagner, "Maneuver Performance Assessment of the Cassini Spacecraft Through Execution-Error Modeling and Analysis," *AAS/AIAA Space Flight Mechanics Meeting*, AAS 14-390, 2014

[13] E. Sturm, "Propellant Budget Update S91", *Cassini Mission Planning Forum*, January 2016

[14] E. Sturm, T. Barber, D. Roth, "Ensuring Cassini's End-of-Mission Propellant Margins", *IEEE*, 2015

[15] S.M. Ardalan, P.G. Antreasian, K.E. Criddle, R. Ionasescu, R.A. Jacobson, J.B. Jones, R.A. MacKenzie, D.W. Parcher, F.J. Pelletier, D.C. Roth, P.F. Thompson, A.T. Vaughan, "Integration of Spacecraft Telemetry into Navigation Operations for the Cassini-Huygens Mission", *SpaceOps 2008 Conference*, AIAA 2008-3412, 2008

[16] R.A. Jacobson, P.G. Antreasian, J.J. Bordi, K.E. Criddle, R. Ionasescu, J.B. Jones, R.A. MacKenzie, M.C. Meek, D. Parcher, F.J. Pelletier, W.M. Owen, D.C. Roth, I.M. Roundhill, J.R. Stauch, "The Gravity Field of the Saturnian System from Satellite Observations and Spacecraft Tracking Data", *The Astronomical Journal*, 132:2520-2526, 2006

[17] R. Jacobson, "Satellite Ephemeris File Release", ftp://ssd.jpl.nasa.gov/pub/eph/satellites/nio/LINUX_PC/, sat375l.txt, 2015

[18] F. Pelletier, et al. "Atmospheric Drag Model for Cassini Orbit Determination During Low Altitude Titan Flybys." AAS 06-141. *American Astronautical Society*, 2006

[19] F. Pelletier, "Results from t87 Atmospheric Density Experiment." *Tech. Rep. 392J-13- 002*, Jet Propulsion Laboratory, 2013.

[20] D.R. Boone, "Titan Atmospheric Density Results from Cassini T107 Flyby", ISSFD, 108, 2015

[21] B. Tapley, B. Schutz, G. Born, "Statistical Orbit Determination", *Elsevier Academic Press*, 2004

[22] M. Vaquero and J. Senent, "An Efficient Method to Design Premature End-of-Life Trajectories: A Hypothetical Alternate Fate for Cassini", ISSFD, 032, 2015

[23] M. Wong, Y. Hahn, D. Roth, M. Vaquero, "Trajectory Dispersion Control for the Cassini Grand Finale Mission", ISSFD, 009, 2015

© 2016 California Institute of Technology. Government sponsorship acknowledged. This paper is released for publication to the American Astronautical Society in all forms.